Paleoecological and paleohydrological reconstruction of Holocene deposits of the Cauca River based on diatoms and sedimentological analyses

A Thesis
Submitted to the Faculty of Graduate Studies and Research
In Partial Fulfillment of the Requirements
For the Degree of
Master of Science
in Geology
University of Regina

By
Andrea Torres Saldarriaga

Regina, Saskatchewan

May, 2014

UNIVERSITY OF REGINA

FACULTY OF GRADUATE STUDIES AND RESEARCH

SUPERVISORY AND EXAMINING COMMITTEE

Andrea Torres Saldarriaga, candidate for the degree of Master of Science in Geology**,** has presented a thesis titled, ***Paleoecological and Paleohydrological Reconstruction of Holocene Deposits of the Cauca River Based on Diatoms and Sedimentological Analyses,*** in an oral examination held on April 17, 2014. The following committee members have found the thesis acceptable in form and content, and that the candidate demonstrated satisfactory knowledge of the subject material.

External Examiner:	Dr. Mary Vetter, Luther College
Co-Supervisor:	Dr. Maria Velez Caicedo, Department of Geology
Co-Supervisor:	Dr. Ian Coulson, Department of Geology
Committee Member:	Dr. Osman Salad Hersi, Department of Geology
Chair of Defense:	Dr. Sandra Zilles, Department of Computer Science

Abstract

Lithofacies and diatom analyses of the Holocene deposits of Sucre, Las Flores, and the San Nicolás core in the middle Cauca Valley, Colombia, indicate that these sedimentary successions were deposited between ~4,300 and <200 cal yr BP, under different hydrological conditions. Based upon a study of diatoms, dominated by aerophil and benthic taxa, and sedimentological analyses it is suggested that the Sucre section was deposited in a proximal environment as indicated by incipient soils, ephemeral swamps, and high-energy river pulses (i.e., massive layers of coarsening-upwards, fine sand beds), controlled by the periodic flooding of the river floodplain. A fluvio-lacustrine environment developed on an ancient, confined floodplain represent a distal environment for the San Nicolás deposit, as evidenced in part by diatom assemblages distinct from those at Sucre, mainly composed of planktonic and epiphytic taxa. By contrast, evidences of fluvial connectivity were not found in the Las Flores section where deposition initiated some 1,000 to 2,000 years later compared, respectively, to Sucre and San Nicolás, according to the age models. The Las Flores deposit is characterized by a succession of soils covered by dry and wet forest, coupled with low to absent diatom contents, indicative of a terrestrial environment.

Despite the sedimentological, stratigraphic and ecological differences observed between the three sedimentary successions, regional climatic conditions can be identified. Fluctuations of dry and wet conditions were recorded for the lowermost parts of the deposits, between ~3,000 to 1,300 cal yr BP; whereas lithofacies and fossil structures (i.e., plant and animal bioturbation) throughout the uppermost parts of the three deposits indicated a change to drier conditions, between ~ 1,300 and <200 cal yrs BP.

This reconstruction contributes to an understanding of the possible mechanisms involved in the formation of these sedimentary successions, the hydrological interaction between the river and its floodplain, and the limnology of floodplain water bodies in braided fluvial systems. Here, I hypothesized that the genesis of these deposits corresponds to a combination of tectonics and climate since they are located on the active Romeral Fault System (RFS) and the hydrology of the Cauca River is most likely controlled by a precipitation regime influenced by the Intertropical Convegence Zone (ITCZ) displacement. This study confirms the complexity of the investigated fluvial deposits with frequent lateral and vertical variations, and presents information that can be used for the production of facies models in tropical-braided fluvial systems, that are still poorly understood.

Keywords: ancient floodplains, river-connectivity, diatom paleoecology, paleolimnology

Acknowledgements

I want to thank to the Faculty of Graduate Studies and Research (University of Regina), the Corporación Geológica – ARES, the Colombian Association of Petroleum Geologist and Geophysicist, the Foundation for the Promotion of Research and Technology – Bank of the Republic of Colombia, Dr. Maria I. Vélez and Dr. Ian Coulson (in the form of NSERC Discovery Grant monies) for the funding provided for this study.

I am also very grateful to my supervisor Dr. Maria Vélez for her support, advice and patience during the development of this project and my stay in Canada, as well as, my co-supervisor Dr. Ian Coulson. They not only directed my research project, but also they were always open to support me with every opportunity that allows me to improve as a professional and a student. Dr. José Ignacio Martínez is also thanked because he provided access to the sedimentary core of San Nicolás and other valuable information, including some radiocarbon dates and pictures of the core. External examiner Dr. Mary Vetter and internal examiner Dr. Osman Salad are thanked for their valuable comments and suggestions.

To my family and friends

"Un río pasa y lo miro, río abajo va.

Un río de agua de río que baja hasta el mar,

¿A dónde queda el mar, qué tan lejos está?

Y cuando un río pasa, adentro mío, por mi voz.

Y como si volara, se me inunda el corazón

También río yo…"

Marta Gómez

Table of contents

List of Tables

List of Figures

CHAPTER 1: Introduction

1.1 Holocene deposits of the Cauca River as potential archives for paleoenvironmental and paleoclimatic reconstructions

Floodplains are areas of sediment deposition adjacent to a river formed by episodic flooding events of the river. Floodplains play a fundamental role in fluvial ecosystems; they are areas for the redistribution and exchange of nutrients, and also CO_2, between the river and the floodplain itself (Thoms, 2003; Wiklund *et al*., 2010). When a river and floodplain connection is established during periods of flood, permanent and temporal aquatic ecosystems, such as ponds, swamps and lakes may also form on the floodplain. The structure, composition and biodiversity of these floodplain ecosystems are determined by ecological conditions of stress regulated by the river pulse (Junk *et al*., 1989; Van der Grinten *et* al., 2008; Ward and Tockner, 2001; Wiklund *et al*., 2010). That is, the periodicity of the flood pulse imposes regimes of wet and dry conditions which alter both the productivity of the ecosystems on the floodplain and interfere in the distribution and the biological processes of the biota (Bayle, 1995; Thoms, 2003; Thoms *et al*., 2005; Reid *et al*., 2011). In addition, deposition and erosion of sediments on floodplains can also occur during various flood stages with these being controlled by water flow and sediment transport (sediment load), which may vary depending on the channel pattern (Bridge, 2003).

Among the most notable landforms in river valleys are sedimentary terraces. These geomorphological features are vertical sedimentary successions deposited along one or both sides of river valley that correspond to ancient abandoned floodplains (Hodges, 1997; Archer *et al*., 2011). Hence, their sediments, sedimentary features and fossils (e.g., pollen, diatoms, sponge spicules) are archives of the past river hydrodynamics, and of a paleoenvironmental and paleoclimatic history (Hodges, 1997; Lowe and Walker, 1997; Archer *et al*., 2011).

River terraces can be preserved as both paired and unpaired deposits depending on the river pattern or channel morphology (i.e., straight, meandering, braided, anastomosing) and may be differentiated by lateral variations of the sediment layers (Lowe and Walker, 1997; Archer *et al*., 2011). There are several potential mechanisms responsible for the formation of terraces: 1) climatic variations, 2) base level changes, 3) tectonics, 4) bedrock lithology and 5) anthropogenic activities (Bull, 1990; Lowe and Walker, 1997; Pierce and King, 2008; Archer *et al*., 2011).

High-resolution sedimentary records, such as those present in the Cariaco Basin (Venezuela; e.g., Haug *et al*., 2001), Pallcacocha Lake (Ecuador; e.g., Rodbell *et al*., 1999), Brainbridge and El Junco Lakes (Galapagos Islands; Riedinger *et al*., 2002) have contributed to our understanding of the Holocene climatic history of the Neotropics. These laminated sedimentary records are located in a unique zone from the point of view of paleoclimate reconstruction, since diverse global phenomena such as the El Niño-Southern Oscillation (ENSO) and the latitudinal displacement of the Intertropical Convergence Zone (ITCZ) are evidenced within. In Colombia, sedimentary records, e.g., El Páramo de Frontino (Antioquia; Velásquez, 2005), and the Fúquene Lake (Van der Hammen and Hooghiemstra, 2003; Vélez *et al.,* 2006) have evidenced the history of these climatic phenomena. However, there is still a lack of high-resolution paleoclimatic information for the northwest region of South America, which is important in understanding the variability of these climatic phenomena on a regional scale. Here, the sedimentary succession of the Cauca River, represented in three sedimentary deposits, is explored as a potential archive for paleoenvironmental and paleoclimatic reconstruction of the late Holocene in the Neotropics.

It is considered that floodplains of braided rivers are not well developed due to the continuous lateral migration of the channel that allows for the erosion and rework of the floodplain deposits (Bridge, 2003; Nichols, 2009). Indeed, most of the studies on paleoecology of aquatic ecosystems on floodplains are focused on meandering rivers because of their wide floodplain extension and the formation of discrete oxbow lakes (e.g., Gell *et al*., 2002; Parolin *et al*., 2007, Grundell *et al.,* 2012).

The terraces studied herein are among those few ancient floodplain examples of braided rivers. These sedimentary successions represent a pristine sedimentary record of high resolution recognized by Page and Mattson (1981) in three late Holocene terraces: Obregón, San Nicolás and Olaya. According to these authors, the sediments of the three terraces represent lacustrine deposits of an ancient paleolake formed by periodic damming of the Cauca River at 3,100 yr BP, 1,500 yr BP and 800 yr BP, in response to the Guásimo mega-landslide that occurred near to the town of Sabanalarga (lower Cauca Canyon). Recent studies (García *et al.*, 2011; Martínez *et al.*, 2013; Vélez *et al*., 2013), however, have indicated that the deposition of the San Nicolás terrace was not the result of the episodic damming of the Cauca River as was formerly proposed by Page and Mattson (1981). Instead, tectonic studies in the Santa Fe-Sopetrán Basin, where the Cauca River deposits are located, suggest that the terraces could have been the result of subsidence within a pull-apart basin (Suter and Martínez, 2009; Suter *et al*., 2010). García *et al*. (2011) studied the San Nicolás succession from the section exposed at “La Caimana Creek” based on palynofacies analysis. Their study indicated that the laminated sediments were deposited between ~3,500 and ~1,000 cal yr BP during alternations of lentic and lotic phases imposed by the Cauca River on the floodplain, but they did not find any evidence for a deep or permanent lake. They also hypothesized that the hydrological phases reflect alternating rainy and dry periods, respectively, as indicated by the composition of the organic matter in the sediments. In addition, Vélez *et al*. (2013) presented a paleolimnological reconstruction of this laminated sedimentary succession using fossil diatoms. This study based on diatoms indicated that shallow lacustrine environments, both ephemeral and permanent, were formed in an ancient floodplain and that their existence depended on the connectivity with the Cauca River as suggested by the diatom aseemblages. Martínez *et al*. (2013) synthesized and compared the earlier findings to isotopic results for the sections (i.e., $\delta^{13}C$ and $\delta^{15}N$), and concluded that the San Nicolás succession was deposited in a ria-type lake, where tributaries are impounded by the main channel, akin to the environments formed in the Amazon Basin. Furthermore, Martínez *et al.* (2013) described preliminarily the Sucre deposit based on radiocarbon dating and included it as part of the San Nicolás succession along with the “La Caimana Creek” section. Moreover, the authors suggest that the sedimentological differences between these two deposits (Sucre and La Caimana) may in fact be explained by the sediment sources, which derive from different tributaries of the Cauca River as evidenced by paleocurrent measurements.

These previous studies presented a paleoenvironmental reconstruction of the San Nicolás succession based on the stratigraphy, paleoecology and geochemistry of the individual deposit of “La Caimana”. However, to establish the connection between deposits outcropping in the area, that is to determine whether the Holocene deposits correspond to a single terrace or represent different depositional environments, and therefore to understand the paleoenvironmental and climatic history of the north Andean region, a sedimentological and paleoecological study of the deposits of Sucre, Las Flores, and the San Nicolás section is needed.

1.2 Objectives of the study

The aims of this study are: 1) to reconstruct the paleoenvironmental history of the individual deposits of Sucre, Las Flores and the San Nicolás section based on fossil diatoms and lithofacies analyses, 2) to reconstruct the hydrological and ecological history of the alluvial paleofloodplain of the Cauca River based on a possible correlation of these sedimentary deposits, 3) to attempt to identify the possible mechanisms involved in the formation of the terraces that may include climate and tectonics, and 4) to explore the potential of these deposits for the extraction of climatic information. In order to reach these objectives the following questions are addressed: 1) Could diatom assemblages be used as markers of local or regional flood pulses traceable within the investigated sedimentary deposits?, 2) What were the hydrological conditions that formed Sucre, Las Flores and San Nicolás deposits?, 3) What were the limnological characteristics of the ancient water bodies formed on the floodplain, and 4) Are the lithological variations among the deposits the result of a structural control (tectonism) on the river or the presence of geomorphological features that caused dissimilar depositional environments on opposing sides of the valley? This information is not only useful in understanding the ecological dynamics of the aquatic ecosystems, as imposed by flood pulses in braided river floodplains, but also in determining how the paleohydrological history may relate to climatic conditions.

This work corresponds to the first regional paleoecological and paleohydrological study in the area, which is necessary to better understand the river pulse concept and its ecological implications in the fluvial environment. The Santa Fe –Sopetrán Basin where the deposits are located is an area of environmental and economic importance for the region and for the local population since many activities, such as alluvial mining and fishing, are developed there, and several endemic species inhabit specific ecosystems in proximity to the river (e.g., *Thryophilus* sernai; Gimena Ruíz Pérez, Aug. 11 of 2012).

Indeed, a big hydro-electric dam is being constructed in the Cauca River Basin, north of the area of study, and the recent deviation of the river flow has impacted the environment and the population near it and downstream (El Tiempo; Victor A. Álvarez, Feb. 17 of 2014). Therefore, studies such as this are very useful for the management of the river flow, to establish the possible ecological impacts and to design environmental plans to mitigate the negative effects on the fluvial ecosystems and the local population.

1.3 Study area and geological setting

The Cauca River, located between the Western and Central Cordilleras of Colombia, runs for ~1,183 km until it flows into the Magdalena River. In the middle Cauca River Valley, lies the Santa Fe-Sopetrán Basin (SFS Basin), a 20 km depression located along the Cauca-Romeral Fault (Suter *et al*., 2011, Figure 1). The SFS Basin is limited in the west by the Cauca Fault, in the east by the Romeral Fault, in the north by the Espíritu Santo Fault, and in the South a strong structural control is identified as a lineament that changed the river flow in W-E direction, forming the depression classified as a pull-apart basin (Suter and Martínez, 2009; Suter *et al*., 2011).

In this basin, the Late Miocene Combia Formation and the Eocene-Oligocene Amagá Formation (e.g., Grosse, 1926; Mejía, 1983; Ramírez *et al*., 2006) and the late Holocene fluvio-lacustrine deposits of the Cauca River that represent the last stage of the sediment accumulation at the north of the basin (Ruíz *et* al, 2002; Suter *et al*., 2011) overlie Precambrian metamorphic basement (Figure 2; Mejía, 1983).

Sucre, Las Flores and San Nicolás correspond to three of the Holocene fluvio-lacustrine sedimentary successions located along the Cauca River, in between the municipality of Santa Fe de Antioquia and the town of Sucre, Antioquia, Colombia (Figure 1). The Sucre section is located at 6°35’44.8’’N75°48’3’’W in the eastern flank of the river (Sucre town) whereas Las Flores deposit and the San Nicolás core are located at 6°35’34.4’’N75°48’19.7’’W and 6°30’N75°50’W in the western flank of the river, respectively (Santa Fe de Antioquia). The sedimentary succession where the San Nicolás core was extracted is confined by narrow and steep hills. Conversely, Sucre and Las Flores deposits are exposed on outcrops along the river.

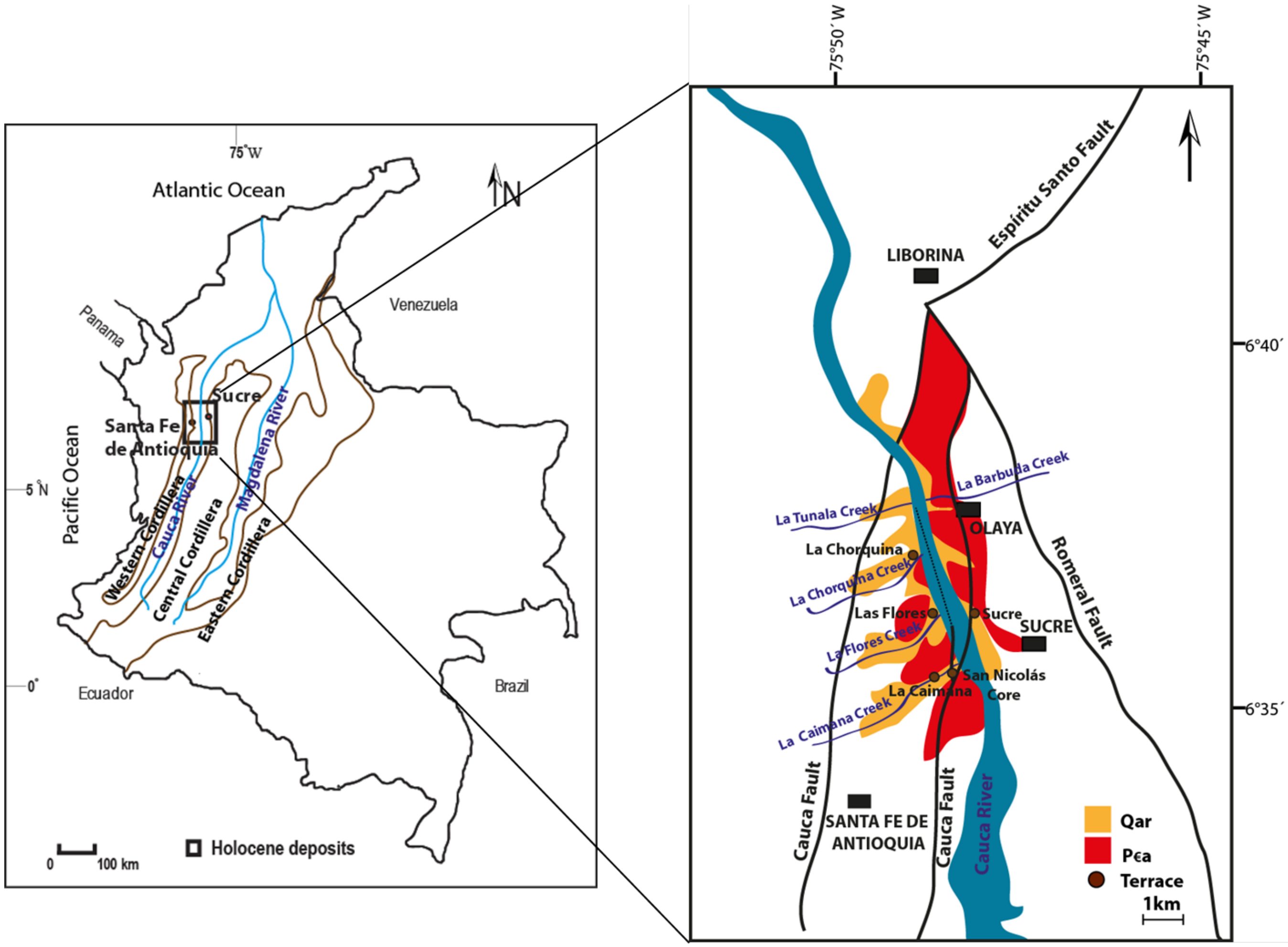


Figure 1. Location of the study area and simplified geologic map of the Santa Fe-Sopetrán Basin, middle Cauca Valley, Colombia. The location of Holocene deposits of Sucre, Las Flores and the San Nicolás core are represented with the black dots. Pєa refers to the Precambrian metamorphic, and Qar to the late Holocene terraces mapped in this study. Note the structural control by the Cauca-Romeral fault system and the Espíritu Santo Fault.

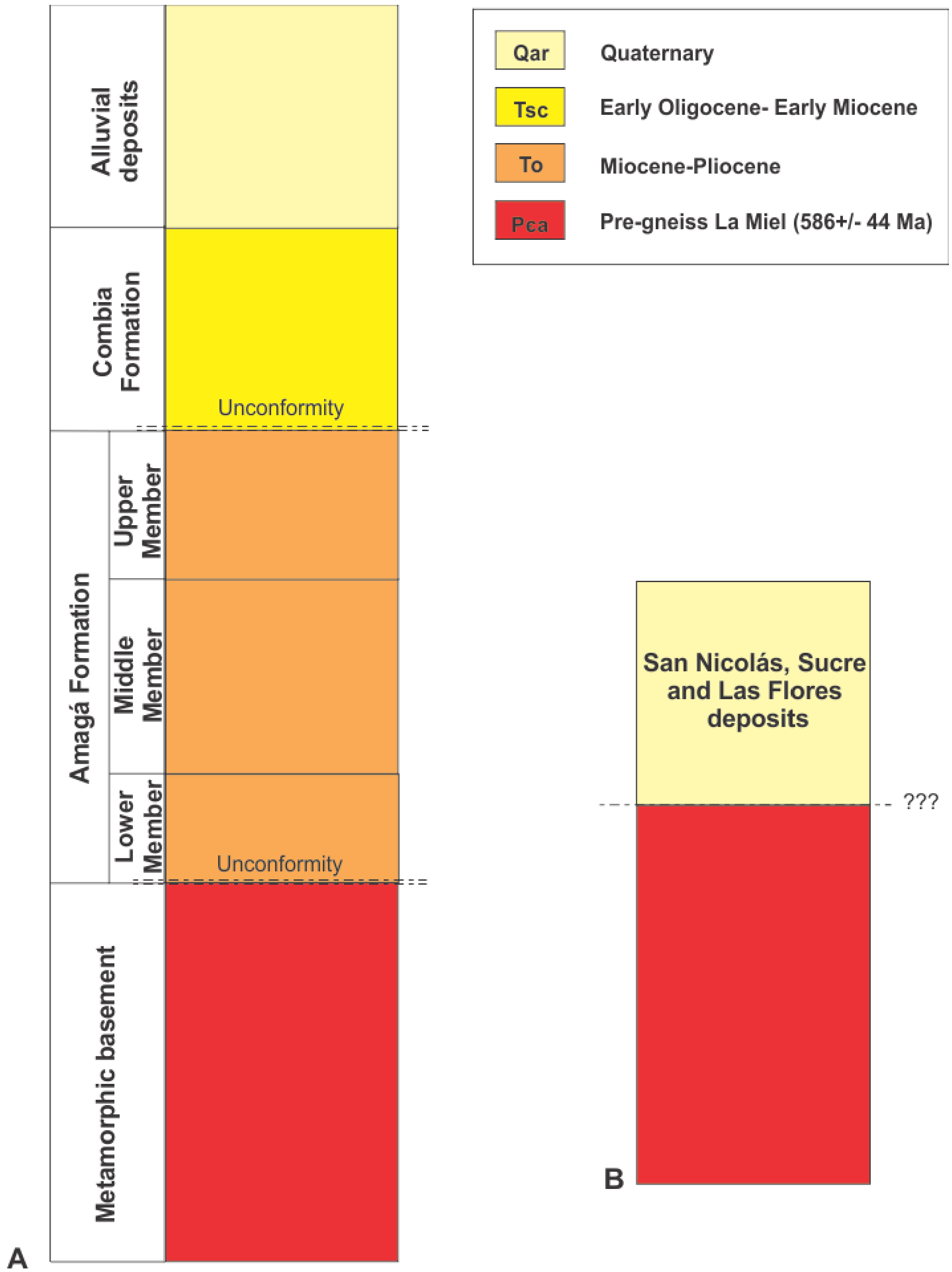


Figure 2. Generalized and idealized stratigraphy of the area of study. A. Note the Amagá Formation (To), the Combia Formation (Tsc) and the recent alluvial deposits (Qar) that overlie the Precambrian basement (Pєa). Contacts between the basement and the Oligocene to Pliocene formations were not observed but are identified as regional unconformities (Mejía, 1983). B. Contacts between the basement and the Quaternary deposits were not observed except for the Las Flores section.

1.4 Modern climatic conditions of the Cauca Valley

In Colombia, the precipitation pattern is bimodal with two rainy seasons between March-May and October-November, and two dry seasons between December-March and June-August (Mesa *et al*., 1997; Poveda *et al*., 2006). This seasonality is caused by the displacement of the ITCZ and the influence of the trade winds (Mesa *et al*., 1997; Poveda *et al*., 2006). However, this bimodal pattern is further modified by the influence of both the Chocó jet stream and the ENSO (Martínez *et al*., 2003). During El Niño, the Chocó jet stream is weakened producing a decrease in precipitation that results in a prolonged dry season (Poveda *et al*., 2006). In contrast, during La Niña this jet stream is reinforced resulting in an increase in precipitation (Poveda *et al*., 2006). Furthermore, because of the presence of the Andean Cordillera, most of the moisture that comes with the Chocó jet stream is delivered as rainfall before it reaches the Western Cordillera, creating a "dry-isolated region" across the eastern inter-montane valleys (Mesa *et al*., 1997; Poveda, 2002) where the middle Cauca River Valley is located. In the Cauca River Valley, El Niño is associated with dry periods while La Niña is related with high precipitation (Restrepo and Kjerfve, 2000) with an average of 1887 mm/yr (Restrepo *et al.,* 2005).

CHAPTER 2: Materials and Methods

This study has two components: field work and laboratory work. The field work was performed in two stages during the summer of 2012 and the winter of 2013. In the laboratory, diatom and sediment analyses were carried out to produce data for lithofacies characterization and paleoecological reconstructions to support the environmental reconstructions related to the studied deposits.

Field work that included logging and sampling of the Sucre deposit was initially carried out by Fiore Suter and Maria Vélez in 2010. Sampling was performed for diatoms analysis (42 samples) and radiocarbon dating (12 samples). In the field work of summer of 2012, additional samples for diatom analysis (n=31) and optical luminescence dating (n=1) were collected and the stratigraphic column of Sucre deposit was revised. In this campaign the logging of Las Flores deposit was also performed and a total of 177 sediment samples for sedimentological analysis and 4 samples for radiocarbon dating (^{14}C) were collected. During this field work detailed mapping of these late Holocene deposits was carried out on the northern part of the basin (La Tunula and La Barbuda Creeks, Figure 1).

In the winter of 2013 a second field season was carried out. During this campaign, I collected samples for pollen analysis (n=5) within the first 7 m of Las Flores deposit. The samples are characterized by organic layers with macrofossils of plant material, and the collection of one additional sample for optical luminescence dating, taken at the top of the sedimentary sequence. This procedure included also the sampling of the Sucre and Las Flores sections for paleosol analysis to be completed at University of Regina as part of an undergraduate student project (Dillon Johnstone). Additionally, a new, previously un-characterized section “Sucre Creek” was mapped and logged, and will form part of a different research project.

2.1 Description of the sedimentary deposits

Descriptions of the sedimentary deposits were performed at outcrops exposed along the modern river floodplain. The outcrops were cleared, removing vegetation and weathered surfaces to ensure descriptions were carried out on “fresh” sediments. Detailed observations were made noting lithology, grain size, sedimentary and deformation structures, presence or absence of paleosols, unit thickness and color using the Munsell soil color chart. Paleocurrent directions were inferred based upon measurements of cross-bedding lamination where present. The differentiation of beds and laminae followed that of Reineck and Singh (1980) in which beds are defined as strata with thickness of > 1 cm and laminations as < 1 cm.

2.2 Description of the San Nicolás core

Description and sediment sampling of the San Nicolás core stored at the Universidad EAFIT (Medellín, Colombia) was performed during the summer of 2012. This core was retrieved in 2006 by means of rotary drilling and a total of 24 m of sediment was recovered (Martínez *et al.*, 2007). For the description, observations of lithology, color, thickness, sedimentary structures, grain size and disturbance of core due to drilling were considered. Conditions of preservation for this core were made taking also into account the degree of disturbance caused during the core recovery/drilling. Conditions of preservation for this core were not optimal; however, organic sediment was collected for diatom analysis.

2.3 Methodology for diatom extraction

In the laboratory, 73 samples of the Sucre deposit and 23 samples of the San Nicolás core were prepared for the analysis of diatoms. From the samples prepared, 37 were found to contain diatoms and subsequently counted as part of the paleoecological reconstruction. At present, most of the methods for diatom research (e.g., Battarbee, 1973; Moore, 1973) are designed for lake-derived samples where the silt content is low and organic matter and diatom concentrations are high. In order to extract samples from these deposits, a novel method was developed in this study (Figure 3). Samples from modern environments for diatom studies were also collected in the lateral bar of the Cauca River (east flank), a temporary pond in the modern floodplain (west flank) and an ephemeral lake in January and February of 2013. Sediment samples were processed using a combined settling method, which applies the principles of conventional procedures (Battarbee, 1973; Moore, 1973; Law, 1983) and the technique used for the quantitative estimation of calcareous nannofossil abundances, proposed by Flores and Sierro (1997). A minimum of 300 valves were counted per sample, which is taken as a reliable population number for statistical analyses (Battarbee, 1986). Diatoms were studied under a light microscope at 1000x magnification and the identification of species was based on taxonomic keys (Krammer and Lange-Bertalot, 1986, 1988, 1991a, 1991b;

Patrick and Reimer, 1966, 1975) and electronic multi-access keys (Kelly *et al*., 2005; Spaulding *et al*., 2010). Diatom relative abundances are presented in parenthesis as a percentage (5-100%) (sections 3.2.3 – 3.4.3).

The process for the mounting of diatoms is novel and the product of research of the present study and such is herein described:

1. Weigh 0.05 g of dry sediment on a balance. The amount of sediment depends upon the diatom richness of the sample as well as the type of sediment (e.g., clay, silt or sand). However, 0.05 g is the maximum amount of sediment that allows the appropriate sediment settling for samples with variable grain size (e.g., fluvial sediments) using this technique. A larger amount of sediment would result in dense sediment microscope slides.
2. Place the sediment sample in a 10 ml beaker and fill with 5 ml of 30 % hydrogen peroxide (H_2O_2). Heat the mixture on a hot-plate to a medium-high temperature. Leave the samples to react until the organic matter and the H_2O_2 are fully consumed. It is important to prevent the sample from drying out.
3. Fill the beaker containing the sample with 10 ml distilled water.
4. Place four circular cover slips on the bottom of an 80 ml Petri dish and fill with 70 ml of distilled water, leaving 10 ml for the sample.
5. Mix the sample in the beaker by pumping with a 10 ml pipette in order to keep all the particles in suspension. Extract the entire sample with the same pipette and poux2r it into a Petri dish in a single pump or alternatively drop the sample

onto the dish fluid by pumping carefully with the pipette several times until the sediment distribution is homogeneous.

6. Leave the solution for 12 to 24 hours at room temperature (~20°C). This time will allow for the settling of the sediment onto cover slips and/or the bottom of the Petri dish. After allowing the sediment to settle out, withdraw any excess of fluid using short strips of filter paper placed around the edge of the Petri dish. Avoid contact with the sediment.

7. Remove the dry cover slips from the Petri dish and mount as permanent microscope slides using Zrax (R.I. 1.7+) or any other mounting media with an appropriated refraction index for diatom identification.

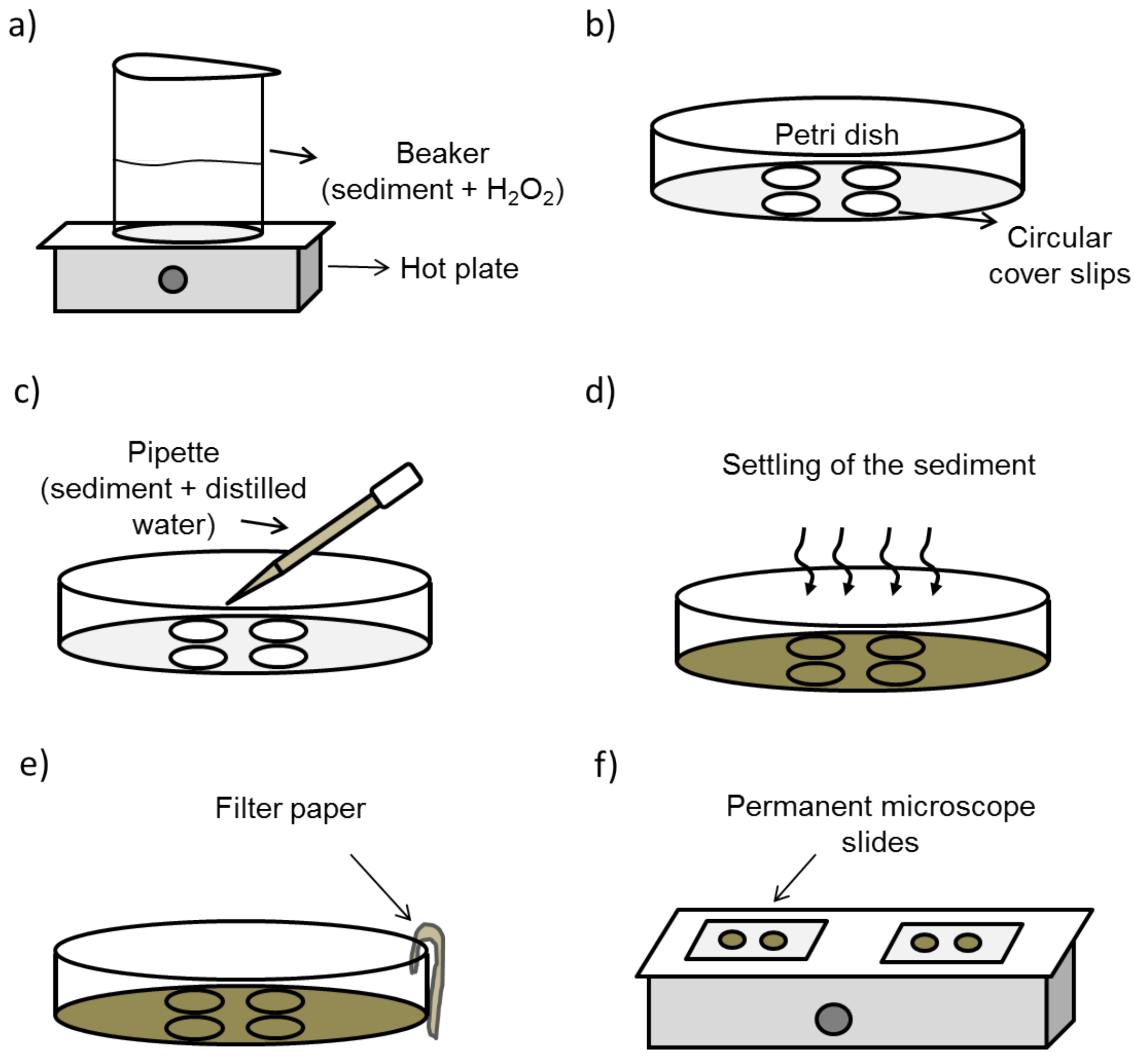


Figure 3. Scheme showing the procedure used in this method for the preparation of the microscope slides. **a)** Mixture of sediment and hydrogen peroxide heated for the digestion of the organic matter, **b)** Four cover slips placed on the bottom of the petri dish, **c)** Sample poured into the petri dish containing distilled water, **d)** Time to allow the sediment to settle out, **e)** Extraction of the excess of water using filter paper, and **f)** Preparation of permanent microscope slides with Zrax for diatom identification.

The above outlined technique allows for the simultaneous preparation of four microscope slides, at one time, with a homogeneous distribution of diatoms that is ideal for the determination of diatom density (number of valves per gram of sample). The technique has proven particularly reliable for fluvial sediments with a low diatom/sediment ratio and poor preservation of diatoms commonly affected by dissolution. In comparison to other methods (e.g. Battarbee, 1973; Laws, 1983; Meng, 1994; Scherer, 1994), this technique also offers a reduction in preparation time.

Diatom diagrams were produced using the C2 Software package (Juggins, 2013) in order to establish the stratigraphic distribution of different species present and/or any changes in their relative abundance within the Sucre deposit and the San Nicolás core. In addition, cluster analyses were performed utilizing Past software (Paleontological Statistics, Hammer *et al*., 2011) for the identification of the diatom zones based on the marker(s) diatom species.

2.4 Sedimentological and mineralogical analyses

Smear slides were prepared for the identification of basic sediment characteristics such as mineral composition, texture and grain size. Thirty-nine samples of sediment from the material collected at Sucre and 88 samples of the Las Flores deposits were analyzed. This semi-quantitative technique was used for an accurate separation of sets of laminae and layers of sediment into lithofacies, especially when diatom assemblages were not indicative or well preserved in the sediment. Samples were prepared using standard procedures

(Rothwell, 1989) and described under examination by a petrographic microscope at 400x. The analysis is based on the identification of relative abundance of three main components (Schnurrenberger *et al*., 2003): 1) biogenic (i.e. diatoms, sponge spicules, phytoliths, charcoal); 2) inorganic clastic (i.e. quartz, feldspar, clay) and 3) inorganic authigenic (i.e. pyrite, hematite, gypsum) types.

For the identification of mineral and biogenic components specialized literature (Rothwell, 1989) and an electronic multi-access key (TIM: Tool for Microscope Identification; Myrbo *et al*., 2011) were used. In addition, mineral composition analyses for 20 samples were performed using the Energy Dispersive spectrometry in conjunction with Scanning Electron Microscopy studies (SEM-EDS) at the Electron Microbeam Facility, University of Regina to help identify some of the detrital grains and clays that cannot easily be classified based on the smear slide technique.

The process for the preparation of the smear slides comprises the following steps:

1. Place a small amount of sediment upon a microscope slide using a flat toothpick.
2. Add one drop of distilled water to the slide. Disperse and spread the sediment across the slide using the flat toothpick.
3. Place the slide on a medium temperature hot-plate and leave for 1 or 2 minutes until the sediment is dry.

4. Put 2 drops of Canada balsam (R.I. 1.53) or similar mounting media with an appropriated refraction index for silicate minerals onto a cover slip.
5. Place the cover slip on the hot-plate at a medium heat until the cement is less viscous and carefully place the cover slip onto the microscope slide.

2.5 Chronology of the Sucre, Las Flores deposits and the San Nicolás core

The chronology of Sucre and Las Flores deposits and the San Nicolás core is based upon 25 radiocarbon (accelerator mass spectometry, AMS^{14}C) analyses of bulk sediment. Samples were retrieved from outcrop using Shelby cores and sealed in aluminum foil to avoid contamination. Samples from the Sucre deposit and San Nicolás core had been previously analyzed at the Scottish Universities Environmental Research Centre (SUERC) and the Australian National University, respectively (Martínez *et al*., 2013). Samples from La Flores were analyzed at the Chronology Laboratory, Université Laval (Canada) and correspond to a new set of dates obtained during this study. Radiocarbon ages were calibrated using OxCal software 4.2 (Bronk Ramsey, 2009) and are presented in calibrated years before present (cal yr B.P.). In addition, optical stimulated luminescence (OSL) analyses were carried out at the University of Chicago on two clastic samples collected from the Sucre and Las Flores deposits, which are considered bed markers, and one sand layer from the Sucre deposit. However, the type of quartz found in these samples presented unusual luminescence characteristics that complicated the determination of the ages. For this reason, additional microprobe analyses are needed before the dating can be obtained (Steven Forman pers. commun., Nov. 14, 2013). Hence, the OSL ages are not available for use at the time of thesis completion and thus for the construction of age models, nor for any chronological correlation between the sedimentary deposits at Sucre and Las Flores.

2.6 Facies characterization based on sedimentary components

The characterization of the sedimentary facies is based upon diatom assemblages, mineral composition, grain size and representative sedimentary structures, following the classification proposed by Miall (1977). The study of sedimentary facies is used in the reconstruction of hydrological and depositional conditions aiding in the identification of river pulses, and the regional paleoenvironmental reconstruction.

The description of single layers or sets of laminae is based on the observation of macroscopic (i.e. bedding, color) and microscopic features of the sediments (identification of major and minor components or modifiers), following the classification scheme proposed by Schnunrrenberger *et al.* (2003): 1. Color + 2. Bedding + 3. Major modifiers + 4. Minor modifiers. In this scheme, features 1 and 2 describe macroscopic observations performed directly at outcrops while features 3 and 4 correspond to microscopic characteristics observable on the smear slides and by SEM-EDS analysis, that are indicative of the nature of the sediments. It is important to mention that major modifiers are considered as the components that occur more than 25% in abundance and minor modifiers are those components with abundances that vary between 10 to 25% (Schnunrrenberger *et al*., 2003).

CHAPTER 3: Results

3.1 Modern diatoms

Diatoms were recovered only in the sample collected from the temporal pond in the Cauca River floodplain. However, the species found in the modern pond, dominated by *Cymbella* sp., were very different from the fossil ones recovered from the geological record. Therefore, the modern assemblages could not be used as analogues for the paleoenvironmental reconstructions. The modern assemblages reflect human induced water conditions not present in the past.

3.2 Sucre deposit

3.2.1 Chronology of the Sucre deposit

The age model for the Sucre deposit was constructed based on a sub-set of 4 samples (out of 8) radiocarbon dates (Martínez *et al*., 2013). Because of the fluvial nature of the sediments (several sources of organic matter and reworked organic matter from different ages) and the absence and/or low recovery of organic material within, there is a lack of chronological control at the basal and the uppermost parts of the deposit. García *et al*. (2011) and Martínez *et al*. (2013) differentiated two groups of ages: 1) "young" utilized for the age models due to its consistency along the SSF Basin deposits, and 2) "old" considered the product of reworked organic matter. This principle is applied in all the age models obtained in the present study.

The radiocarbon ages presented by Martínez *et al*. (2013) were recalibrated herein using the last version of OxCal 4.2 to standardize the models for the three sedimentary successions. However, no representative differences were found in the calibrated distributions and the linear interpolation equations between the age models presented by Martínez *et al*. (2013) and the ones obtained in this study (Table 1).

The calibrated distribution of the Sucre ages indicates that this sedimentary succession was deposited between ~3,000 and <200 cal yr BP if the linear tendency is extrapolated both at the top and at the base of the sequence (Figure 4). Nevertheless, the date when deposition started may be older since the contact of the sedimentary succession with the basement was not observed. Radiocarbon ages FS-60, FS-72 and FS-75 are considered outliers (Figure 4). This deposit imposed many difficulties in the production of a chronological model due to its proximity to the Cauca River as evidenced with the massive sand layer beds. Thus, a permanent connection with the river would allow the re-deposition of older organic matter within the upper layers of the stratigraphic succession (samples FS-72 and FS-75). In addition, infiltration of younger material as a result of plant bioturbation and/or weathering would have contaminated the underlying layers (i.e., sample FS-60).

Table 1. Radiocarbon ages obtained from the analysis of sediments at Sucre deposit.

Sample	Height (cm)	C^{14} yrs BP	Unmodelled BP (94.5%)		Cal yrs BP
			From	To	
FS60	250	1875±30	1881	1726	1803.5
S5V10**	640	3060±25	3356	3185	3270.5
FS65*	730	2040±30	2111	1904	2007.5
FS66*	810	1940±30	1969	1821	1895
FS68*	870	1860±30	1870	1720	1795
FS71*	1275	1235±30	1264	1070	1167
FS72	1368	2750±30	2925	2771	2848
FS75	1865	1555±30	1529	1381	1455

*^{14}C dates used in the age model from Martínez *et al*. (2013), **^{14}C date obtained in this study

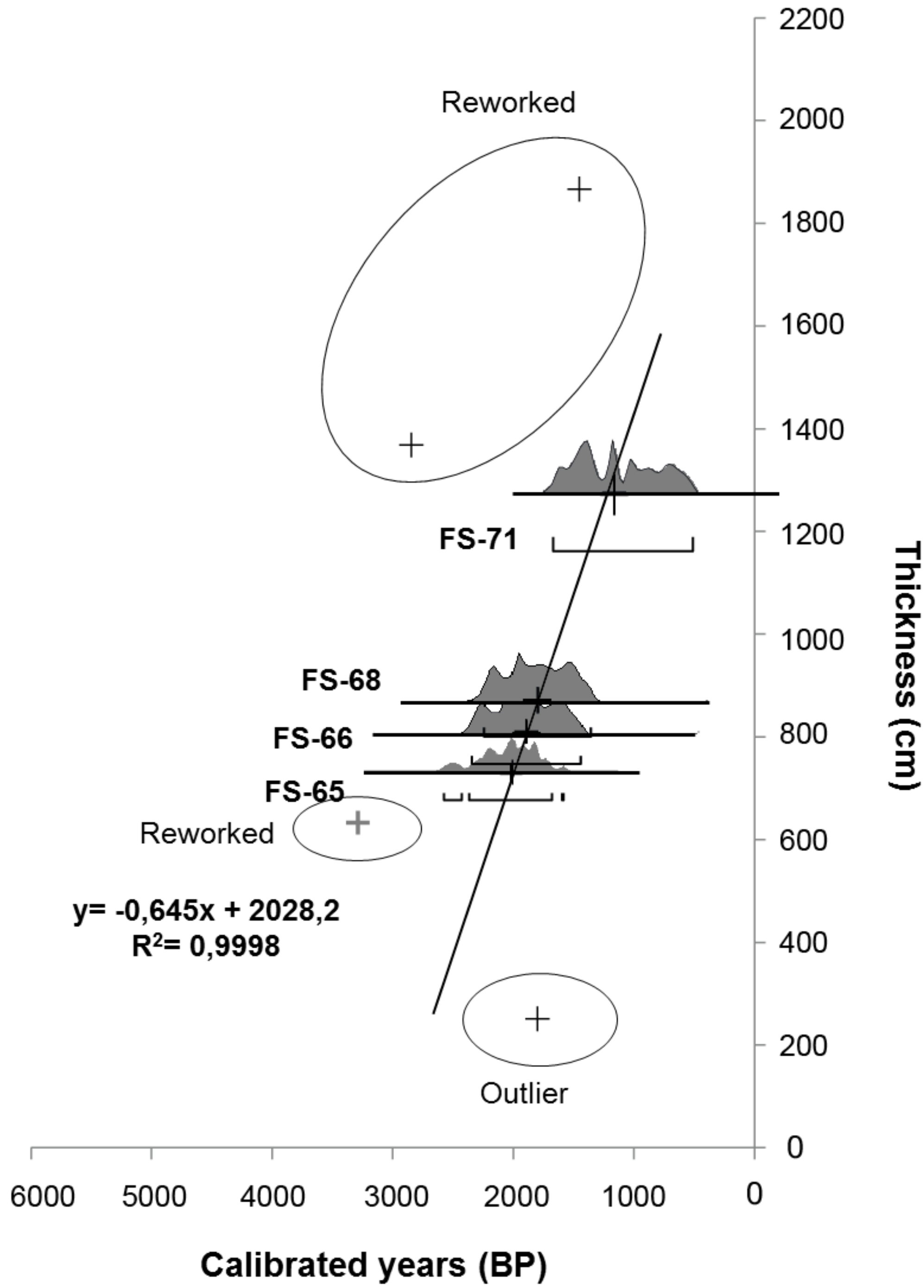


Figure 4. Age model for the Sucre deposit based on AMS^{14}C calibrated dates. Clustered points (+) correspond to reworked or outlier samples. Modified from Martínez *et al.* (2013).

3.2.2 Lithofacies and stratigraphic succession of Sucre

Lithofacies were characterized based on: 1) the analyses of 44 smear slides (Appendix 1); 2) scanning electron microscope analysis in 7 samples, and 3) field observations. In total, seven lithofacies were identified according to the grain size, abundance of biogenic (i.e., diatoms, charcoal) and authigenic (i.e., oxides) components and type of sedimentary and fossil structures (Table 2, Figure 5).

The stratigraphic column presented for the Sucre deposit was constructed based on three sources of information: 1) the preliminary stratigraphic column by Fiore Suter in 2010; 2) a more detailed description performed by Maria Vélez in 2010, and 3) my own observations of the previous stratigraphic columns during the field work in the summer of 2012 and winter of 2013.

The Sucre deposit corresponds to ~24 m of silty-clay beds at the base and fine sand layers with clay and silt layers towards the top of the succession. The metamorphic basement clearly observed in the western flank of the river is not exposed at Sucre (Figure 6).

Table 2. Description of the facies identified in the sedimentary succession of Sucre

Facies	Bed thickness	Contacts	Sedimentary structures and components	Interpretation of the facies
F1: Organic silty clay lamina	≤ 1mm	Irregular	Charcoal as elongated pieces, opaque oxides associated with organic matter and as coatings on quartz grains. Diatoms, phytoliths and sponge spicules are common but not abundant.	Wetland
F2: Clay lamina with siliceous fossil	≤ 1mm	Irregular	Well-preserved diatoms, phytoliths, sponge spicules and charcoal. Sets of these laminae occur separated by silt layers throughout the succession. Animal bioturbation, *Scoyenia* ichnofacies	Ephemeral lakes-like conditions. Wet soils, swamps, and shallow ponds
F3: Coarse silt layer	10-15 cm	Sharp and irregular	Deformation structures, diatoms and hematite are main components, common iron nodules (siderite?). Usually overlain by thick sand layers.	Paleosol A
F4: Oxidized silt layer	~25 cm	Sharp	Abundant root traces, oxidation halos around the root traces.	Paleosol B
F5: Coarsening upwards fine sand	35-75 cm	Common: Sharp Rare: basal erosional	Cross lamination, sand lenses, conglomeratic channel, and abundant amphibole grains. Towards the top the layers are commonly orange in color.	Splay
F6: Laminated silt and clay bed	100-175 cm	Sharp	Orange and beige laminae. Hematite is common, few to absent content of diatoms, intercalated organic laminae are conspicuous, plant macrofossil are rare.	Distal splay, fluvial-lacustrine deposit
F7: Coarse silt	16-20 cm	Sharp	Light grey in color, common to sparse root traces	Paleosol C
F8: Pale green silt	12 cm	Sharp	Intercalation of oxidized organic matter	Paleosol D

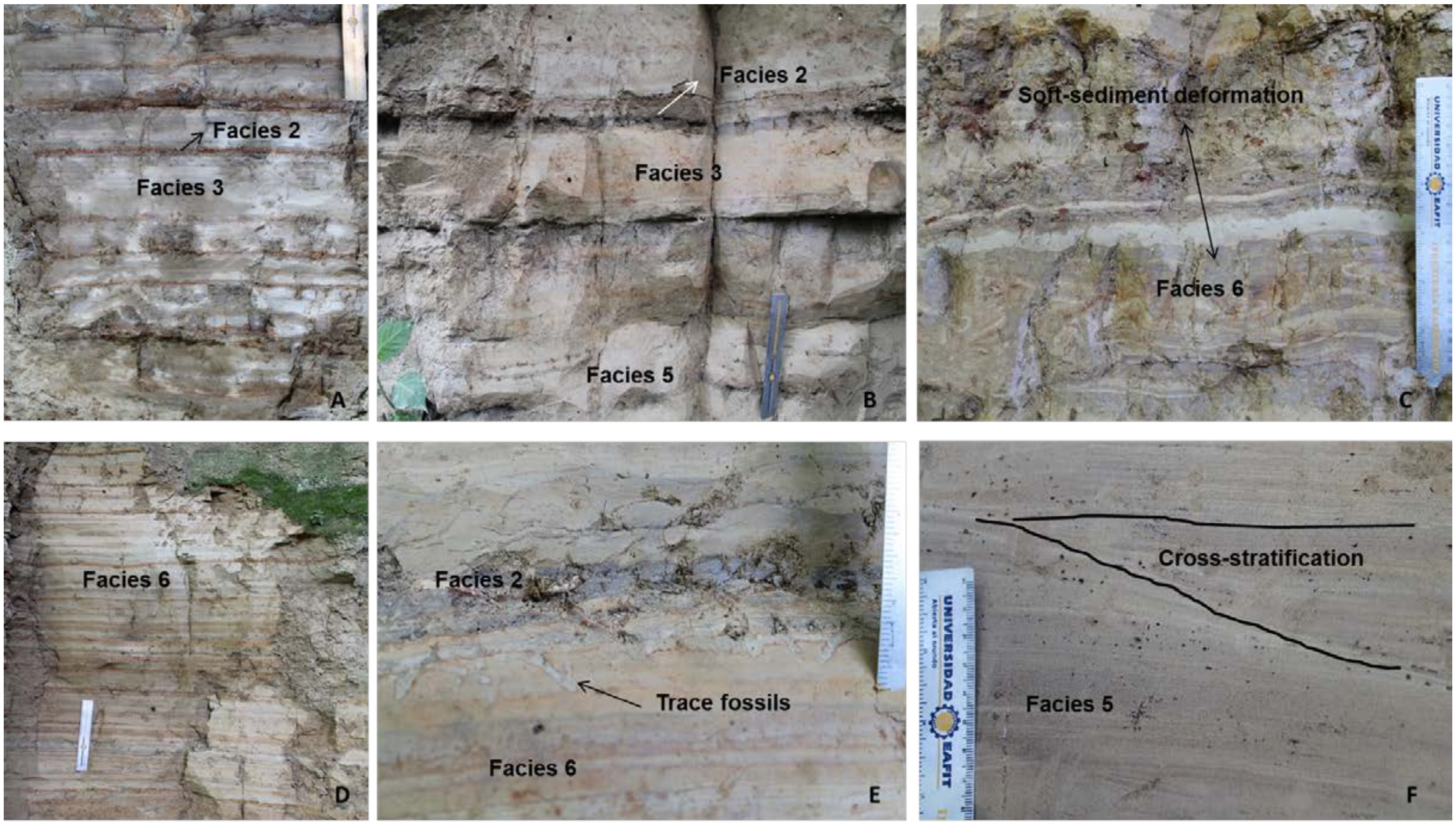


Figure 5. Facies, sedimentary and fossil structures of the Sucre deposit. **A**. Interstratification of clay laminae (facies 2) and silt beds (facies 3); **B.** Basal contact of facies 3 with facies 5 (fine sand beds); **C, D.** Laminated silt and clay beds, characterized by convolute lamination (C) and planar lamination (D); **E.** Animal traces typical in fine sediments, assigned to *Scoyenia* ichnofacies (Buatois and Mangano, 2011), and **F.** Trough cross-lamination in coarsening upwards, fine sand beds.

The first 600 cm of the sedimentary succession are characterized by coarsening upward, fine sand beds > 50 cm in thickness (facies 5), separated by a ~200 cm of orange to grey laminated silty clay layer (facies 6). Organic laminae conspicuously occur through the first meter of this interval. The second interval (600-1,100 cm) comprises a set of silt beds (facies 3) intercalated with millimeter-scale organic laminae (facies 2) at the base; whereas the top is mainly composed by clay and silty-clay laminated sediments with the occurrence of organic laminae at several levels. At ~ 900 cm a fine sand bed in erosional contact with the underlying laminated sediments and cross lamination occurs. In addition, at ~1,100 cm there is a ~12 cm thick layer, the first of four grey silty-clay layers with plant bioturbation (facies 7). These layers are also recorded in Las Flores deposit at the same stratigraphic levels. The overlaying interval (1,100-1,600 cm) is characterized by the occurrence of thick, coarsening upward, fine sand beds intercalated with clay layers with root traces (facies 4), mainly at the base. At 1,450 cm the second grey layer occurs (facies 7).

Moving upward in this interval, fine sand and clay intercalations as well as oxidized fine sand beds predominate. The uppermost interval (1,600-2,400 cm) of this sedimentary succession comprises several centimeters (<50 cm) of fine sand beds intercalated with incipient but conspicuous clay beds. Plant and less common animal bioturbation are also conspicuous along this interval associated with the organic-rich clay beds. Towards the top two grey layers occur at ~1,740 and ~2,000 cm, respectively (facies 7).

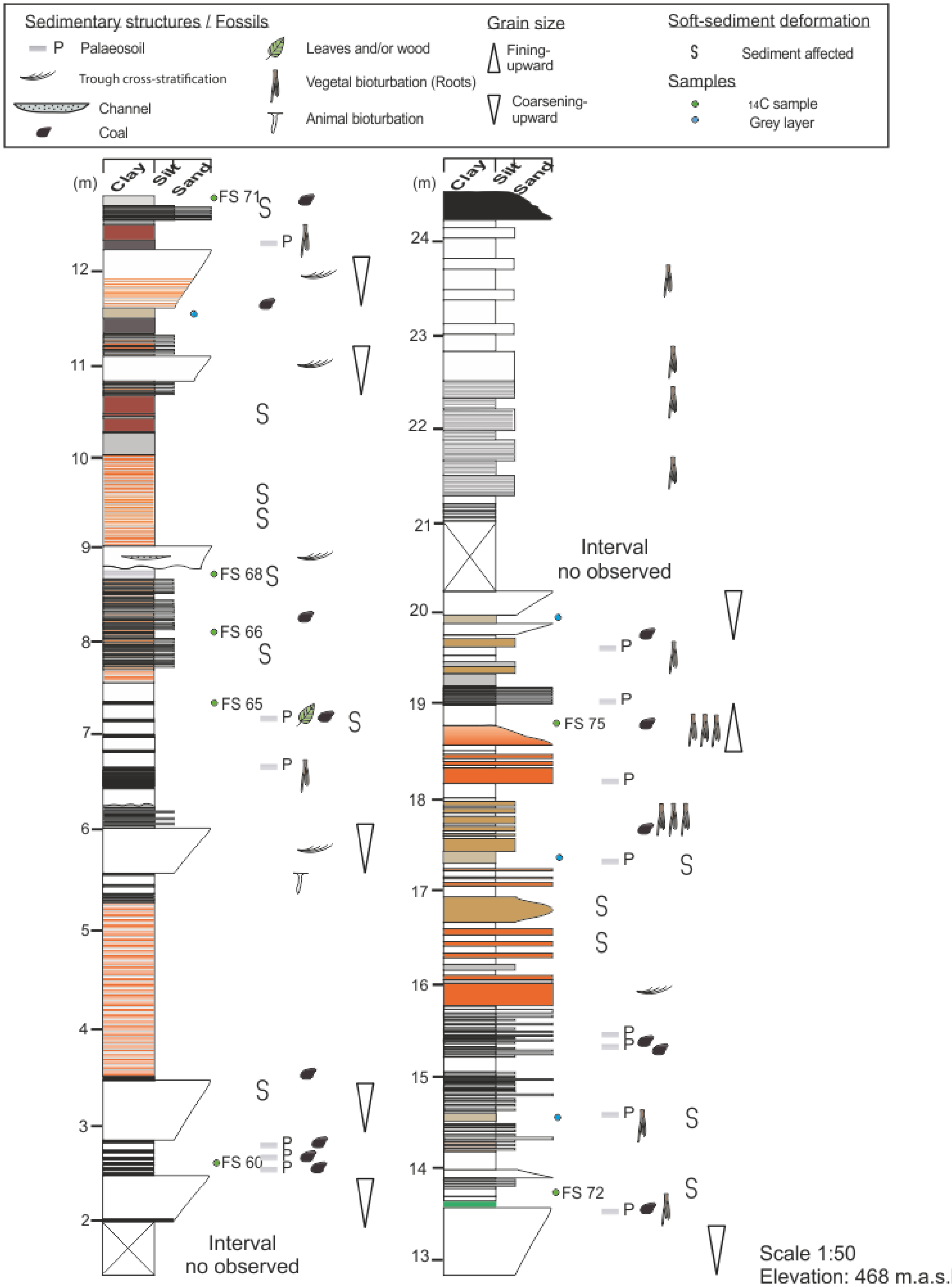


Figure 6. Stratigraphic section of Sucre. Note the conspicuous levels with plant bioturbation and the increase in grain size towards the top. Sediment deformation is also common, mainly in the middle part of the succession. Bottom 13 m are presented on the left, upper 11 m on the right. Contact with the basement was not observed but estimated to be 2 m as concluded by Suter in his 2010 field work.

3.2.3 Diatom assemblages and zones in the Sucre section

From the 73 samples analyzed, only 26 were found to contain diatoms with a minimum of 300 valves and that were counted as part of the paleoecological reconstruction. In total 41 diatoms species were found to be common (≥5%) or abundant (≥20%), with a predominance of aerophilic and benthic species (Appendix 2).

The most common species along the sedimentary succession are *Diadesmis confervacea* (10-84%) and *Nitzschia amphibia* (5-21%). Other species such as *Gomphonema gracile*, *Cocconeis placentula* and *Orthoseira roeseana* also occur with low abundance (≤10%) (Appendix 3). Diatom species were grouped based on their ecological preferences as planktonic, benthic, aerophilic and epiphytic. According to the cluster diagram, five diatom zones were established (Figure 7). The range of dates for the diatoms zones were estimated using the linear regression equation obtained from the age model (Figure 4).

Diatom zone 1 (275-325 cm above the base, ~ 2,718-2,641 cal yr BP): This zone is characterized by the aerophilic species *Diadesmis. confervacea* with variable but high relative abundances (49-70%) with the highest peaks at the base and top of the zone. The benthic species *Nitzschia amphibia* occurs throughout the zone (3-21%), as well as *Pinnularia* spp. (2-35%). Other epiphytic species are present throughout the succession with low relative abundances, e.g. *Gomphonema angustum* (7%), *Gomphonema gracile* (2-7%), *Pinnularia maior* (1-5%), and *Rhopalodia gibba* (1-8%). It is important to mention that diatom species were not recorded between 325 and 500 cm (Figure 7).

Diatom zone 2 (500-560 cm above the base, ~2,369-2,276 cal yr BP): This zone is mainly composed of epiphytic species. The most abundant epiphytic species are *Cocconeis placentula* (2-30%), G*omphonema. gracile* (1-17%), and *Synedra ulna* (1-25%); the latter with a peak at the base, with decreasing abundances towards the top of the zone. *Pinnularia* spp. (2-35%) are recorded throughout this zone. Other epiphytic species, i.e. *Pinnularia gibba* (1-5%) (1-17), *Rhopadolia gibba* (1-5%), *Navicula* cf. *gastrum* (5%), and *Navicula viridula* (1-10%) are also present with low values. In comparison with diatom zone 1, the aerophilic species *Diadesmis confervacea* (3-10%) present a decreasing tendency, occurring only towards the top of the zone. The benthic species *Amphora ovalis* var. *lybica* (2-16%) peaks at the top of the zone whereas *Nitzschia amphibia* (1-8%), *Nitzschia levidensis* (1-6%), and *Fragilaria capucina* var. *vaucheriae* (1-8%) occur with low relative abundances. Diatoms were not recorded between 560 and 625 cm (Figure 7).

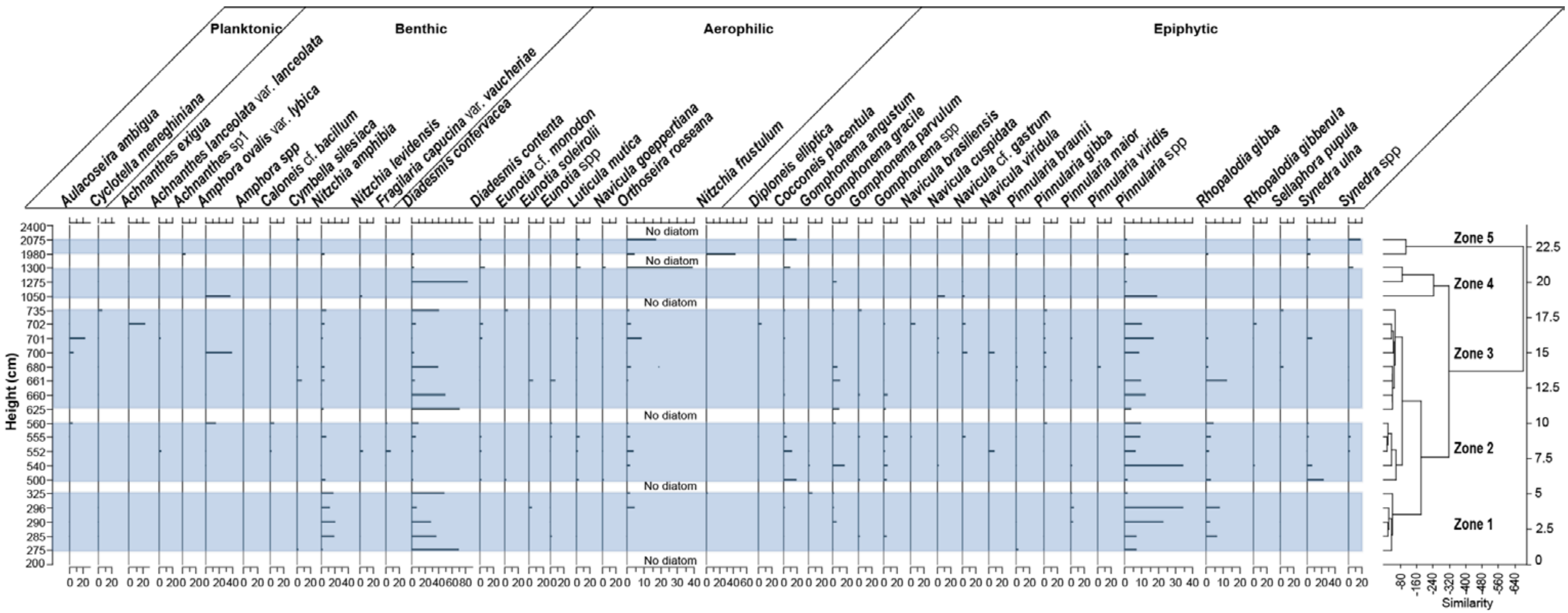


Figure 7. Distribution diagram of the diatom taxa and cluster diagram with the diatom zones. Note the high relative abundance of *D. confervacea* along the stratigraphic succession.

Diatom zone 3 (625-735 cm above the base, ~2,175-2,005 cal yr BP): This zone is dominated by the aerophilic species *Diadesmis confervacea* (2-71%) with higher values at the base, a decrease in the middle of the zone, and a peak at the top. Other aerophilic species, i.e. *Orthoseira roeseana* (1-9%) and *Diadesmis contenta* (1-6%) are also present with low values. The planktonic species *Aulacoseira ambigua* (1-23%) is common at the middle of the zone, and a single low peak of *Cyclotella meneghiniana* (7%) is recorded at the top of the zone. Single and relatively high peaks of the benthic species *Achnanthes exigua* (24%) and A*mphora ovalis* var. *lybica* (40%) are also recorded with high single peaks whereas *Nitzschia amphibia* occurs throughout the zone, although with a low relative abundance (1-8%). The epiphytic *Navicula* cf. *gastrum* (6-7%), *Pinnularia gibba* (1-5%), and *Synedra ulna* (1-8%) also occur with low values. Slightly higher values of *Gomphonema gracile* (10-11%), *Navicula viridula* (2-10%), and *Rhopalodia gibba* (1-13%) are recorded at the base and the middle of the zone. *Pinnularia* spp. (4-18%) are present throughout the zone. Between 735 and 1,050 cm diatoms were not recorded (Figure 7).

Diatom zone 4 (1,050-1,300 cm above the base, ~1,516-1,129 cal yr BP): This zone is characterized by relatively high peaks of benthic, aerophilic and epiphytic diatom species. The benthic species *Amphora ovalis* var. *lybica* (37%) and the epiphytic *Navicula cuspidata* (12%) are recorded with single peaks at the base of the zone. The aerophilic species *Orthoseira roeseana* (39%) and the epiphytic *Cocconeis placentula* (11%) peak at the top of the zone whereas the aerophilic *Diadesmis confervacea* (84%) is recorded with high relative abundance in the middle of the zone. Other aerophilic taxa with single peaks of low values include *Diadesmis contenta* (8%), *Luticula mutica* (7%), and *Navicula goeppertiana* (6%). Diatoms were not recorded between 1,300 and 1,980 cm above the base (Figure 7).

Diatom zone 5 (1,980-2,075 cm above the base, ~1129-<200 cal yr BP): This zone is dominated by the aerophilic species *Nitzschia frustulum* (44%), which peaks at the base of the zone. *Orthoseira roeseana* (5-17%) is present throughout the zone, with a relatively high value at the top. The epiphytic species *Cocconeis placentula* (2-26%) is also recorded with relatively high abundance towards the top of the zone. Other taxa such as the aerophilic species *Luticula mutica* (3-6%) and the epiphytic species *Synedra ulna* (5%) occur throughout the zone, though with low values. Diatoms were not recorded in the middle of the zone (~95 cm, Figure7).

3.3 Las Flores deposit

3.3.1 Chronology of Las Flores deposit

The age model for the Las Flores deposit was constructed based on a sub-set of 4 samples out of 7 radiocarbon dates. Organic rich material was mainly collected at the base of the sedimentary succession. Therefore, the chronologic control is better at the base than at the top, where the organic materials were not well preserved. The radiocarbon ages used for the model were obtained from 3 samples collected for this study during the field work of the summer 2012 and the winter 2013, and 1 sample that was previously dated by Fiore Suter in 2010 (Table 3).

The model of the Las Flores deposit suggests that the sedimentary succession was deposited between ~2,300 and <200 cal yr BP if the linear tendency is extrapolated both at the top and the base. For this deposit, the age when the sediment deposition started can be better determined as compared to Sucre since this sedimentary succession is in contact with the basement. Radiocarbon ages LF-3, FS-20, FS21 and FS-22 are consistently older and thus considered reworked (Figure 8).

Table 3. Radiocarbon ages obtained from the analysis of sediments at Las Flores.

Samples	Height (cm)	C^{14} yrs BP	Unmodelled BP (94.5%)		Cal yrs BP
			From	To	
LF*	250	2090±15	2117	2002	2060
FS21**	330	2455±75	2728	2353	2540.5
LF1*	360	1455±15	1375	1307	1341
FS22**	460	1655±130	1862	1309	1585.5
LF2*	590	1405±15	1338	1292	1315
FS20**	1000	1645±135	1864	1302	1583
LF3*	1300	1520±15	1516	1353	1434.5

*^{14}C dates used in the age model obtained in this study, **^{14}C samples taken by Fiore Suter (2010)

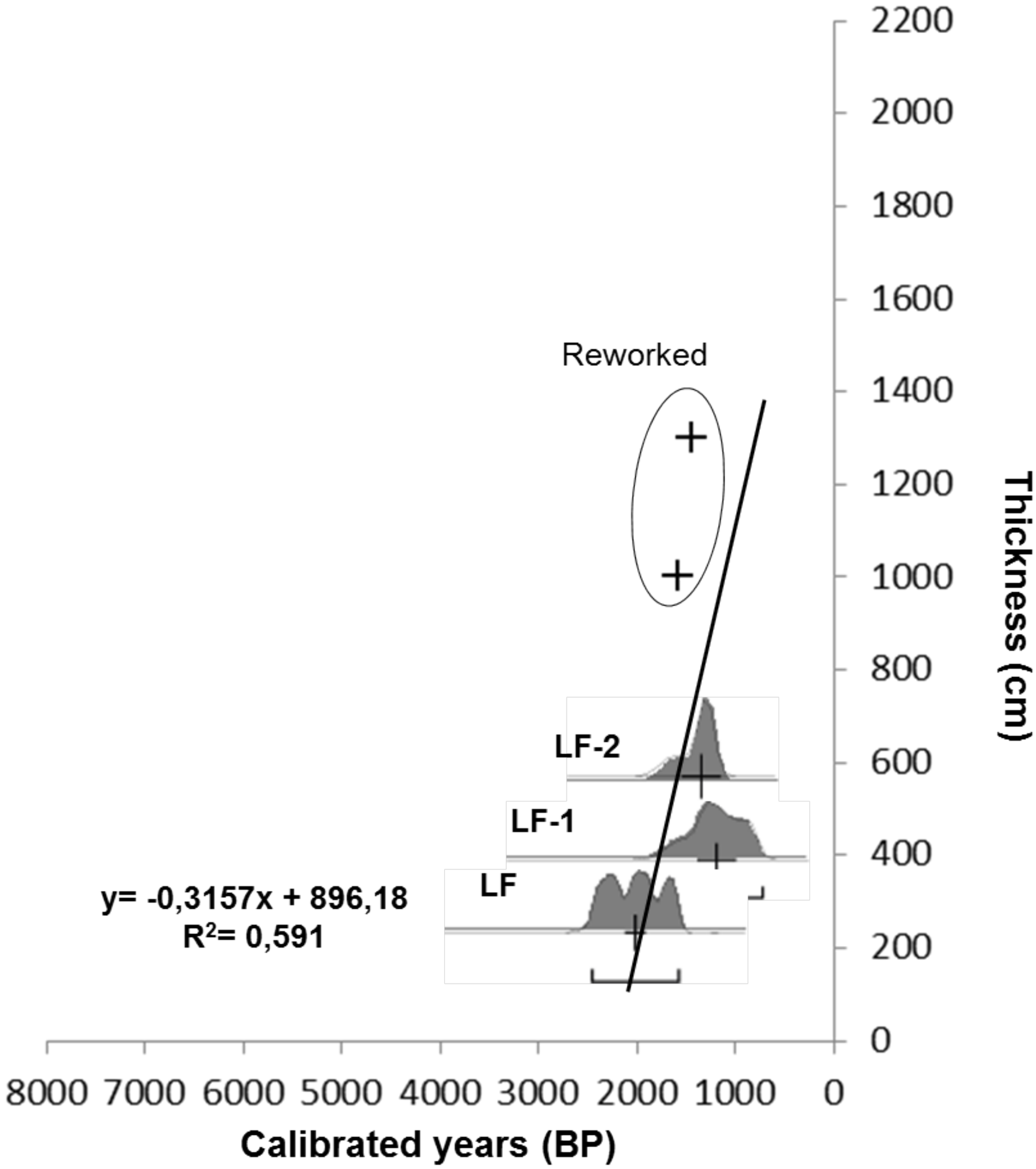


Figure 8. Age model for Las Flores deposit based on AMS^{14}C calibrated dates. Clustered points (+) correspond to reworked samples.

3.3.2 Lithofacies and stratigraphic succession of Las Flores

Lithofacies for Las Flores were identified based on: 1) the analyses of 91 smear slides (Appendix 4); 2) scanning electron microscope identification in 9 samples, and 3) field observations. In total, twelve lithofacies were characterized according to grain size, color, content of plant macrofossils and/or charcoal, and sedimentary structures. The analyses of sediment composition based on the smear slides, and the scanning electron microscope studies were used to corroborate similarities among layers; previously grouped according to the outcrop descriptions (Table 4).

Fossil plant material, e.g, oxidized leaves and carbonized wood, were conspicuously found at several stratigraphic levels, mainly throughout the first 426 cm of the sedimentary succession. However, the fossil leaves were not well preserved for taxonomic identification or taphonomic studies. In addition, four samples of organic matter collected from the first 610 cm above the base were prepared and analyzed at the Universidad Nacional (Medellín) for palynological studies. Preliminary analyses of pollen indicate a change in the vegetation between ~1,594 and 1,315 cal yr BP. At ~1,594 cal yr BP vegetation corresponds to Arecaceae (palms), Poaceae (grasses), Cyperaceae (herbs), and Caesalpiniaceae (legumes, typical of dry forest). Around 1,341 cal yr BP, a more developed forest is characterized by the presence of Asteraceae (herbs and trees), Anacardiaceae (trees of a well-developed forest), Passifloraceae and Bombacaceae (trees), Caesalpiniaceae and Macrolobium (legumes) and ferns (disturbed environments). At ~1,315 cal yr BP, vegetation is composed mainly of

Table 4. Description of the facies identified in the sedimentary succession of Las Flores.

Facies	Bed thickness	Contacts	Sedimentary structures and components	Interpretation of the facies
F1: Medium coarse silt with clay matrix	12-20 cm	Irregular with basement Sharp in the top	Mottled silt, no biogenic components, no oxides	Paleosol A Lixiviated?
F2: Coarse silt to fine sand with lithics and clayey matrix	4-34 cm	Sharp	Dark gray to black, amphibole-rich, abundant charcoal, common iron oxides and root traces with halos, low content of phytoliths	Organic paleosol, poor-drained, wet soil
F3: Fine to medium silty clay	13-25 cm	Sharp	Mottled clay with very fine to medium silt, low abundances of organic matter, and oxidized root traces	Poorly-drained paleosol, wet soil
F4:Organic-rich fine silty clay	16-25 cm	Sharp	Oxidized leaves and wood, charcoal, desiccation craks, light brown in color, and abundant hematite, rare aerophilic diatom species.	Wetland- dried out litter
F5: Fine silty clay and organic-rich laminae	25-40 cm	Sharp	Silty clay intercalated with organic millimeter-laminae, common charcoal, rare aerophilic diatoms and phytoliths	Paleosol B
F6: Fine silt, clay and oxidized silt	32-57 cm	Sharp	Thick layers of hematite-rich fine silt intercalated with few centimeter-thick, dark greyish-brown clay, and millimeter-thick oxidized laminae; common oxidized root traces associated with the dark-grey clay layers	Incipient paleosol succession
F7: Clay	2-4.5 cm	Sharp	Clay layer, few centimeter-thick, common hematite	Paleosol C
F8: Mottle clay	13-50 cm	Sharp	Mottled reddish and grey clay layers, with mud balls, oxidized organic matter	Well-drained paleosol
F9: Massive fine silt	72 cm	Sharp	Light yellow-brownish fine silt with clayey matrix, with deformation, rare organic laminae	Paleosol D
F10: Massive silty clay	15-1400 cm	Irregular and sharp	Massive silty clay, yellowish-brown in color with incipient and irregular millimeter-lamination, common intercalation of organic laminae or organic lenses	Paleosol E
F11:Oxidized clay	28-43 cm	Sharp	Mottled clay, black and grey in color, with intercalations of organic laminae, oxides	Poorly-drained paleosol
F12: Coarse silt	15-20 cm	Sharp	Light grey in color, common to sparse root traces	Paleosol F

Myrtaceae (guava trees) and ferns of disturbed environments (Ligia Estela Urrego per. commun., Sept 18, 2013). Samples for diatom analysis were also prepared from sediments collected from the various organic levels. However, only 1 sample (AT94) was found to contain diatoms, being dominated by the aerophilic species *Diadesmis contenta*. Other siliceous fossils, i.e., phytoliths, also are abundant.

The sedimentary succession of Las Flores is a ~25 m thick deposit that irregularly rests on the metamorphic basement, which in turn determines the paleo-topography at the west side of the Cauca River. The exposed basement is ~600 cm thick where the succession of Las Flores outcrops (Figure 9). The first 511 cm of the succession are characterized by coarse silt layers (facies 1), olive grey (4/2 5Y) in color, mainly at the base. Intercalated with this facies there are organic silty clay layers (facies 2), very dark greyish-brown (3/2 10YR) in color with lithics, abundant charcoal and root traces (Figure 9,10); as well there are layers of variable thickness, characterized by fine to medium silty clay (facies 3) with mottling and oxidized root traces. Towards the top of this interval, thick layers composed of fine silty clay (facies 4) are conspicuous. These layers are characterized by the high concentration of oxidized plant macrofossils (Figure 10), e.g., leaves and wood fragments, and charcoal, which is reflected in their color (dark greyish brown- 4/2 10YR). Plant fossil material is usually associated with desiccation cracks (Figure 10). The base of facies 4 is delineated by layers of fine silty clay with organic laminae (facies 5); whereas towards the top, three layers of facies 4 are intercalated with a few centimeter-thick layers of clay (facies 7).

Thick layers of oxidized fine silt, that are denoted by their light yellowish brown (6/3 2.5Y) color intercalated with dark grey (4/1 2.5Y) clay (facies 6) occur both underlaying and overlaying the intercalation of facies 4 and facies 7. Root traces surrounded by oxidized halos conspicuously occur throughout facies 6, especially associated with the grey clay (Figure 10). It is important to mention that this facies corresponds to few to several cm-scale laminated silt and clay layers.

The second interval (509-885 cm) comprises a set of five layers that are composed of mottled clay (facies 8), reddish black (2.5/1 2.5YR) and grey (5/1 2.5Y) in color. These layers (facies 8) are intercalated with layers of clay (facies 7). A massive, mottled and deformed layer of clayey silt (facies 9) overlies the set of mottled clay (facies 8). At the top, this layer is in sharp contact with a ~39 cm thick layer of laminated silt and clay. Laminae vary in color, ranging from orange to grey. The top 140 cm of this interval is characterized by a massive silty clay layer, yellowish brown (5/4 10YR) in color, with intercalations of organic laminae and gypsum crystals (facies 10). The next ~200 cm were not observed since access to this part of the section was limited by the high slope and vegetation cover.

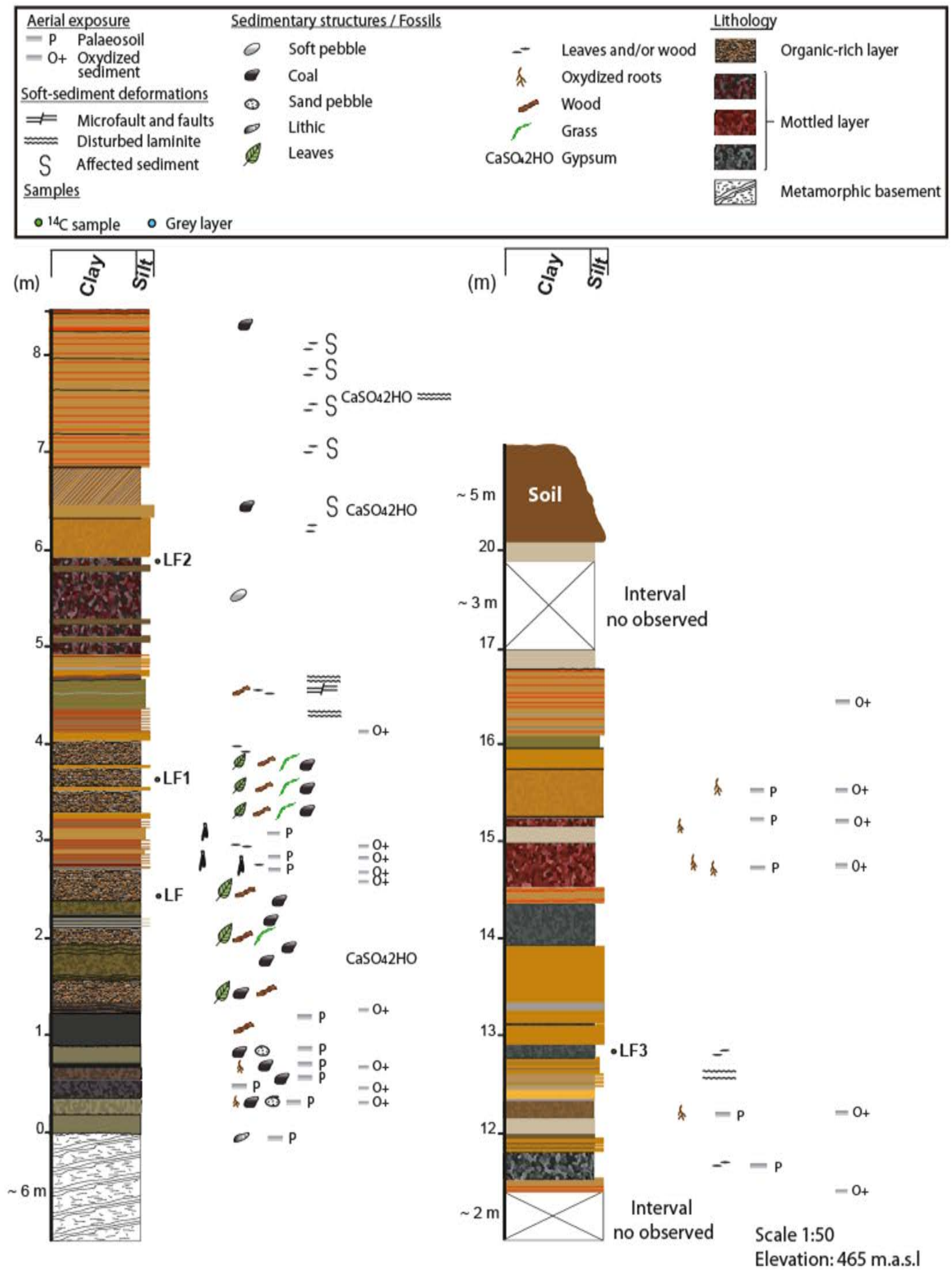


Figure 9. Stratigraphic section of Las Flores. Note the conspicuous levels with plant macrofossils in the lowermost part of the succession and oxidized layers with root traces at the top. Fine sediments (clays and silts) predominate throughout the succession. Bottom 16 m are presented on the left, upper 8 m on the right. No animal traces were observed.

The uppermost interval (1,085-1,635 cm) starts with a layer, a few centimeters in thickness (facies 10). This facies is conspicuous throughout the interval; varying in thickness from 13 to 70 cm. Mottled dark grey clay layers (facies 11), that are oxide-rich and with organic laminae are restricted to the base of the interval, whereas the reddish and grey clay (facies 8); common in the second interval, are present in the middle part of the interval separated by a coarse silt layer (facies 12), light grey in color. Four coarse silt layers are conspicuous at the top of the sedimentary succession (Figures 9-10). Moving upwards, there is a ~300 cm gap which is overlain by the ultimate coarse silt layer.

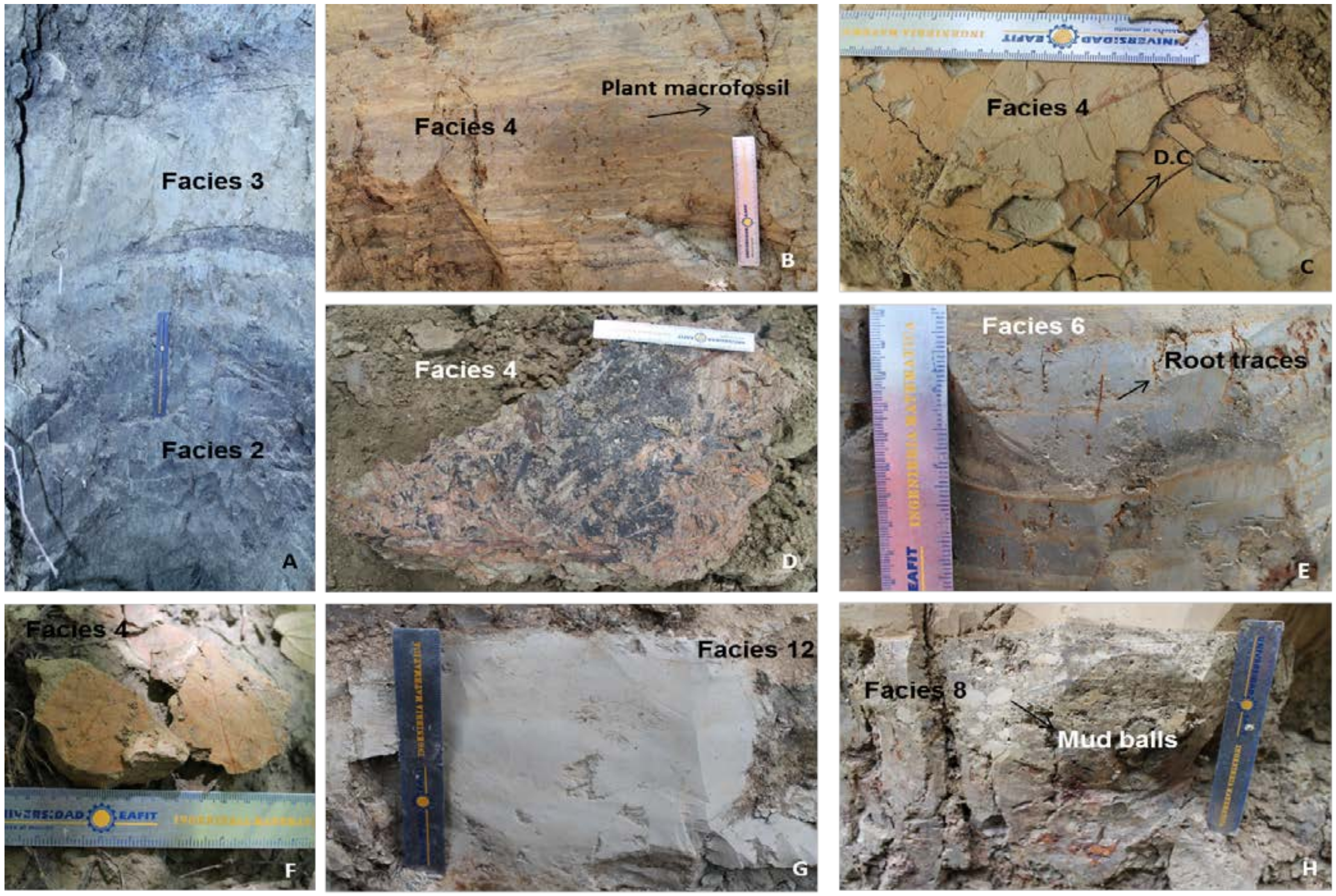


Figure 10. Facies, sedimentary structures and fossil of the Las Flores deposit. **A.** Organic-rich with lithics, coarse silt – clayey matrix (facies 2); and mottled clay with oxidized root traces (facies 3); **B, C, D, F.** Silty clay with high concentration of fossil plant material, abundant charcoal, and desiccation cracks (D.C) associated with oxidized leaves; **G.** Light grey coarse silt layer, with common to sparse root traces; and **H.** Mottled clay with mud balls and oxidized organic matter.

3.4 San Nicolás core

3.4.1 Chronology of the San Nicolás core

The age model for the San Nicolás core was constructed on the basis of a sub-set of 4 samples out of 14 radiocarbon dates (Martínez *et al*., 2013). Sediment was collected throughout the core, where organic material was present. However, towards the top of the core the absence of organic matter did not allow for a better chronological control. The radiocarbon ages used for the model correspond to those presented by Martínez *et al.* (2013) but have been recalibrated herein using the last version of OxCal 4.2 to standardize the models (Table 5).

The calibrated distribution of the ages in the San Nicolás core indicates that the sedimentary succession was deposited between ~4,700 and <200 cal yr BP, if the linear tendency is extrapolated both at the top and the base (Figure 11). Nevertheless, the age when the deposition started may be older since the core drilling did not reach the lowermost part of the succession. Radiocarbon ages SN4, SN10, SN12, SN18, SN20, SN37, and, SN49 are considered as reworked; whereas, SN46 and SN51 are identified as outliers.

Table 5. Radiocarbon ages obtained from the analysis of sediments for the San Nicolás core.

Samples	Depth (cm)	C^{14} cal yrs	Unmodelled BP (94.5%)		Cal yrs BP
			From	To	
SN4	84	5860$\pm$100	6930	6442	6686
SN10	335	2600$\pm$70	2860	2465	2662.5
SN12	415	3980$\pm$40	4567	4296	4431.5
SN18	678	3940$\pm$40	4517	4248	4382.5
SN20	764	4580$\pm$40	5449	5053	5251
SN22*	852	1790$\pm$20	1813	1625	1719
SN26*	1035	2500$\pm$20	2724	2491	2607.5
SN31*	1226	2660$\pm$30	2844	2743	2793.5
SN33	1321	1720$\pm$30	1703	1560	1631.5
SN37	1512	2320$\pm$30	2378	2184	2281
SN40*	1623	3010$\pm$30	3335	3077	3206
SN46	1979	1990$\pm$30	1998	1878	1938
SN49	2015	2680$\pm$20	2844	2751	2797.5
SN51	2123	1760$\pm$20	1721	1610	1665.5

*^{14}C dates used in the age model

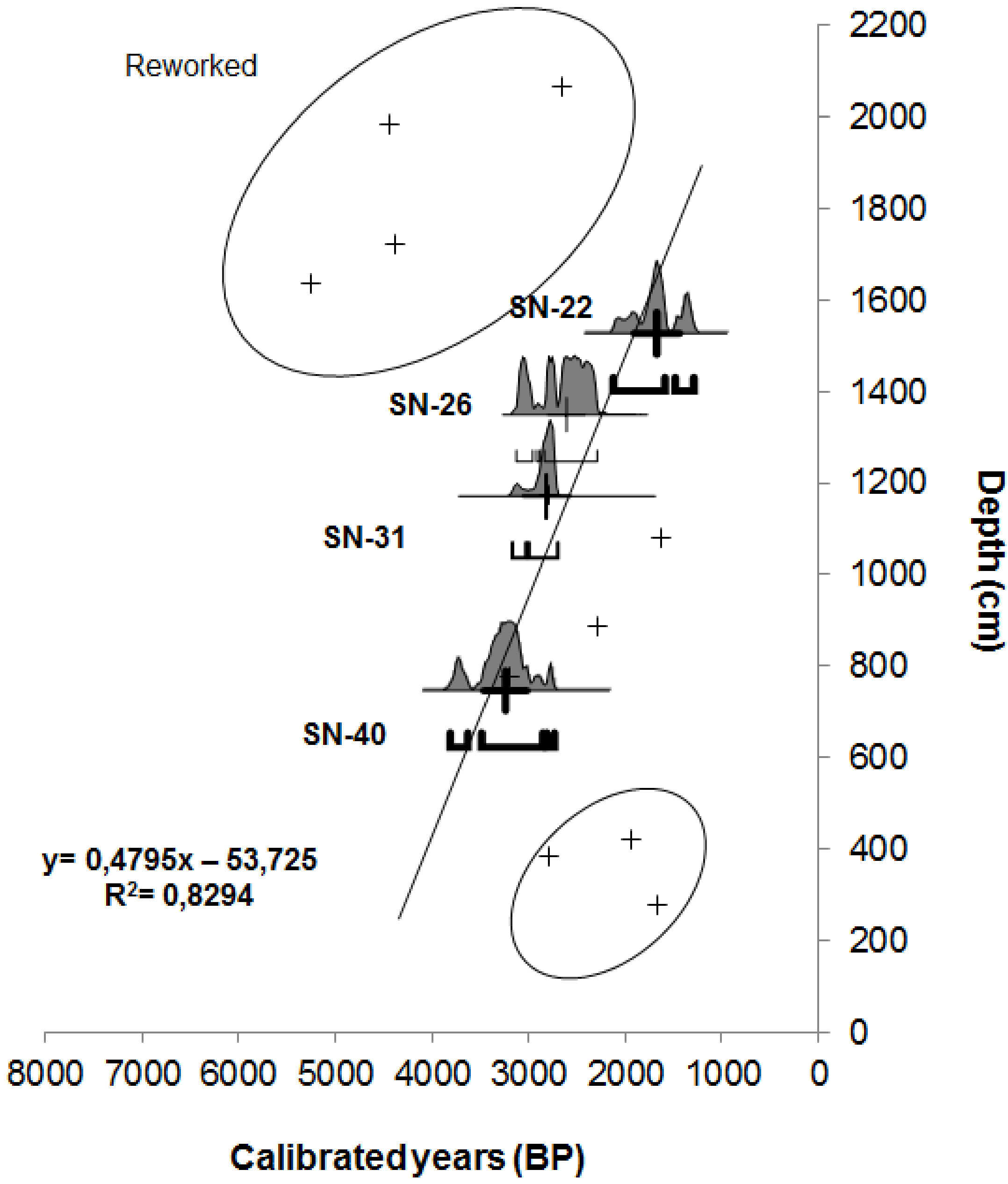


Figure 11. Age model for the San Nicolás core based on AMS^{14}C calibrated dates. Clustered points (+) correspond to reworked or outlier samples. Modified from Martínez *et al.* (2013).

3.4.2 Lithofacies and stratigraphic succession of San Nicolás

The stratigraphic succession of the San Nicolás section comprises ~21 m of laminated silt, silty clay and fine sand at the base, intercalated with massive beds of sandy silt and clay (Figures 12, 13). The middle part of the succession is characterized by fining upwards beds where clay and silt sediments predominate, with a few fine to medium sand beds of cm scale. The uppermost part of the section comprises coarsening upwards silt and fine sand beds. The basal contact with the regional unconformity observed in the section exposed at La Caimana creek (Vélez *et* al., 2013) was not recovered in this core; for this reason the sedimentary succession of the San Nicolás section may be greater than 21 m (Figures 12, 13).

The first 601 cm are composed of laminated silt and silty clay with a few millimeters to centimeter-scale sandy silt and fine sand layers. At the top of this interval massive clay beds are common. The color of the laminae and layers vary from greyish green to orange and beige. Animal bioturbation is common in the first 100 cm from the bottom to the surface while mechanical deformation is dominant throughout the whole interval. The second interval (601-1,090 cm) is characterized by silt and fine sand laminations; a few thick clay beds occur towards the top. Trough cross-stratification and clay lenses occur in the middle part of the section, although they are not very common. Mechanical deformation is also recurrent throughout the interval. Between 1,090 and 1,484 cm, laminated silt, clay and fine sand beds are common. Animal bioturbation becomes dominant; occurring throughout the interval mainly associated with silt beds. Sediments are beige, grey and orange in color. No mechanical deformation is observed for this section of the core.

The uppermost part of the core (1,484-2,091 cm) is characterized by a coarsening-upwards sequence of silt intercalated with medium to coarse sand beds of a few centimeter-thickness, especially at the base. Mechanical deformation, as a result of the core extraction, is conspicuous at the base of this interval, whereas animal bioturbation are restricted to the top. Fining-upwards silt and clay are predominant towards the upper part of the interval.

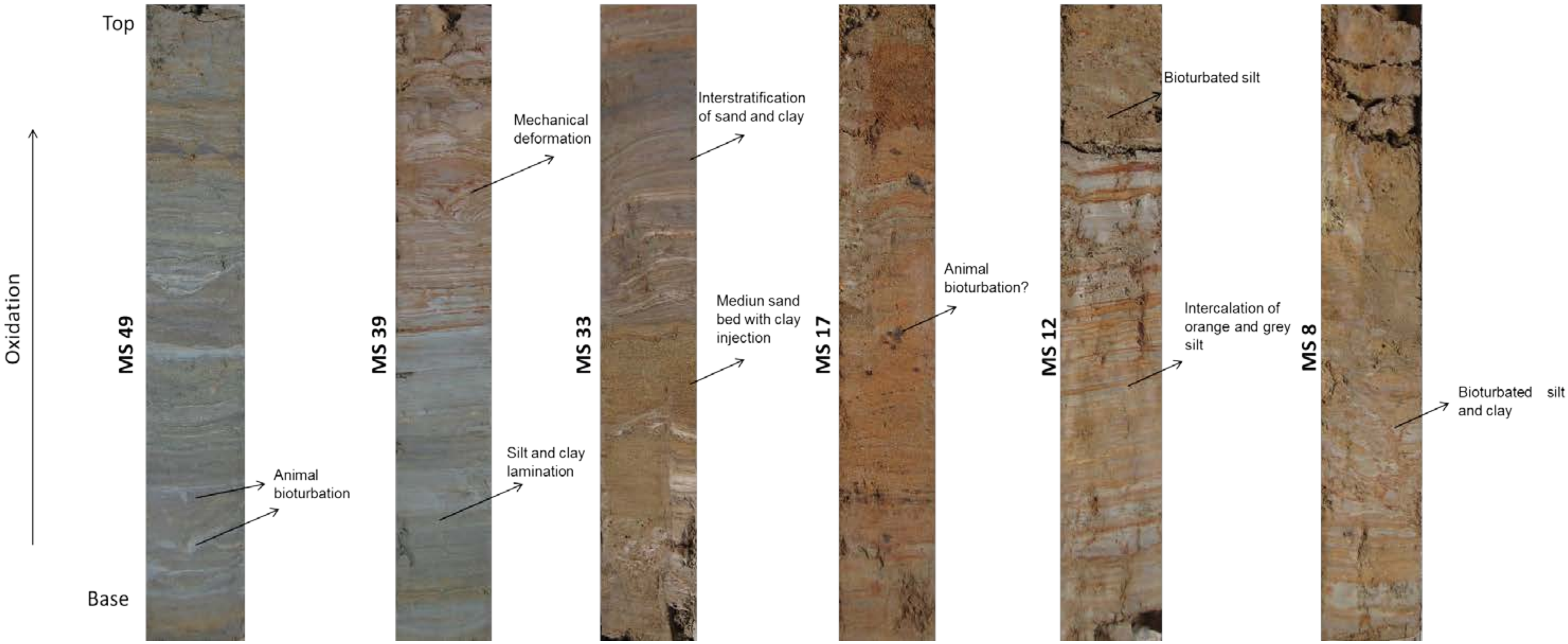


Figure 12. Examples of the San Nicolás sedimentary succession. Note the variation in the lithology and color near the base (MS49) to near the top (MS8) with conspicuous levels of medium sand, and orange to red coloration towards the top. Photographs by permission of José I. Martínez.

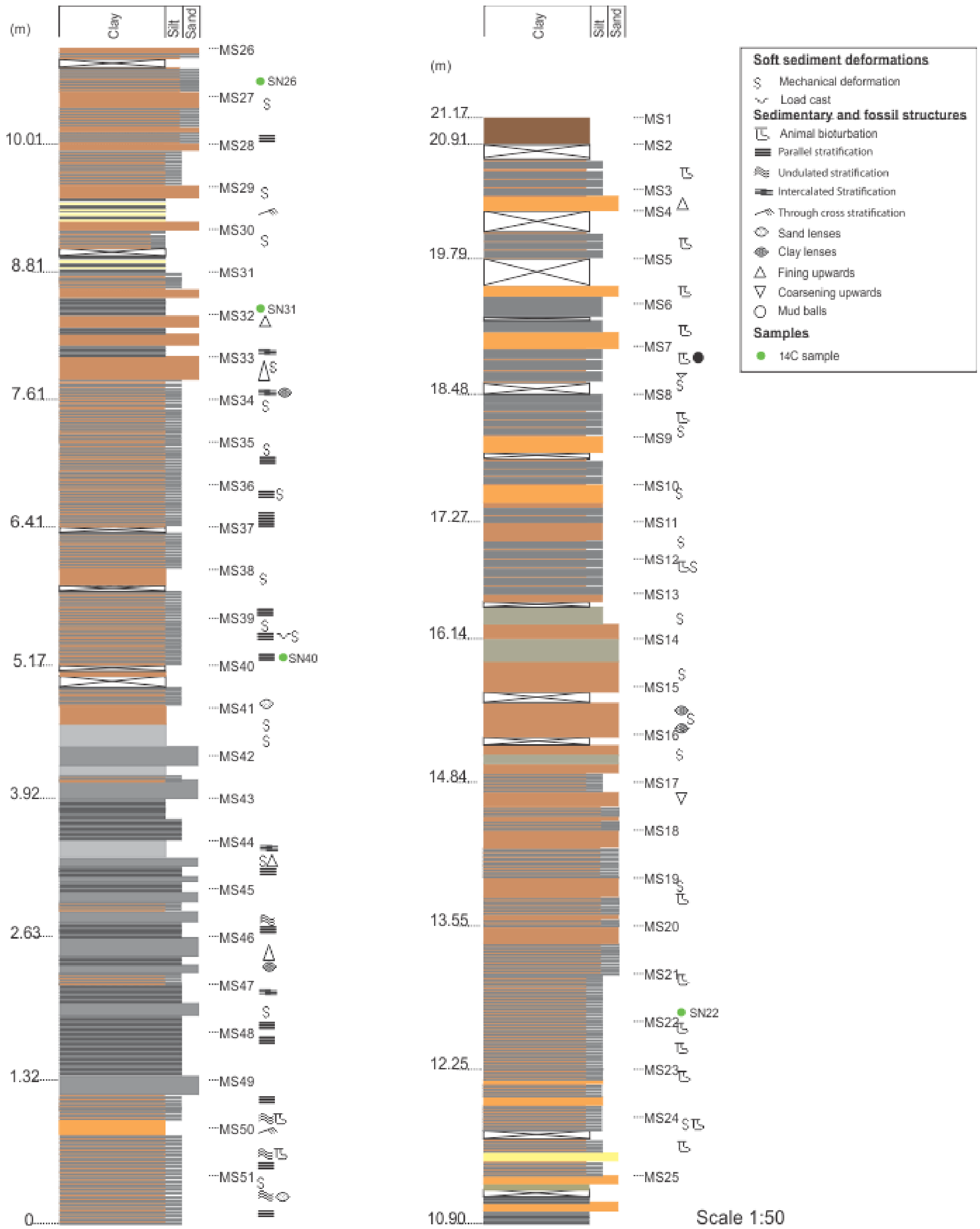


Figure 13. Sedimentary succession of the San Nicolás core. Note that mechanical deformation is recurrent throughout the core, and animal bioturbation dominates at the top. The basal 10 m of the succession are represented on the left and upper 11 m on the right. Sediment color were taken from photographs provided by Jose I. Martínez.

3.4.3 Diatom assemblages and zones in the San Nicolás core

From the 23 samples analyzed, only 11 were found to contain diatoms with a minimum of 300 valves. In total 13 diatom species were found to be common (≥5%) or abundant (≥20%), with a predominance of planktonic and benthic species. The most common species occurring throughout the sedimentary succession are *Aulacoseira granulata* (1-51%) and *Nitzschia amphibia* (2-90%) (Appendix 5). Other species such as *Fragilaria crotonensis*, *Cocconeis placentula* and *Synedra ulna* also occur in relatively high abundances (≤15%) (Appendix 4). Diatom species were grouped based on their ecological preferences as planktonic, benthic, aerophilic and epiphytic. According to the cluster diagram, four diatom zones were identified (Figure 14). The range of dates for the diatoms zones were estimated using the linear regression equation obtained from the age model (Figure 11).

Diatom zone 1 (68-337 cm above the base, ~ 4386- 3,824 cal yr BP): This zone is dominated by the planktonic species *Aulacoseira granulata* with high relative abundances (37-48%) throughout the zone. Another planktonic species *A. granulata* var. *angustissima* (4-7%) is also present, although with low values. The benthic species *Nitzschia amphibia* occurs throughout the zone (2-25%) with a maximum peak (value) at the base, whereas *Fragilaria crotonensis* (7-20%) is present with variable but relatively high values. The epiphytic species *Synedra ulna* also occurs along the succession with relatively low abundances (3-9%). Diatoms were not preserved from 337 to 477 cm.

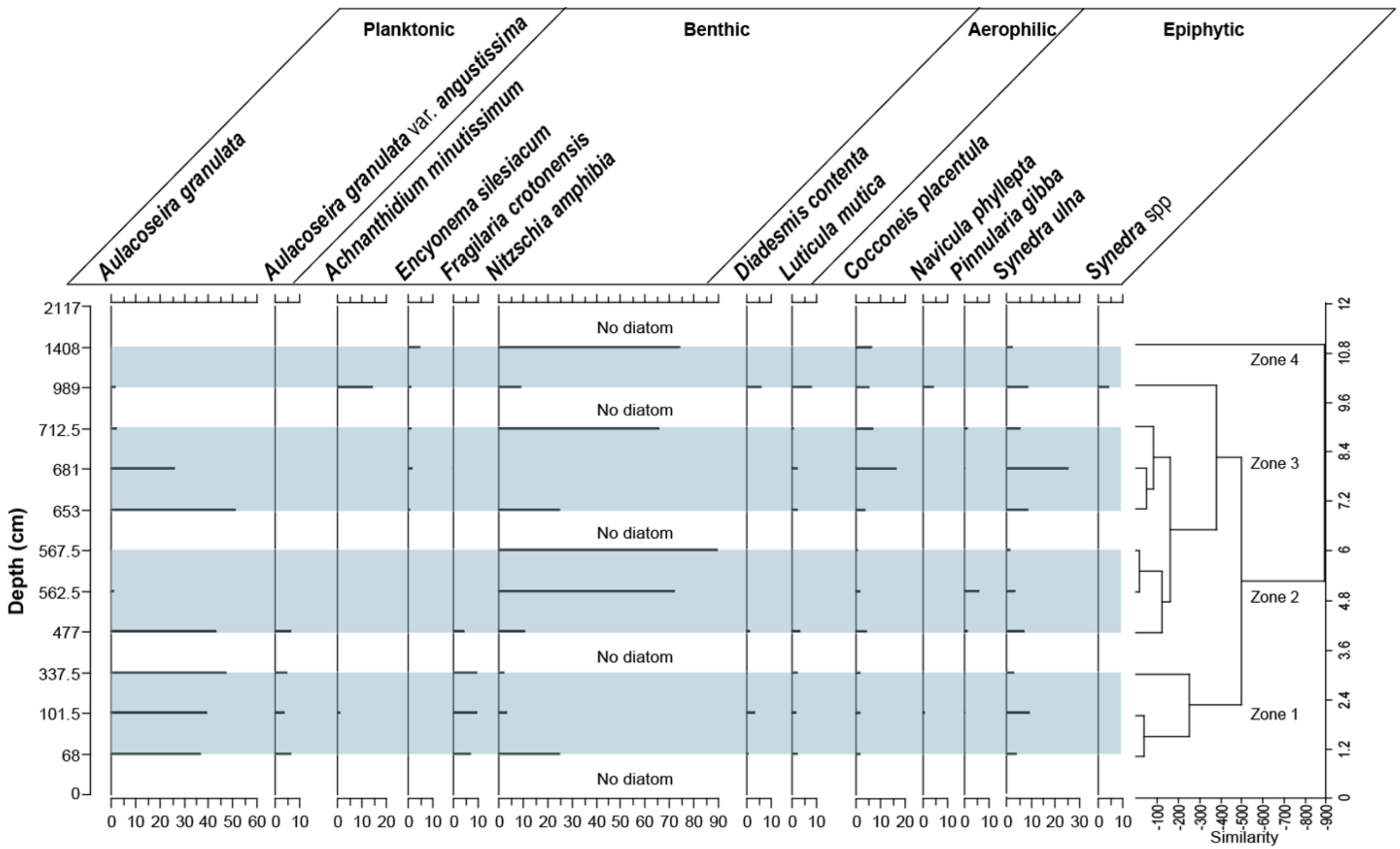


Figure 14. Distribution diagram of the diatom taxa and cluster diagram with the diatom zones. Note the high relative abundance of *N. amphibia* and *A. granulata* throughout the stratigraphic succession.

Diatom zone 2 (477-567 cm above the base, ~3,824-3,342 cal yr BP): This zone is characterized by the benthic species *Nitzschia amphibia* (11-90%), with increasing relative abundances towards the top. The planktonic species *Aulacoseira granulata* (44%) peaks at the base of the zone (447 cm). Other epiphytic and planktonic taxa that are present with low values include: *Synedra ulna* (2-8%), *Pinnularia gibba* (2-6%), and *Aulacoseira granulata* var. *angustissima* (7%). Diatoms were not recorded between 567 and 653 cm.

Diatom zone 3 (653-712 cm above the base, ~3342-3042 cal yr BP): This zone is mainly composed of the benthic species *Nitzschia amphibia* (26-66%), with increasing relative abundances towards the top, and the planktonic *Aulacoseira granulata* (2-51%), which is more abundant at the base. The epiphytic species *Cocconeis placentula* (7-14%) and *Synedra ulna* (6-26%) occur with relatively high values within the zone 3. Diatoms were not preserved between 712 and 989 cm.

Diatom zone 4 (989-1,408 cm above the base, ~3,042-1,592 cal yr BP): This zone is dominated by the benthic species *Nitzschia amphibia* (9-75%), whereas *Achnanthidium minutissimum* is present with a single peak at the base. Other epiphytic and aerophilic species, e.g., *Cocconeis placentula*, *Synedra ulna*, *Diadesmis contenta* and *Luticula mutica*, also occur with low relative abundances. Diatoms were not recorded in the middle part of the zone (~419 cm).

CHAPTER 4: Paleoenvironmental reconstruction

4.1 Paleoenvironmental reconstruction of the Sucre deposit

The association of lithofacies, the diatom assemblages, and the ^{14}C dates were used to reconstruct the history of deposition of Sucre. Four paleoenvironmental periods were established according to the main lithofacies and the diatom zones between ~2,718 to <200 cal yr BP.

The first period (first 600 cm, ~2,718-2,214 cal yr BP, diatom zones 1-2, lithofacies 1,2,3,5,6) corresponds to the beginning of river deposition as indicated in the several centimeters-thick, coarsening-upwards, fine sand beds at the base. These sand layers would represent proximal splay-type deposits (Miall, 1996; Flaig *et al*., 2011). After the sand splay deposition, hydrological conditions changed from river pulse to lacustrine environments formed on the floodplain as indicated by the decrease in grain size to silt. This lacustrine phase was characterized by swamp-wet soils of relatively long-term duration as indicated by the high relative abundances of the aerophilic-shallow water species *Diadesmis confervacea* (Patrick and Reimer, 1966; Sala *et al*., 2002; Torgan and Santos, 2008), and the transitional succession of the epiphytic species *Gomphonema angustum*, *Gomphonema gracile*, *Cocconeis placentula* and *Synedra ulna* that indicate gradual colonization of macrophytes. An interval of infrequent flooding is characterized by distal splay deposition as indicated by silt and clay lamination (Flaig *et al*., 2011). No diatoms were recorded in this interval. In summary this period records two fluvial environments in respect to the channel. The first environment is proximal and the second one distal.

The second period (600-1,100 cm, ~2,214-1,439 cal yr BP, diatom zones 3-4, lithofacies 1,2,3,5,6) records low-energy sedimentation as indicated by the occurrence of a few centimeter-scale, fining- upwards, silt beds; intercalated with organic laminae. These fining-upwards silt and clay sediments are indicative of distal splays or waning flows that would allow the formation of swampy environments, as indicated by the occurrence of aerophilic diatom species, e.g. *Diadesmis confervacea*, *Orthoseira roeseana*, and *Diadesmis contenta* (Gaiser and Johansen, 2000; Vélez *et al*., 2013). A single high peak of the planktonic species *Aulacoseira ambigua* suggests a high-energy river pulse as indicated by a sand layer in erosional contact with the underlying clay. This river connectivity allowed the formation of shallow swamps where benthic and aerophilic diatoms colonized. The end of this period is marked by infrequent floods suggested by thick paleosols lacking diatoms. Fine-grained beds with root traces of a few to several centimeters-thick are considered paleosols (Retallack, 2001).

The third period (1,100-1,600 cm, ~1,439-664 cal yr BP, diatom zones 4-5, lithofacies 4, 5,7,8) corresponds to intervals of variable hydrological conditions, with high energy pulses as indicated by thick sand layers, and low energy environments like shallow swamps as indicated in the occurrence of epiphytic diatom species. Periods of no river connectivity are evidenced by the formation of paleosols and diatom assemblages dominated by aerophilic species.

The last period (1,600-2,400 cm, ~664-<200 cal yr BP, diatom zone 5, lithofacies 4,5,7) marks the beginning of longer-term intervals without river connectivity, as indicated by the conspicuous occurrence of thicker paleosols, and the absent and/or low contents of diatoms. These quiet conditions were interrupted by high-energy river pulses as suggested by thick and frequent sand beds. Long-term dry conditions are also evidenced by the occurrence of the aerophilic species *Orthoseira roeseana* throughout this period and the orange coloration of the sand layers that suggest oxidizing conditions, most likely the result of long-term aerial exposure.

4.2 Paleoenvironmental reconstruction of the Las Flores deposit

The lithofacies characterization of the Las Flores deposit indicates that this deposit corresponds to a succession of palaeosols (Flaig *et al*., 2011; Ashley *et al*., 2013). Thick and rich-organic paleosols, grey to greyish brown in color are conspicuous throughout the basal part, whereas orange and yellowish brown paleosols with oxidized root traces and absence of charcoal predominate towards the top.

The lowermost part of the succession (~2500-1315 yr BP) is composed of organic-rich paleosols (facies 2) with root traces and abundant charcoal, which is intercalated with several cm-scale, fine-grained sediments with well-preserved carbonaceous plant material, and leaves (facies 4). The high concentration of plant macrofossils and charcoal are interpreted as wetlands, waterlogged lands or stagnant water bodies with poor drainage conditions (Retallack, 1997; Flaig *et* *al*., 2011). However, the presence of oxidized root traces, oxidized organic matter (leaves and wood fragments) associated with mud cracks, and relatively high abundances of hematite and limonite (observed in the smear slides) suggest a transition from wet/anoxic to oxidizing conditions, that possibly occurred after the deposition of the organic matter (Ashley *et al*., 2013). In addition, a change in the vegetation evidences a fluctuation of wet and dry conditions as indicated by the intervals characterized by palms and legumes typical of dry forest, followed by well-developed forest and fern colonization, normally indicative of wetter conditions. This time interval thus reflects soil development under changing water tables which in turn are related to precipitation regimes.

Towards the top of the succession (1315-<200 yr BP), mottled reddish-grey paleosols are present, underlying yellowish-brown paleosols with a high content of oxides (hematite) and root traces, characterized by conspicuous organic laminae. Mottled dark grey and grey and organic-rich paleosols are less frequent, whereas silty clay and, light grey paleosols with root traces are conspicuous throughout ~ the upper 800 cm of the succession. The uppermost part of the sedimentary succession is predominantly composed of yellowish brown, thicker paleosols with abundant oxidized root traces and low to absent amounts of carbonaceous material. The occurrences of mottled red, mottled grey and light grey paleosols are typical of those formed in waterlogged environments (Retallack, 1997 in Ashley *et al*., 2013). Conversely, millimeter-thick carbonaceous laminae associated with oxidized and rooted paleosols would indicate better-drained conditions and/or dry periods that control the formation of peats (Fiorillo *et al*., 2010 in Flaig *et al*., 2011).

4.3 Paleoenvironmental reconstruction of the San Nicolás deposit

The association of lithofacies and the diatom assemblages were used to reconstruct the history of deposition of the San Nicolás core from ~4,386 to <200 cal yrs BP, and allow for the identification of four paleoenvironmental periods.

The first interval (0-600 cm, ~4,386-3,277 cal yr BP, diatom zone 1-2) marks the beginning of shallow lacustrine-like conditions on the floodplain as indicated by the presence of a few cm scale silt, fine sand, and clay laminations and the occurrence of the benthic species *Nitzschia amphibia* (Kelly *et al*., 2005) . Scarce animal bioturbation is present at this stage. The formation of shallow lakes/swamps coincides with a period characterized by frequent flooding as indicated by the high relative abundance of the planktonic species *Aulacoseira granulata*, which is used as a marker of the connectivity of the Cauca River and its floodplain (Baker *et al*., 2000; O'Farrell *et al*., 2001; Gell *et al*., 2002; Gell *et al*., 2005a; Gell *et al*., 2005b; Vélez *et al*., 2013). After a period of high-energy flooding regime, a period of decrease in the hydrologic energy is evidenced by the high relative abundance of the species *Nitzschia amphibia* and the occurrence of massive clay beds.

The second period (600-1,090 cm, ~3,277-2,255 cal yr BP, diatom zones 3-4) is characterized by frequent river connectivity at the beginning marked by the occurrence of *Aulacoseira granulata* and coarsening-upwards silt and fine sand laminations. This connection allowed for the existence of ephemeral swamps to permanent shallow lakes as indicated by the diatom assemblage characterized by the benthic species *Nitzschia amphibia* and ephyphitic species *Cocconeis placentula* and *Synedra ulna* (Kelly *et al*., 2005; Gari and Corigliano, 2007; Abuhatab and Donato, 2012). Between 700 and 989 cm above the base (~3068-2465 cal yr BP) high-energy pulses prevailed as suggested by coarsening-upwards fine to medium grain sands, which were the result of distal crevasse splay deposition. High energy flows are also supported by the absence of diatoms during this time. At the end of this period, stable and quiet hydrological conditions of shallow but permanent ponds are established, as indicated by the occurrence of benthic and aerophilic diatom taxa and few epiphytic diatom species, and the decrease in grain size.

The last period (1,090-2,091 cm, ~2.255-<200 cal yrs BP, top of diatom zone 4) is characterized by the transitional change from frequent river pulses as evidenced by the fine sand and silt beds, and lacking in diatom preservation, indicating frequent river connectivity to very low and quiet energy conditions brought about by infrequent river pulses, as indicated by fining-upwards clay and silt oxidize-massive beds with a high concentration of animal bioturbation. This can be interpreted as a change from a high precipitation to low precipitation regime. This further coincides with a high peak of *N. amphibia* (1,408 cm, ~1592 cal yr BP) and the absence of *A. granulata* throughout this period, that also suggest the end of the river connectivity.

4.4. Regional paleoenvironmental and paleoclimaticclimatic reconstruction

Lithofacies and diatom assemblages analyses indicate that the three Holocene deposits of the Cauca River represent different depositional environments formed between 4,300 and <200 yr BP, and deposited under different hydrological dynamics. Age differences for the start of the depositional stage that formed the deposits if the tendencies are extrapolated towards the base, could be: 1) the result of the lack of chronological control due to the lack of enough dates for the bottom part, and 2) the absence of complete stratigraphic sections as is the case for the Sucre deposit and the San Nicolás core in which the contact with the basement was not observed. Independently of the lack of chronological control for the bases of Sucre and San Nicolás, it can be assumed that these deposits formed earlier than Las Flores. The Las Flores deposit lies on top of an exposed 600 cm of metamorphic basement which is topographically higher on the west side of the area of study but outcrops irregularly on the eastern side. It is proposed in this study that the basement formed a paleo-topographic high that shielded the sedimentary succession of the modern Cauca River and worked as a barrier to river floodings. These paleo-topographic highs are observed south in La Caimana section and north in La Chorquina section (Figure 1, observed in a recent field work during January 2014). The elevation explains the exclusive non-fluvial and terrestrial character of Las Flores and thus the younger depositional age of Las Flores; 1,000 or 2,000 years later as compared, respectively, to Sucre and San Nicolás. This would have been the time necessary for the river to weather metamorphic rock that allowed changes in the channel to have any influence on the creation of accommodation space in this part of the sub-basin.

Except for the Las Flores deposit, the sedimentary succession of Sucre and San Nicolás evidenced the hydrologic dynamic imposed by the Cauca River as suggested by the sedimentology (e.g., coarse silt and fine-medium sand beds) and the occurrence of diatoms and other siliceous aquatic microfossils. The San Nicolás section represents a distal environment in respect to the river, similar to La Caimana, of low energy where lacustrine-like conditions were commonly developed, and punctuated by the occurrence of large floods. The Sucre section represents a proximal floodplain with respect to the river, with high energy floods and the formation of shallow lacustrine deposits. The Las Flores section represents terrestrial conditions protected from the river pulses. However, the three deposits reflect similar climatic conditions (i.e. increase in precipitation, drier climates) of regional scale that may be related with the shift of the ITCZ during the Mid-Late Holocene (Vélez *et al.,* 2006). Flood events related with high precipitation, probably in the upper and middle Cauca Valley, and water level fall events related to long-term periods of dryness in the sub-basin were observed during the field works performed between 2010 and 2013, and may reflect variations in the climatic conditions induced by the ENSO (Figure 15).

Evidences of fluvial connectivity were not found the in Las Flores deposit. Nevertheless, today, in the modern Cauca fluvial environment, the Las Flores section occurs closer to the river channel than the Sucre section, which is separated from the modern river channel by a ~200 m wide floodplain.

As previously mentioned, the study area is located on the transcurrent Romeral Fault System (RFS), active since the Early Cretaceous, and responsible for seismic activity in this area (Suter *et al*., 2008; Suter *et al*., 2011). Several soft-sediment deformation structures, possibly related to syndepositional seismicity, have been reported in other deposits located south of the study area (i.e., the Pleistocene Zarzal Formation, Suter *et al*., 2008; and the El Aeropuerto section, Suter *et al*., 2011). Similar soft-sediment deformation structures were also observed in some intervals of the Las Flores and Sucre deposits. Therefore, it is suggested that the paleo-Cauca River channel has migrated laterally due to tectonic activity, since faulting and earthquakes may affect the river course (Nichols, 2009).

Based on this hypothesis, the river channel may have changed its position, being the area where the Sucre section was deposited proximal to the river. Conglomeratic paleo-channels were identified at the Sucre Creek, located ~2 km south of the Sucre section, and on the eastern flank of the river. These deposits would be stratigraphically related towards the uppermost part according to ^{14}C dates obtained in an oncoming study. In this transect between the Sucre deposit and the Sucre Creek, a slight change in the river direction SW-NE to NE-NW is evidenced and may be the result of structural control.

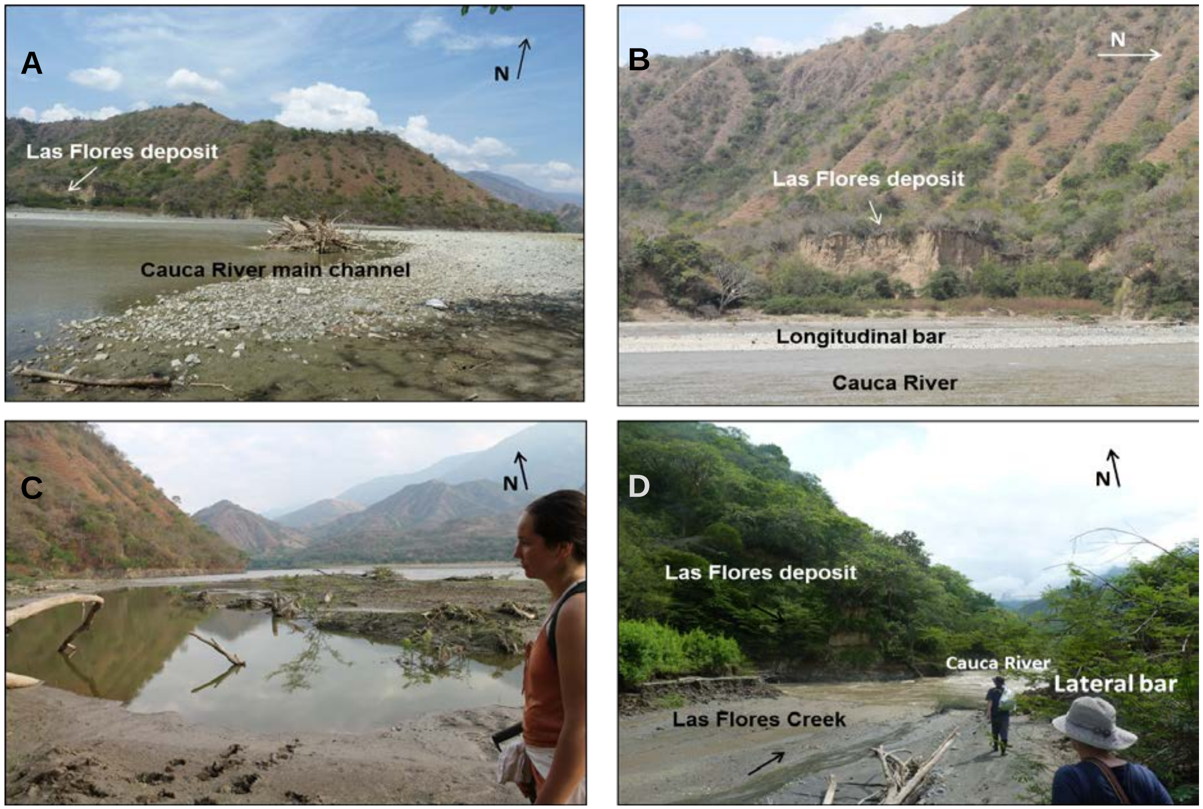


Figure 15. Modern depositional environments and geomorphological units of the studied basin. A. Main channel of the Cauca River exposed due to low flow stage (photo taken in late-January, 2013), B. Cauca River-low water level, note the vegetated lateral bar at the bottom (photo taken in late-January, 2013), C. Ephemeral pond formed in less than 15 days on the narrow floodplain of the river on the eastern flank (Las Flores section) after high flow stage (photo taken in mid-February, 2013), and D. Lateral bar in the eastern flank eroded by the river during a high flow stage, note Las Flores section at the bottom (photo taken by Maria I. Vélez in late-June, 2013).

According to the paleoenvironmental reconstruction of the individual deposits and the evident influence of the active RFS for the structural control of the river channel, a combination of tectonics and climate variations has been the likely mechanism for the deposition and sediment accumulation of these late Holocene deposits.

Correlation between the sections allowed the identification of four depositional periods identified based upon the integration of the paleoenvironmental information obtained from the lithofacies and diatoms assemblages of the individual deposits (Figure 16-17).

The first period (~4,300-3,000 yr BP) records the beginning of sedimentation on a confined floodplain at La Caimana Creek. This period is characterized by frequent distal high flow stages, as indicated by the thick intervals of laminated silt, fine sand and clay typical of fluvial-lacustrine conditions. River flooding into the floodplain as indicated by the high abundance of *A. granulata* allowed for the formation of temporal shallow ponds. At the end of this period a decrease in the hydrologic energy is evidenced by massive clay layers. No deposition in Sucre and Las Flores sites would have yet begun.

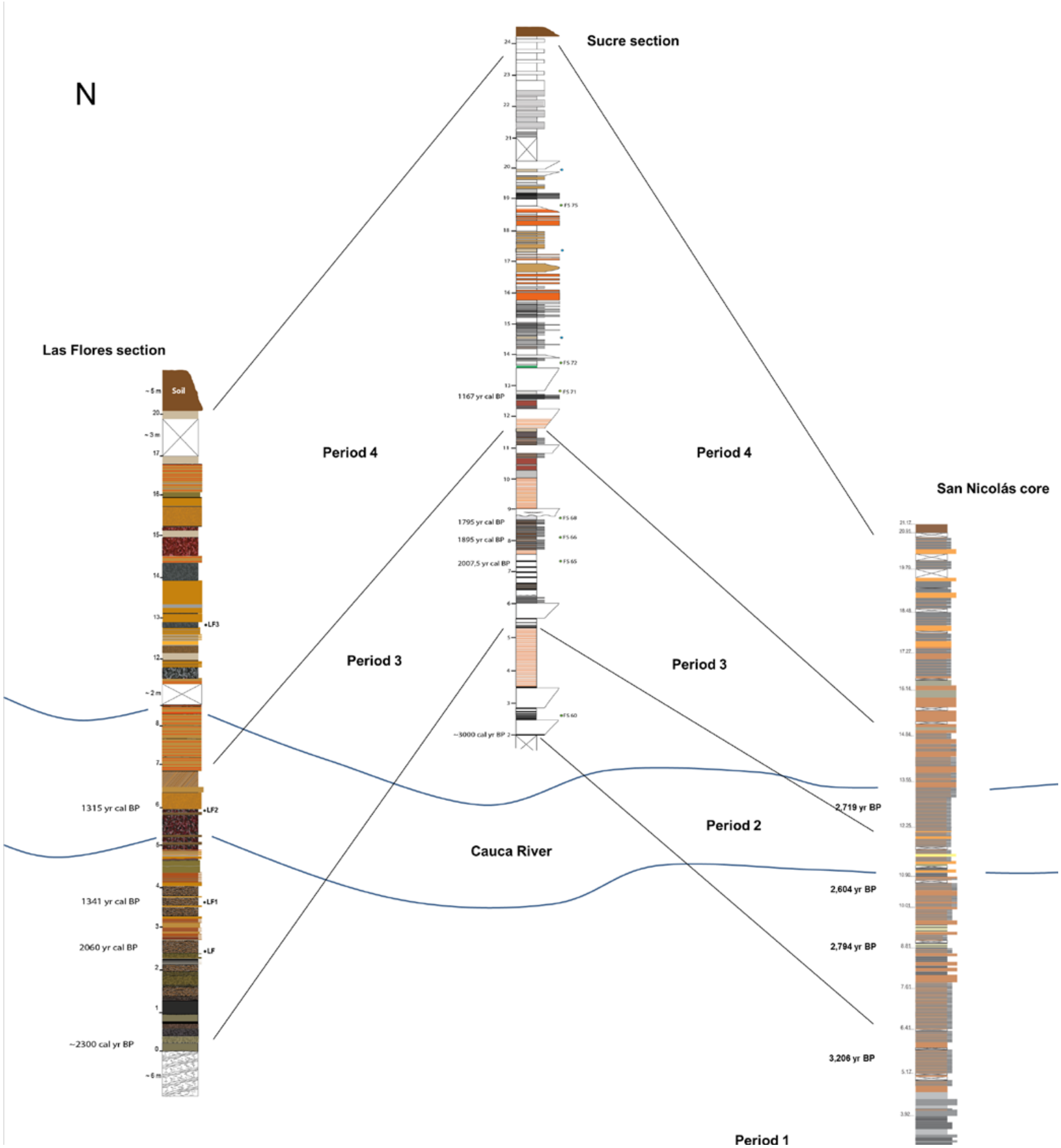


Figure 16. Correlation of the Holocene deposits based on ^{14}C ages, grey layers – paleosols (•) and lithofacies. The sedimentary record for San Nicolás stars at ~4,000 yr BP, Sucre at ~3000 yr BP, and Las Flores at ~2300 yr BP. Note that for the San Nicolás and Sucre succession the contact with the base was not observed. See figures 6, 9 and 13 for legends.

The second period (~3,000-2,300 yr BP) starts with high flow energy pulses as indicated by massive fine sand layers at the Sucre site as well as at the San Nicolás site. In La Caimana Creek, these frequent pulses are also evidenced by coarsening-upwards silt and fine sands and the occurrence of *Aulacoseira granulata* (Baker *et al*., 2000; O'Farrell *et al*., 2001, Vélez *et al*., 2013). This interval is followed by more stable hydrological conditions that allow for the formation of shallow to permanent ponds, as indicated by the transitional shift from aerophilic and benthic diatom assemblages to epiphytic assemblages at both sites. No sediment accumulation had yet occurred at the Las Flores site.

The third period (~2,300-1,300 yr BP) marks the start of the sediment accumulation at Las Flores site characterized by thick organic-rich paleosols and terrestrial plant colonization, as evidenced by the presence of the root traces and the accumulation of plant remains within wetlands. Fluctuations between dry and wetter conditions are evidenced by the high degree of oxidation of the plant macrofossils possibly after deposition and the transitional change from dry forest to well-developed forest. Low-energy sedimentation is recorded at the Sucre site, characterized by distal splays and the formation of swamps and wet soils as indicated by the dominance of aerophilic diatom taxon *Diadesmis confervacea*. This interval is followed by a high-energy event evidenced by a fine sand bed in erosional contact with the underlaying fine-grained sediment. After this high-energy event conditions of low flow prevail as indicated by permanent shallow ponds (dominance of epiphytic diatom species) and soil development. Similar hydrological conditions are recorded at the San Nicolás site where frequent river

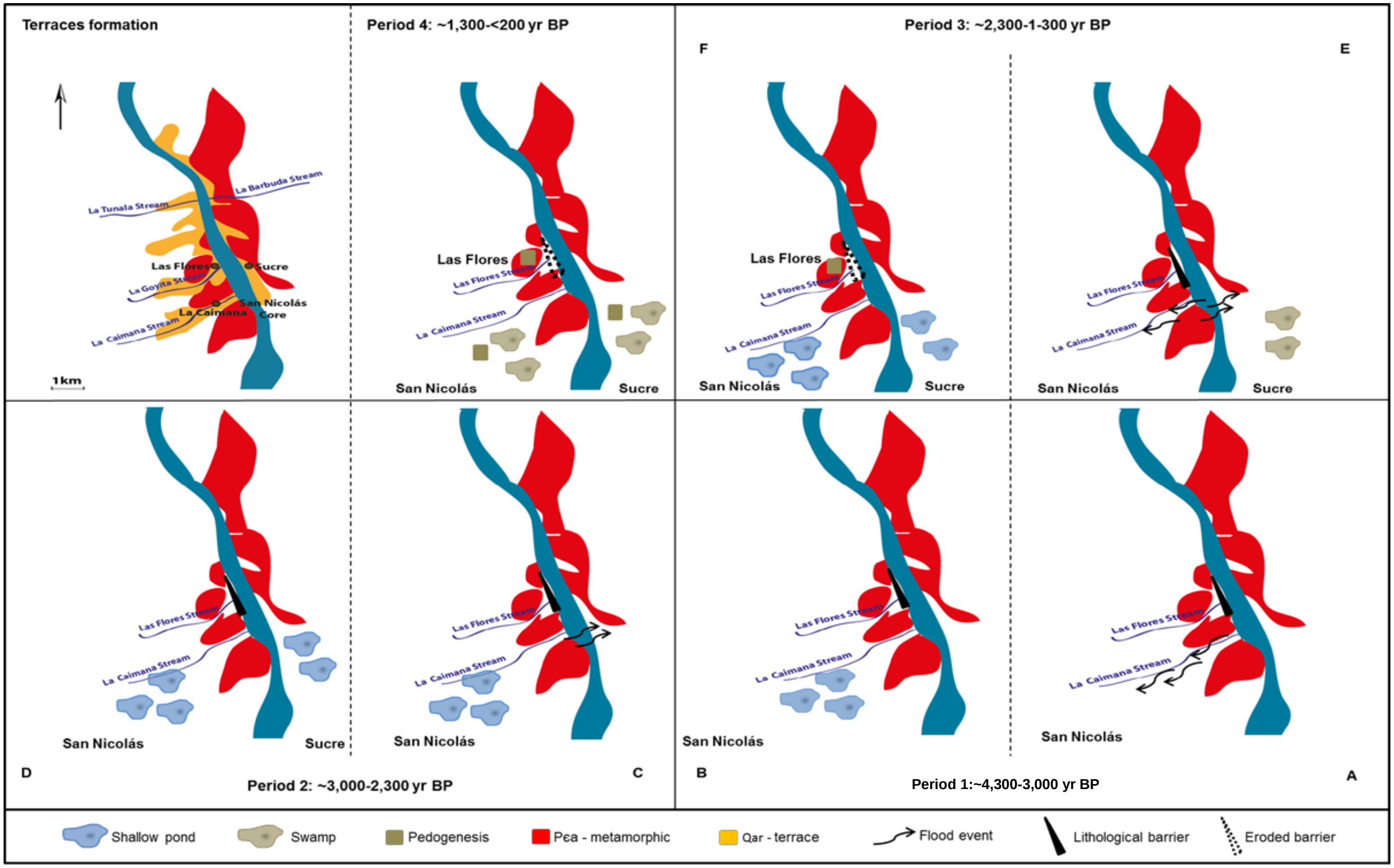


Figure 17. Reconstruction of the depositional periods. **Period 1.** Sedimentation initiates at La Caimana Creek, **A**- flood event, **B**- ephemeral ponds formation; **Period 2.** Deposition begins at Sucre site, **C**-flood event, **D**-ephemeral ponds formation; **Period 3-E.** Flooding at San Nicolás and Sucre sites, **F**- Pedogenesis initiates at Las Flores site and ponds form at San Nicolas and Sucre sites; **Period 4.** River connectivity ends, swamps formation and pedogenesis, and last stage after deposition with the incision and the terraces formation.

connectivity is evidenced by fine sand and silts. However, no diatoms were recovered in this interval in the San Nicolás.

The first three periods suggest a fluctuation between wet and dry climatic conditions. Wet conditions appear to be more recurrent, most likely due to an increase in precipitation as reflected in the pedogenesis process and forest development mainly at Flores, and the high-energy floods in Sucre and San Nicolás. Conversely, the last period of deposition (~1,300-<200 yr BP), is characterized by the end of the river connectivity at both Sucre and San Nicolás sites, and the alternation of wetland soils and dry climate soils, indicating a shift from wetter to dryer climatic conditions at the end of the depositional stage. At the Sucre site short-term high energy pulses are evidenced by fine sand followed by the development of soils while at San Nicolás dryer conditions are indicated by fining-upwards oxidized clays, and animal trace fossil (*Scoyenia* ichnofacies), typically preserved in fluvio-lacustrine sediments and associated to subareial paleosols (Buatois and Mángano, 2011), which suggest low energy settings.

CHAPTER 5: Conclusions

From the study of the sedimentary deposits of the middle Cauca River Valley, Colombia it is concluded that:

1. The Sucre sedimentary succession corresponds to a proximal deposit of the paleo-Cauca River, indicated by the presence of massive sand layers throughout the section. Formation of incipient paleosols suggests periods of stable to low energy hydrological conditions as evidenced in the plant bioturbation and the dominance of aerophilic diatom species.

2. Fluctuation of oxidizing and reducing conditions can be recognized from the paleosols of the Las Flores succession and may be related to water variations responding to periodic climatic changes. Wetland conditions are not herein associated with paleoflood events since there is no evidence of river connectivity (e.g., coarse sediment beds, diatoms) recorded in the Las Flores deposit. However, this study demonstrates the potential application of paleosols for the reconstruction of climate conditions based on the characterization of dry and wet phases.

3. The sedimentary succession of the San Nicolás core represents a distal deposit in respect to the river characterized by fining-upwards silt and clay beds throughout the succession with infrequent few cm scale sand beds that mark relatively high-energy events. Diatom assemblages evidence the existence of lacustrine-like conditions controlled by the river connectivity.

4. Despite the sedimentological, stratigraphic and ecological differences observed between the studied deposits of the Cauca River, regional climatic conditions may be identified from the individual sections. This affirmation is supported by the fluctuations recorded between dry and wet conditions throughout the lowermost part of the three sedimentary successions between ~ 4,300 and 1,300 cal yrs BP. In contrast, the facies present along the uppermost parts of these successions suggest a marked change to dry conditions as evidenced in the abundant oxidized beds with plant bioturbation in Sucre and Las Flores, and the high concentration of animal traces in the San Nicolás core, which occurs as a response to changes from high to low energy conditions between ~ 1,300 and <200 cal yrs BP.

5. A possible regional event of pedogenesis may be marked in the light grey, 15 to 20 cm in thick layers that conspicuously occur towards the top of the Las Flores and Sucre deposits at the same stratigraphic levels. Nevertheless, more detailed study is needed to classify these paleosols and understand the conditions under which they formed.

6. This study demonstrated the high potential of the sedimentary deposits of the Cauca River for a local-scale ecological and climatic reconstruction. However, the genesis of these deposits is still uncertain and better age model constraints must be obtained, using methods different from ^{14}C dating (e.g., OSL). As such, a combination of detailed geological and geomorphogical maps are needed as well as high-resolution stratigraphic studies to better understand the mechanisms involved in the formation of these deposits. Here, I suggest a

combined mechanism that involves tectonics and climate since the deposits are located on the active RFS, and the river hydrology of the Cauca Basin is controlled by a precipitation regime that in turn is influenced by a regional climatic phenomenon, the ITCZ displacement.

7. The Holocene deposits of the Cauca River represent a unique, well-preserved sedimentary record of braided rivers with high potential for paleoenvironmental and paleoclimatic reconstructions in the Andean region of northern South America.

8. A now absent paleo-topographic high or basement rock must have existed between the channel and the Las Flores section. Its removal was most likely caused by gradual erosion of the river. The implications of high erosive capacity of the Cauca River should be considered for long-lasting man-made structures on the river such as the building of a dam, only a few kilometers north of the study area.

9. This study demonstrated the high potential of preservation of diatoms compared to other microsfossils (i.e. pollen, ostracods) in fluvio-lacustrine sediments and their use as an indicator of hydrologic changes for paleolimnological reconstruction of ancient floodplains.

10. This study confirms the complexity of fluvial deposits with frequent lateral and vertical changes. Results herein can be used in the production of facies models for tropical, braided river systems that are still poorly understood.

List of References

Abuhatab-Aragón, Y.A; Donato-Rondón, J.C. 2012. *Cocconeis placentula* and *Achnanthidium minutissimum* especies indicadoras de arroyos oligotróficos andinos. Caldasia, 34 (1): 205-212.

Archer, S.G; Reynisson, R.F; Schwab, A.M. 2011. River terraces in the rock record: An overlooked landform in geological interpretation? In: From river to rock record: The interpretation of fluvial sediments and the subsequence interpretation. SEMP Special Publication, 97: 63-85.

Ashley, G.M; Deocampo, D; Kahmann-Robinson, J; Driese, S.G. 2013. Groundwater-fed wetland sediments and paleosols: it´s all about water table. In: New Frontiers in Paleopedology and terrestrial Paleoclimatology: Palaeosols and Soils Surface Analog Systems. SEPM Special Publication, 104: 47-61.

Baker, P.D; Brookes, J.D; Burch, M.D; Maier, H.R; Ganf, G.G. 2000. Advection, growth and nutrient status of phytoplankton populations in the Lower River Murray, South Australia. Regul. Rivers: Res. Mgmt, 16: 327–344.

Battarbee, B. 1973. A new method for the estimation of absolute microfossil numbers, with reference especially to diatoms. Limnology and Oceanography, 18 (4): 647-654.

Battarbee, B. 1986. Diatom analysis. In the Handbook of Holocene palaeoecology and palaeohydrology. Berglund, B.E. (Ed.), Wiley: 527-570.

Bayle, P.B. 1995. Understanding Large Rivers: Floodplain Ecosystems. BioScience, 45 (3): 153-158.

Bradbury, J.P; Colman, S.M; Reynolds, L.M. 2004. The history of Recent Limnological Changes and Human Impact on Upper Klamath Lake, Oregon. Journal of Paleolimnology, 31: 151-165.

Bridge, J.S. 2003. River and floodplains forms, processes, and sedimentary records. Blackwell.

Bronk Ramsey, C. 2009. Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.Flores, J.A., Sierro, F.J. 1997. Revise technique for calculation of calcareous nannofossil accumulation rates. Micropaleontology, 43(3): 321-324.

Brugam, R.B, Patterson, C. 1983. The A/C (Araphidineae/Centrales) ratio in high and low alkalinity lakes in eastern Minnesota. Freshwater Biology, 13: 47-55.

Bull, W.B. 1990. Stream terraces genesis: implications for soil development. Geomorphology, 3: 351-357.

Buatois, L.A; Mangano, M.G. 2011. Ichnology: Organism-substrate Interactions in Space and Time. Cambridge University Press, pp 358.

Cocquyt, C., De Wever, A. 2002. Ephiphytic diatom communities on herbarium material from Lake Naivasha and Lake Sonachi, Eastern Rift Valley, Kenya. Belg. Journ. Bot. 135 (1-2): 38-49.

Flaig, P.P; McCarthy, P.J; Fiorillo, A.R. 2011. A tidally influenced, high-latitude coastal-plain: The Upper Cretaceous (Maastrichtian) Prince Creek Formation, North Slope, Alaska. In: From river to rock record: The interpretation of fluvial sediments and the subsequence interpretation. SEMP Special Publication, 97: 233-264.

Flores, J.A., Sierro, F.J. 1997. Revised technique for calculation of calcareous nannofossil accumulation rates. Micropaleontology, 43(3): 321-324.

Gaiser, E; Johansen, J. 2000. Freshwater diatoms from Carolina Bays and other isolated wetlands on the Atlantic coastal plain of South Carolina, U.S.A., with descriptions of seven taxa new to science. Diatom Res, 15:75–130.

García, Y., Martínez, J. I., Vélez, M., Yokoyama, Y., Battarbee, R., Suter, F. 2011. Palynofacies analysis of the late Holocene San Nicolas terrace of the Cauca paleolake and paleohydrology of the norther South America. Palaeogeogr. Palaeoclim. Palaeoecol., 299:298-308.

Gari, E.N; Corigliano, M.C. 2007. Spatial and temporal variations of *Cocconeis placentula* var. *euglypta* (Ehrenb.) 1854 Grunow, 1884 in drift and periphyton. Braz. J. Biol, 67 (4): 587-595.

Gell, P.A; Sluiter, I.R; Fluin, J. 2002. Seasonal and interannual variations in diatoms assemblages in Murray River connected wetlands in north-west Victoria, Australia. Marine and Freshwater Research, 53: 981-992.

Gell, P.A; Tibby, J; Fluin, J; Leahy, A; Reid, M; Adamson, K; Bulpin, S; MacGregor, A; Wallbrink, P; Hancock, G; Walsh, B. 2005a. Accessing limnological change and variability using fossil diatom assemblages, South-east Australia. River Res. Applic, 21: 257-269.

Gell, P.A; Bulpin, S; Wallbrink, P; Hancock, G; Bickford, S. 2005b. Tareena Billabong –a paleolimnological history of an ever-changing wetland, Chowilla Floodplain, lower Murray-Darling Basin, Australia. Marine and freshwater Research, 56: 441-456.

Gómez, N; Riera, J.L; Sabater, S. 1995. Ecological and morphological variablity of *Aulacoseira granulata* (Bacillariophyceae) in Spanish reservoirs. Journal of Plankton Research, 17(1): 1-16.

Grosse, E. 1926. Estudio geológico del Terciario Carbonífero de Antioquia en la parte occidental de la Cordillera Central de Colombia, Berlín, Verlag Von Dietrich Reimer (Ernst Vohsen). 361 p.

Grundell, R; Gell, P; Mills, K; Zawadzki, A. 2012. Interaction between a river and its wetland: evidence from the Murray River for spatial variability in diatom and radioisotopes records. J. Paleolimnol, 47: 205-219.

Haug, G., Hughen, K., Sigman, D., Peterson, L., and Röhl, U. 2001. Southward migration of the intertropical convergence zone through the Holocene. Science, 293: 1304-1308.

Hammer, Ø., Harper, D. A. T. & Ryan, P. D. 2011. PAST - PAlaeontological STatistics, version 2.09. http://folk.uio.no/ohammer/past.

Hodges, J. D. 1997. Development and ecology of bottomland hardwood sites. Forest ecology and Management, 90: 117-125.

Juggins, S. 2013. C2 Software for ecological and palaeoecological data analysis and visualization. http://www.staff.ncl.ac.uk/staff/stephen.juggins/software.htm

Junk, W. J., Bayley, P. B., Sparks, R. E. 1989. The Flood Pulse Concept in River-Floodplain Systems. In: Proceedings of the International Large River Symposium. Can. Spec. Publ. Fish. Aquat. Sci, 106: 110-127.

Kelly, M.G; Bennion, H; Cox, E.J; Goldsmith, B; Jamieson, J; Juggins, S; Mann, D.G; Telford, R.J. 2005. Common freshwater diatoms of Britain and Ireland: an interactive key. Environment Agency, Bristol. http://craticula.ncl.ac.uk/EADiatomKey/html/index.html

Krammer, K. & Lange-Bertalot, H. 1986. Süsswasserflora von Mitteleuropa. Bacillariophyceae 2/1 Naviculaceae. Stuttgart. Gustav Fischer.

_____________. 1988. Süsswasserflora von Mitteleuropa. Bacillariophyceae 2/2 Epithemiaceae, Surirellaceae. Stuttgart. Gustav Fischer.

_____________. 1991a. Süsswasserflora von Mitteleuropa. Bacillariophyceae 2/3 Centrales, Fragilariaceae, Eunotiaceae. Stuttgart. Gustav Fischer.

_____________. 1991b. Süsswasserflora von Mitteleuropa. Bacillariophyceae 2/4 Achnanthaceae und Gomphonema. Stuttgart. Gustav Fischer.

______________. 1999. Süsswasserflora von Mitteleuropa. Bacillariophyceae 1/1 Naviculaceae. Stuttgart. Gustav Fischer.

Law, R. A. 1983. Preparing strewm slides for quantitative microscopical analysis: A test using calibrated microspheres. Micropaleontology, 29 (1): 60-65.

Lowe, J. J., Waker, M. J. C. 1997. Reconstructing Quaternary Environments. Addison Wesley Longman, Second Ed., Edinburgh, U.K., 68-72.

Martínez, J.I; Ruíz, O; Escobar, J; Yokohama, Y, Vélez, M.I. 2007. El registro paleoclimático de los sedimentos laminados aluvio-lacustres holocénicos del río Cauca. Internal report. Fundación pra la promoción de la Investigación y la Tecnología – Universidad EAFIT. 78p.

Martínez, J.I; Mayr, C; Yokoyama, Y; Vélez, M.I; Battarbee, R.W. 2013. The San Nicolás succession of the Cauca paleolake: a late Holocene laminated ria lake record from the Neotropics. J. Paleolomnol, 49: 287-300.

Mejía, M. 1983. Plancha 130 – Santa Fe de Antioquia. Escala 1:100.000. Ingeominas, Bogotá.

Meng, L. 1994. How Accurate Is the Random Settling Method for Quantitative Diatom Analysis? A Test Using Lycopodium Spore Tablets. Micropaleontology, 40(3): 261-266.

Mesa, O., Poveda, G., Carvajal, L. 1997. Introducción al clima de Colombia. Universidad Nacional de Colombia. Santafé de Bogotá, Colombia. 390 pp.

Miall, A. 1996. The geology of fluvial deposits. Sedimentary Facies, basin analysis and petroleum geology. Springer, Berlin.

Moore, T.C. 1973. Method of randomly distributing grains for microscopic examination. Journal of Sedimentary Petrology, 43 (3): 904-906.

Myrbo, A; Morrison, A; McEwan, R. 2011. Tool for Microscopic Identification (TMI). http://tmi.laccore.umn.edu.

Nichols, G. 2009. Sedimentology and Stratigraphy. Second Edition. Blackwell, UK, pp. 411.

O'Farrell, I; Tell, G; Podlejski, A. 2001. Morphological variability of Aulacoseira granulata (Ehr.) Simonsen (Bacillariophyceae) in the Lower Paraná River (Argentina). Limnology, 2: 65-71.

Page, W. D., Mattsson, L. 1981. Landslide lakes near Santa Fe de Antioquia. Revista CIAF, 6 (1-3): 469-478.

Parolin, M; Volkmer-Ribeiro, C; Stevaux, J.C. 2007. Sponge spicules in peaty sediments as paleoenvironmental indicators of the Holocene in the Upper Paraná River, Brazil. Rev. bras. paleontol, 10 (1): 17-26.

Patrick, R; Reimer, C.W. 1966. Diatoms of the United States. Vol. I. Monograph 13, Acad. Nat. Sci. Philadelphia.

Patrick, R; Reimer, C.W. 1975. Diatoms of the United States. Volume II, Part 1. Monograph 13, Acad. Nat. Sci. Philadelphia.

Pierce, A. R., King, S. L. 2008. Spatial dynamics of overbank sedimentation in floodplain systems. Geomorphology, 100: 256-268.

Poveda, G. 2002. El chorro del Chocó y su influencia sobre la hidroclimatología de la costa Pacífica y el occidente de Colombia. In: Geología y oceanografía del delta del río San Juan. Eds. Correa, I.D; Restrepo, J.D. Fondo Editorial Universidad Eafit, Medellín, Colombia, pp. 169-187

Poveda, G., Waylen, P. R., Pulwarty., R. S. 2006. Annual and interanual variability of the present climate in northern South America and southern Mesoamerica. Palaeogeogr, Palaeoclim, Palaeoecol, 234: 3–27.

Ramírez, D., López, A., Sierra, G., Toro, G. 2006. Edad y proveniencia de las rocas volcánico sedimentarias de la Formación Combia en el Suroccidente Antioqueño-Colombia. Boletín de Ciencias de la Tierra, 19: 9-26.

Reid, M.A; Ogden, M; Thoms, M.C. 2011. The influence of flood frequency, geomorphic setting and grazing on plant communities and plant biomass on a large dryland floodplain. Journal of Arid Environments, 75: 815-826.

Reineck, H.E; Singh, I.B. 1980. Depositional sedimentary environments. Springer-Verlag, Berlin.

Reid, M.A; Ogden, R.W. 2009. Factors affecting diatom distribution in floodplain lakes of the southeast Murray Basin, Australia and implications for paleolimnological studies. J. Paleolimnol, 41: 453-470.

Riedinger, M., Steinitz-Kannan, M., Last, M., Brenner, M. 2002. A ~6100 14C record El Niño activity from the Galápagos Islands. J. Paleolim., 27: 1–7.

Restrepo, J.D; Kjerfve, B. 2000. Magdalena River interannual variability (1975-1995) and revised water discharged and sediment load estimates. Journal of Hydrology, 235: 137-149.

Restrepo JC, Restrepo JD, Miranda J (2005a) Erosión en la cuenca del Magdalena: Factores humanos y visión preliminar del impacto humano. In: Restrepo JD (ed) Los Sedimentos del Río Magdalena: Reflejo de la Crisis Ambiental. Edit. Universidad EAFIT, Medellín, pp 139–158.

Retallack, G. 1997. A Color Guide to Paleosols. Wiley, Chichester, UK, pp175.

Retallack, G. 2001. Soils of the past. An introduction to paleopedology, 2nd edn. Blackwell Science, Malden.

Rodbell, D., Seltzer, G., Anderson, D., Abbott, M., Enfield, D., Newman, J. 1999. An ~15,000 year record of El Niño-driven alleviation in Southwestern Ecuador. Science, 283: 517–520.

Rothwell, R. G. 1990. Minerals and mineraloids in marine sediments. An optical Identification Guide. Elsevier Applied Science, London, New York. 279p.

Ruíz, O. D., Sánchez, D. P., Parra, C.E. 2005. Un registro Holocénico de alta resolución: Los lodos de la Batea, Santa Fé de Antioquia. Reporte y Perspectivas. Boletín de Ciencias de la Tierra 17: 109-116.

Sala, S; Duque, S; Nuñez-Avellaneda, M; Lamaro, A. 2002. Diatoms from the Colombian Amazonia. Cryptogam Algol, 23:75–99

Sanchez, J.D; Bradbury, J.P; Bohor, B.F; Coates, D.A. 1987. Diatoms and Tonsteins as Paleoenvironmental and Paleodepositional Indicators in a Miocene Coal Bed, Costa Rica. Palaios, 2: 158-164.

Scherer, R.P. 1994. A new method for the determination of absolute abundance of diatoms and other silt-sized sedimentary particles. Journal of Paleolim., 12: 171-179.

Schnunrrenberger, D; Rusell, J; Kelts, K. 2003. Classification of lacustrine sediments based on sedimentary components. Journal of Paleolim, 29: 141-154.

Spaulding, S.A; Lubinski, D.J; Potapova, M. 2010. Diatoms of the United States. http://westerndiatoms.colorado.edu

Suter, F; Neuwerth, R; Gorin, G; Guzman, C. 2008. (Plio-)Pleistocene alluvial-lacustrine basin infill evolution in a strike-slip active zone (Northern Andes, Western-Central Cordilleras, Colombia). Geologica Acta, 6(3): 231-249.

Suter, F., Martínez, J. I. 2009. Tectónica transpresiva cuaternaria en la sutura de El Romeral: ejemplo de la cuenca de Santa Fé - Sopetrán, Antioquia. XII Colombian Geol. Congr. Paipa, Colombia.

Suter, F., Martínez, J. I, Vélez, M. I. 2011. Holocene soft-sediment deformation of the Santa Fé– Sopetrán Basin, northern Colombian Andes: evidence for pre-Hispanic seismic activity? Sed. Geol, 235: 188-199.

Thoms, M. C. 2003. Floodplain-river ecosystems: lateral connections and the implications of human interference. Geomorphology, 56: 335-349.

Thoms, M.C; Southwell, M; McGinness, H.M. 2005. Floodplain-river ecosystems: Fragmentation and water resources development. Geomorphology, 71: 126-138.

Torgan, L.C; dos Santos, C.B. 2008. Diadesmis confervacea (Diadesmiaceae Bacillariophyta): morfologiaexterna, distribuição e aspectos ecológicos. IHERINGIA, Sér. Bot., 63 (1): 171-176.

Van der Grinten, E; Admiraal, W; Kraak, M.H.S. 2008. Periodic flooding restrains local succession of microphytobenthos in floodplain lakes. Fundamental and apply limnology. Archiv für Hydrobiologie, 173 (3): 227-236.

Van der Hammen, T; Hooghiemstra, H. 2003. Interglacial-glacial Fuquene-3 pollen record from Colombia: an Eemian to Holocene climate record. Global and Planetary Change 36, 181-199

Velásquez, C.A. 2005. Paleoecología de alta resolución del Holoceno tardío en el Páramo de Frontino. The Quaternary of Colombia 30, 199 pp.

Vélez, M.I; Hooghiemstra, H; Metcalfe, S; Wille, M; Berrío, J.C. 2006. Late glacial and Holocene environmental and climatic changes from a limnological transect through Colombia, northern South America. Palaeogeography, Palaeoclimatology, Palaeoecology, 234: 81-96.

Vélez, M.I; Martínez, J.I; Suter, F. 2013. Late Holocene history of the floodplain lakes of the Cauca River, Colombia. J. Paleolimnol, 49: 591-604.

Ward, J. V., Tockner, K. 2001. Biodiversity: towards a unifying theme for river ecology. Freshwater Biology, 46: 807-819.

Wiklund, J. A., Bozinoski, N., Hall, R.I., Wolfe, B.B. 2010. Ephiphytic diatoms as flood indicators. J. Paleolimnol, 44: 25-42.

www.unperiodico.unal.edu.co/dper/article/cucarachero-paisa-en-la-lista-de-nuevas-especies.html. Published by: Gimena Ruíz Pérez, August 11 of 2012.

www.eltiempo.com/colombia/medellin/articulo-WEB_NEW_NOTA_INTERIOR 13513095.html. Published by: Victor A. Álvarez, February 17 of 2014.

Appendix 1. Relative percentage abundances estimated for the sediment components of the Sucre deposit based on the smear slides analysis.

Sample	**Depth (cm)**	**Clay**	**Quartz**	**Feldspar**	**Amphibole**	**Muscovite**	**Biotite**	**Chlorite**	**Volcanic glass**
MV44	**200**	20	40	5	5	2			
AT03	**285**	50	5		3				
MV3	**287**	40	10	5	5			2	
AT04	**290**	46	5	3	15			1	
AT05	**296**	13							
AT07	**325**		7	3	5	1		2	
MV7	**500**	10	40	10	10	1		3	
AT14	**540**	55	4	5					
AT16	**552**	43	20	15	5			4	
AT17	**555**	51	5	7	2			1	
350	**560**	50		1				2	
MV8	**575**	5	50	10	15			5	
AT18	**625**	10	3	3					
MV10	**660**	50	10	7	5				
AT19	**661**	22	15	10	3			1	
480	**680**	20	5	3	1				
AT21	**700**	51	5	2	1			1	
MV11	**701**	15	25	20	5	1			
MV12	**702**	19	7	5	5				
YS1MO	**735**	46	10	7					
MR2	**760**	15							

Appendix 1. Extended

Sample	Depth (cm)	Clay	Quartz	Feldspar	Amphibole	Muscovite	Biotite	Chlorite	Volcanic glass
MV13	**775**	34	5	2	2				
MV16	**885**	7	40	10	20	1		5	
MV18	**995**	40	30	10	7			3	
MV19	**1050**	35	9	7	1			3	
S6V10	**1100**	48	7	5	15			10	5
MV22	**1240**	2	40	10	35			3	
MV23	**1275**	20							
MV24	**1300**	10	40	10	20	1		6	
Green layer	**1350**		8		5			75	
MV26	**1400**	25	10	5	40			3	
Grey layer 2	**1450**	49	20	10	7	3		5	
MV30	**1592**	11	35	20	30		1		
MV32	**1690**	20	35	13	20				
MV33	**1725**	55	20	10	10			5	
MV36	**1865**	30	25	7	10			10	
MV39	**1980**	40	3		1			5	
MV41	**2075**	60	20	5	10			2	
MV42	**2190**	7	35	10	45			2	

Appendix 2. Relative percentage abundances of the diatom species recovered in the sediments of the Sucre deposit.

Sample	Depth (cm)	*Aulacoseira ambigua*	*Achnanthes exigua*	*Achnanthes laceolata var. lanceolata*	*Achnantes sp1*	*Amphora ovalis var. lybica*	*Amphora spp*	*Caloneis cf. bacillum*	*Cocconeis placentula*	*Cymbella silesiaca*	*Cyclothella meneghiniana*	*Diadesmis confervacea*	*Diadesmis contenta*
AT03	275	0	0	0	0	0	0	0	1	3	0	70	0
MV3	285	1	0	0	0	1	0	0	1	0	1	37	0
AT04	290	1	0	0	0	0	0	0	0	1	1	29	0
AT05	296	0	0	0	0	0	0	0	2	0	1	8	0
AT07	325	0	0	0	0	0	0	0	1	0	0	49	0
MV7	500	0	1	0	0	0	0	0	30	0	0	3	3
AT14	540	0	0	0	0	2	0	0	2	0	0	0	0
AT16	552	0	0	5	0	2	0	2	14	1	0	3	3
AT17	555	1	1	1	0	0	0	2	6	1	0	7	3
MV350	560	5	0	0	0	16	0	6	3	1	0	10	1
AT18	625	0	0	0	0	0	0	0	0	0	0	71	0
MV10	660	0	0	0	0	2	2	0	3	0	2	50	0
AT19	661	0	0	0	0	0	0	0	1	8	0	6	1
MV480	680	0	0	0	1	0	0	0	2	2	1	40	2
AT21	700	7	0	0	0	40	0	0	1	0	0	4	0
MV11	701	23	1	3	0	1	0	0	3	0	1	2	4
MV12	702	1	24	1	0	0	0	1	0	0	0	6	6
YS1MO	735	1	0	0	2	0	0	0	2	0	7	41	1
MV19	1050	1	0	0	0	37	0	0	1	0	0	0	0
MV23	1275	0	2	0	0	0	0	0	0	0	1	84	0
MV24	1300	0	0	1	0	0	0	0	11	0	0	5	8
MV39	1980	0	0	0	5	0	0	1	2	0	2	4	0
MV41	2075	0	1	1	0	0	0	0	26	4	0	1	2

Appendix 3. Relative percentage abundances estimated for the sediment components of Las Flores deposit based on smear slides analysis.

Sample	Depth (cm)	Clay	Quartz	Feldspar	Amphibole	Muscovite	Chlorite	Hematite	Opaque	Diatoms	Phytoliths	Charcoal	Oxidized O.M	Lithics	Others
AT01	20	58	10	7	5		15		5						
AT02	27	65	15	7	3		3		5			2			
AT04	41	75	7	5	3		1	5	1			3			
AT05	58	20	7		10			22	2		3	20		15	1
AT07	70	72	5	7	3		5	3	5						
AT08	72	20	5		10			30			5	15		20	
AT09	75	68	5	7	2		5	7	3		3				
AT11	77	15	3		15			30			7	10		20	
AT13	129	32	3		15			10				20		20	
AT14	131	63	5	5	2		3	10			1	10			1
AT16	141	67	7	10	3		5	5	1			2			
AT19	166	61		7	3		2	15	1		1	10			
AT21	169	37	7	3	5	1	3	30	3		1	10			
AT23	170,5	76	1	5	1		5	7				5			
AT24	171,5	81	1	5	1		3	3			1	5			
AT26	200,7	47	10	15	2		3	3			7	15			
AT27	201,7	44	7	10	3		1	5			10	20			
AT29	205,7	55	2	7			3	20			3	10			

Appendix 3. Extended

Sample	Depth (cm)	Clay	Quartz	Feldspar	Amphibole	Muscovite	Chlorite	Hematite	Opaque	Diatoms	Phytoliths	Charcoal	Oxidized O.M	Lithics	Others
AT31	218	30	21	3	7		2	10			10	15			
AT33	222	30	20	15	8			20				7			
AT34	231	30	15	5	6	1		10			3	30			
AT36	234,1	50	15	10	5			5				15			
AT38	238,1	58	10	5				5			5	17			
AT39	242,6	40	10	7	5			16			7	15			
AT41	248	15	10	25	35		3	9				3			
AT42	249	30	8	15	17			10				20			
AT44	251	50	15	10	1		6	13				5			
AT47	270	35	15	10	5		15	15	5						
AT49	279	49	15	7	2		7	15	5						
AT51	281,8	60	15	7	1		9	5	3						
AT53	283	10						85							5
AT54	285	30	15	20	10	10		10	5						
AT56	288	50	20	10		5	4	10	1						
AT58	291,6	37	20	15	5	3	3	10	5		1	1			
AT60	293	78	5					10	7						
AT62	297	63	10	7			5	10	5						

Appendix 3. Extended

Sample	Depth (cm)	Clay	Quartz	Feldspar	Amphibole	Muscovite	Chlorite	Hematite	Opaque	Diatoms	Phytoliths	Charcoal	Oxidized O.M	Lithics	Others
AT64	301	30	20	7	5	3	10	20				5			
AT66	305	51	10	5	3	3	5	10	3			10			
AT67	306	60	12	5		7	1	10				5			
AT68	307	39	10	5		3	3	20				20			
AT71	310	57	10	5	1		5	15				7			
AT74	313	53	15	7	2	3	3	10				7			
AT76	323	58	10	1		3	3	15				10			
AT77	327	22	20	7	10		10	20	3			7			1
AT80	339	64	15	10			3	7	1						
AT82	342	57	10	5			3	20	1			3			1
AT85	356	58	10	7		1		20	3			1			
AT87	371	70	10	3	3		3	10	1						
AT89	382	63	10				1	20	1			5			
AT91	393	58	15			10		10	7						
AT93	407	43	15				7	20				15			
AT94	418	22	10		3		5	20		10	15	15			
AT95	420	49	20	10	7		10	3	1						
AT97	422	37	30	15	10		7					1			

Appendix 3. Extended

Sample	Depth (cm)	Clay	Quartz	Feldspar	Amphibole	Muscovite	Chlorite	Hematite	Opaque	Diatoms	Phytoliths	Charcoal	Oxidized O.M	Lithics	Others
AT98	423	19	10	5			3	30	3			30			
AT100	427	46	20	10	5		7	7	5						
AT104	432	46	15	7			5	15	7			5			
AT107	440	23	15	10	5	2		20			7	8	10		
AT109	450	54	10	3			3	20				10			
AT111	452	70	10		1		3	15	1						
AT114	482	66	10					10			7				7
AT116	492	62	15	7	1		5	7	3						
AT118	501	74	10				3	10				3			
AT120	509	62	10				3	15				10			
AT122	512	55	7					25				20			
AT123	527	67	10	7	3		5	5	3						
AT124	538	78	7	5				10							
AT128	604	45	15	10	1	5	3	20	1						
AT130	616	47	20	10	5			10	3			5			
AT133	730	46	20	10				20	1			3			
AT134	747	56	20	10	5		3	5	1						
AT135	765	22	15	10		3		20				30			

Appendix 3. Extended

Sample	Depth (cm)	Clay	Quartz	Feldspar	Amphibole	Muscovite	Chlorite	Hematite	Opaque	Diatoms	Phytoliths	Charcoal	Oxidized O.M	Lithics	Others
AT138	839	55	20	10	7			7	1						
AT142	874	57	20	10	3		5	5							
AT146	893	49	10	5				10	3		3	20			
AT149	1106	45	20	15				10				10			
AT150	1137	44	10	20				10	1		5	10			
AT154	1151	38	20	30			1	5	1		5				
AT155	1167	58	10	7				20				5			
AT157	1194	41	20	10				20	5		1	3			
AT160	1228	55	10	5	3			20				7			
AT163	1302	9	30	20	10			20	10		1				
AT165	1342	52	10	7				30				1			
AT168	1391	60	20	10				5	5						
AT170	1452	36	20	30				7	5		2				
AT171	1505	60		10				20			10				
AT172	1534	40		5				30			5	20			
AT174	1569	70	10	5	1			10	3		1				
AT175	1581	67	10	5	5			10	3			20			
AT176	1649	57	15	10	50			10	3						

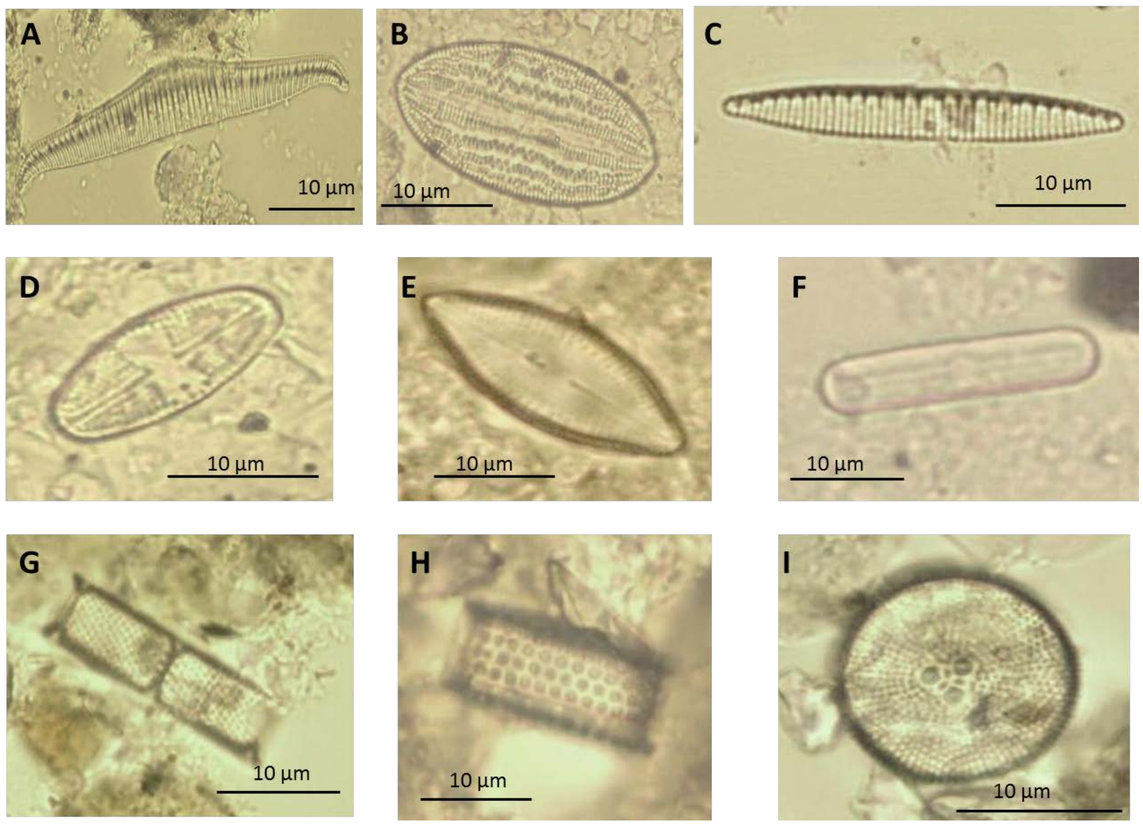
Appendix 3. Extended

Sample	Depth (cm)	Clay	Quartz	Feldspar	Amphibole	Muscovite	Chlorite	Hematite	Opaque	Diatoms	Phytoliths	Charcoal	Oxidized O.M	Lithics	Others
AT177	1675	27	20	30	5		1	7	10						

Appendix 4. Relative percentage abundances of the diatom species recorded in the sediments of the San Nicolás core

Sample	Depth (cm)	*Achnanthidium minutissimum*	*Aulacoseira granulata*	*A. granulata var. angustissima*	*Cocconeis placentula*	*Encyonema silesiaca*	*Fragilaria crotonensis*	*Luticula mutica*	*Diadesmis contenta*	*Navicula phyllecta*	*Nitzschia amphibia*	*Pinnularia gibba*	*Synedra ulna*	*Synedra spp*
MS50 SN09	68	0	37	7	2	1	7	3	1	0	25	1	4	0
MS49 SN16	101,5	1	40	4	2	0	16	2	3	1	3	1	9	0
MS44 SN45	337,5	0	48	5	2	0	20	3	0	0	2	1	3	0
MS40 SN62	477	0	44	7	5	0	5	3	1	0	11	2	8	0
MS38 SN71	562,5	0	2	0	2	0	0	0	0	0	73	6	4	0
MS38 SN72	567,5	0	1	0	1	0	0	1	0	0	90	0	2	0
MS36 SN79	653	0	51	0	4	1	0	3	0	0	26	0	9	0
MS36 SN80	681	0	27	0	17	2	0	3	0	0	0	0	26	0
MS35 SN82	712,5	0	2	0	7	2	0	1	0	0	66	2	6	0
MS27 SN94	989	15	2	0	6	2	0	9	6	5	9	0	9	5
MS18 SN101	1408	0	1	0	7	5	0	0	0	0	75	0	2	0

Appendix 5. Dominant diatom taxa recorded in the sediments of the Sucre deposit and the San Nicolás core. Photographs were taken at 1000x.



A. *Rhopadolia gibba* – epiphytic, **B.** *Cocconeis placentula*-epiphytic, **C.** *Nitzschia amphibia* – benthic, **D.** *Luticula mutica*-aerophilic, **E.** *Diadesmis confervacea*-aerophilic, **F.** *Diadesmis contenta*-aerophilic, **G.** *Aulacoseira ambigua*-planktonic, **H.** *Aulacoseira granulata*-planktonic, and **I.** *Orthoseira roesseana* –aerophilic.

Appendix 6. Ecological preferences of the dominant diatom species.

Species	**Ecology**	**Reference**
Achnanthes exigua	1. Benthic, epiphytic, epipelic, shallow fresh water to slightly acidic swamps 2. Not clear habitat preferences	1. Sanchez et al. (1987) 2. Cocquyt and De Wever (2002)
Achnanthidium minutissimum	1. Epiphytic, on algae or macrophytes 2. Epipelic 3. Epiphytic	1. Cocquyt and De Wever (2002) 2. Reid and Ogden (2009) 3. Abuhatab-Aragón and Donato-Rondón (2012)
Amphora ovalis var. *lybica*	1. Littoral, cosmopolitan, slightly brackish waters	1. Krammer and Lange-Bertalot (1999)
Aulacoseira ambigua	1. Planktonic, open-waters in ponds and lakes where is suspended by turbulence 2. Planktonic, shallow waters, small lakes, marginal areas of lakes 3. Planktonic, greater flow-through	1. Sanchez et al. (1987) 2. Cocquyt and De Wever (2002) 3.Bradbury et al. (2004)
Aulacoseira granulata	1. Mesotrophic, moderately alkaline reservoirs 2. Planktonic, high turbulance and well mixed water columns	1. Gómez et al. (1995) 2. Baker et al. (2000)
Cocconeis placentula	1. Periphyton in lakes, epiphytic 2. Epiphytic 3. Epiphytic 4. Epiphytic	1. Cocquyt and De Wever (2002) 2. Gell et al. (2005) 3. Gari and Corigliano (2007) 4.Abuhatab-Aragón and Donato-Rondón (2012)
Cyclotella meneghiniana	1. Planktonic, tolerant of high salinity levels	1. Gell et al. (2002)
Diadesmis confervacea	1. Shallow water, aerophilic 2. pH 4,0-6,0, high temperatures (29-32°C), low electrical conductivity 3. Aerophilic, shallow water conditions 4. Lacustrine environments, high electrical conductivity, low temperatures (16-18°C)	1. Patrick and Reimer (1966) 2. Sala et al. (2002) 3. Gell et al. (2005) 4.Torgan and dos Santos (2008)
Diadesmis contenta	1. Subaerial habitats	1. Cocquyt and De Wever (2002)
Fragilaria crotonesis	1. Eutrophic	1. Brugam and Patterson (1983)
Gomphonema gracile	1. Littoral, shallow waters 2. Epiphytic, lacustrine environments	1. Patrick and Reimer (1966) 2. Cocquyt and De Wever (2002)
Luticula mutica	1. Benthic, epiphytic, aerophilic 2. Aerophilic 3. On soils from the modern Cauca river floodplain	1. Cocquyt and De Wever (2002) 2. Gell et al. (2002) 3. Vélez et al. (2013)
Nitzschia amphibia	1. Epipelic in lakes and rivers 2. Not attached	1. Cocquyt and De Wever (2002) 2. Kelly et al. (2005)
Nitzschia frustulum	1. Not clear habitat preferences	1. Cocquyt and De Wever (2002)
Orthoseira roeseana	1. Aerophilic	1. Gaiser and Johansen (2000)
Rhopalodia gibba	1. Epiphytic 2. Epiphytic	1. Patrick and Reimer (1966) 2. Gell et al. (2005b)
Synedra ulna	1. Epiphytic 2. Epiphytic	1. Kelly et al. (2005) 2. Gell et al. (2005b)