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Original article

Mangroves: coastal vegetation and marine influence in La Caimanera wetland (Sucre) during the last 6000 years

Manglares: vegetación costera e influencia marina en la ciénaga La Caimanera (Sucre) durante los últimos 6000 años

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Abstract

We recovered a 7.25 m sediment core from the center of La Caimanera wetland (department of Sucre, 9°24'11.88"N 75°37'52.39"W) using a Russian probe. We sent samples from different depths for radiocarbon dating (C14 by AMS at the University of Colorado, USA). We characterized the main sediment components (minerals, organic matter), micro-stratigraphy (organic matter classes), moisture variations (%), organic and inorganic carbon, and palynological associations. We linked these to the current types of vegetation in the wetland and its surroundings. In the paleoenvironmental reconstruction, two well-defined and contrasting periods were observed, as follows: between the beginning or base of the sediment column analyzed (at 725 cm, 6185 years BP, and at the upper middle part, 175 cm, 2142 years BP), the environment was that of a continental freshwater wetland, including all the phases of the hydric ecological series (aquatic vegetation, marsh vegetation, floodplain vegetation with *Symmeria paniculata* forests, and mainland forests of *Mabea montana, Spondias mombin*, and *Anacardium excelsum*). The mineral fraction dominated the sediment, while peat and plant remains predominated inside the organic fraction of continental origin. Towards the upper part of the core, a transition towards a brackish environment was evident, related to the greatest expression of marine components (shells). In the last 1000 years BP, the mangrove (*Rhizophora mangle*) grew vigorously, and the high representation of mollusk shells and crustacean remains consolidated at a sedimentation rate (accretion) of 1.14 cm/year; this marked marine influence could not be correlated with changes in sea level documented for the Colombian Caribbean.

Keywords: Mangroves; neotropical estuaries; microstratigraphy; coastal paleoenvironments; paleoecology.

Resumen

Con una sonda rusa se recuperó un núcleo de sedimento de 7,25 metros en el centro de la ciénaga La Caimanera, Sucre (9°24'11,88" N 75°37'52,39" O). Se enviaron muestras de varios intervalos de profundidad para datación radiocarbónica (C14 by AMS, University of Colorado, USA). Se caracterizaron los componentes principales del sedimento (minerales, materia orgánica), la microestratigrafía (clases de materia orgánica), las variaciones de humedad (%), el carbono orgánico e inorgánico y las asociaciones palinológicas. En la reconstrucción paleoambiental se diferenciaron dos épocas bien definidas y contrastantes, así: entre el inicio o base de la columna de sedimento analizada (725 cm, 6185 años AP, y la parte media superior, 175 cm, 2142 años AP) el ambiente era de ciénaga continental de agua dulce, con todas las fases que incluye la serie hídrica (vegetación acuática, de pantano, de planicie de inundación con los bosques de *Symmeria paniculata* y los bosques de tierra firme de *Mabea montana*, *Spondias mombin* y *Anacardium excelsum*). En el sedimento dominaba el componente mineral y en el componente orgánico de origen continental, las turbas y los restos vegetales. Hacia la parte superior hubo transición hacia un ambiente salobre y la mayor expresión de componentes de origen marino (conchas). En los últimos 1000 años AP

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se desarrolló vigorosamente el manglar (*R. mangle*) y se consolid**ó** una marcada representación de conchas de moluscos y restos de crustáceos, con una tasa de sedimentación (acreción) de 1,14 cm/año; la marcada influencia marina no se logró correlacionar con los cambios en el nivel del mar documentados para el Caribe colombiano.

Palabras clave: manglares; estuarios neotropicales; microestratigrafía; paleoambientes costeros; paleoecología.

Introduction

In the coastal areas of the Colombian Caribbean, numerous marshes (swamp areas) protected by coastal cordons are affected by fluvial-marine dynamics, as is the case with La Caimanera wetland, where strips of natural mangrove vegetation persist. Such a condition makes these environments an ideal setting for detecting the effects related to sea level fluctuations (marine transgressions or regressions), the variations in aspects of the geomorphology and sedimentation of the basin, and other events associated with the evolution of the territory.

Among the palaeoecological contributions on mangroves and their relationship with sea level fluctuations and the subsequent changes in the Colombian Caribbean coastline we can mention those of **Urrego, *et al*.** (2013) and **Díaz** (2016) in La Guajira; **Van der Hammen & Noldus** (1984), **Vélez, *et al*.** (2014), and **Betancurt** (2019) in the Ciénaga Grande de Santa Marta, and **García, *et al*.** (2022) in the Tayrona National Natural Park in the department of Magdalena, and **Castaño, *et al*.** (2010), **Palacios, *et al*.** (2012), and **Rodríguez** (2011) in the Cispatá Bay (department of Córdoba).

In our biostratigraphic study of a sediment column, we characterized palynological associations and substrate conditions, as well as their relationship to external influences (channel flow, sea level, and precipitation). We sought to detect changes at different levels: biological (vegetation succession), climatic (precipitation fluctuations), and stratigraphic (sedimentation). This information is essential for comparing our results with those from other Caribbean areas and consolidating our understanding of the paleoecological history of these coastal environments.

Study area

La Caimanera wetland is located in the Gulf of Morrosquillo, Colombian Caribbean region, department of Sucre (9° 24’39” N, 75° 37’ 44” W). There, the water surface covers approximately 192 ha, with the flood plain reaching up to 2200 ha; the main body is connected to the sea by a permanent water channel. Some streams and temporary channels, such as San Antonio, Petaca, Escobalito, La Lata, and Amansaguapos, flow into the wetland (**Figure 1**). As of the second half of the last century (1950), the construction of land roads between Coveñas and Tolú has impacted this natural area, reducing the original extension covered by the mangrove (**Moré-Sierra**, 2025).

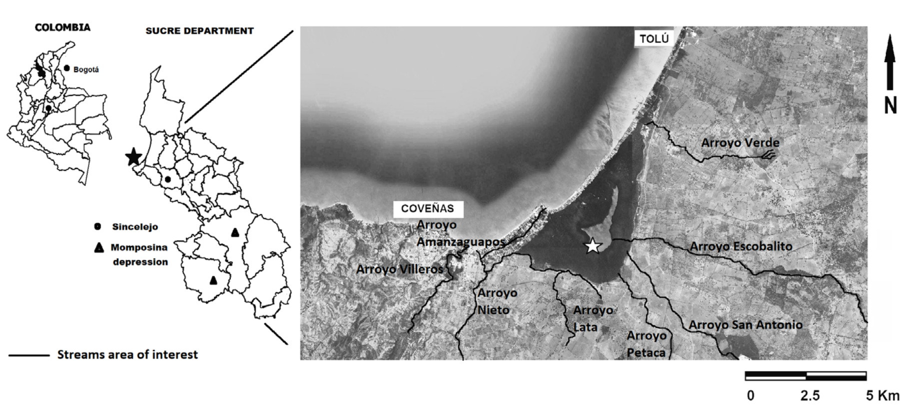

Figure 1. Location of La Caimanera wetland. Modified from Google maps

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Two distinct environments are seen in the study area: the estuarine and the dry land zone. The vegetation of the estuarine-mangrove zone (**Cortés & Rangel-Ch.**, 2023) belongs to the phytosociological class *Rhizophoretea mangle* and the order *Rhizophoro manglis-Laguncularietalia racemosae*, with two phytosociological formations or alliances: *Lagunculario racemosae-Rhizophorion manglis*, which groups the *Lagunculario racemosae-Conocarpodetum erecti* associations established near the beach limit, and the dry land vegetation of the tropical forest. Another typical mangrove is the *Lagunculario racemosae-Rhizophoretum manglis* association, where *Avicennia germinans* appears as dominant, and the monospecific mangrove of the *Rhizophoretum manglis* association is related to intervention processes (selective logging). The *Lagunculario racemosae-Avicennion germinantis* alliance is also present in the basin with the *Avicennio germinantis-Rhizophoretum manglis* associations and the monospecific mangroves of *Avicennietum germinantis* in areas with intervention traces (urbanization).

The dry and semi-humid tropical forest vegetation (rainfall amounts to 1800 mm per year) in the area belongs to the *Cratevo tapiae-Spondiadetea mombinis* class, common in areas surrounding the Caribbean wetlands in the departments of Magdalena, Cesar, and Córdoba (**Rangel-Ch. & Suárez**, 2022). It groups the phytosociological formations or alliances dominated by *A. excelsum* (*Erythroxylo amazonici-Anacardion excelsi*) with others, such as *Astronio graveolentis-Guazumetum ulmifoliae*, established near the channels and water currents in which *S. mombin*, *Astronium graveolens*, *Brownea ariza,* and *Cavanillesia platanifolia* are frequent, while *Tabebuia rosea*, *Myrospermum frutescens*, and *Uribea* cf. *tamarindoides* have lower coverage values. *Bursero simaroubae-Poulsenietum armatae* forests, dominated by *Bursera simarouba*, *Handrohanthus chrysanthus*, and *S. mombin*, are also present, accompanied by *Ficus, Sapium, Cassia, Cecropia, Byrsonima*, and *Myrcia* species.

In the Caribbean wetlands ecological hydric series, among the marsh vegetation, there are communities dominated by *Thalia geniculata* and *Polygonum caucanum*, which reach their greatest coverage and vigor during high water periods. In the floodplain that circles like a belt the wetland, low scrub forests dominated by *S. paniculata* (*Symmerio paniculatae-Tabebuietum roseae*) are established. There, *Samanea saman*, *Phyllanthus elsiae*, *Bactris guineensis*, *Coccoloba densifrons*, *C. obtusifolia*, *A. graveolens*, *Crateva tapia*, *Ceiba pentandra*, and *Alchornea castanaefolia* are among the accompanying species. These forests adjacent to the wetland complexes are subject to water level variations and can be flooded at certain times of the year. In the larger plains, during the dry season (low water level), shrubby vegetation grows dominated by *Ambrosia peruviana*, with accompanying species such as *Solanum campechiensis* and *Heliotropium indicum* (**Cortés & Rangel-Ch.**, 2023).

Methodology

Sampling

We recovered a 7.25-meter core from the center of the wetland (9°24’11.88” N 75°37’52.39” W) using a Russian probe during the high water season. We made the lithological characterization and stored the cores in PVC tubes (50 cm long, 5 cm diameter), labeled them (location, date, and depth), and transported them to the Palynology Laboratory at the Institute of Natural Sciences, National University of Colombia in Bogotá, where they were stowed in a refrigerator until processing. We sent several samples (from different depths) to the University of Colorado (USA) for Carbon 14 dating (C-14 by AMS, Accelerator Mass Spectroscopy). We made quantitative sedimentological-microstratigraphic analyses to estimate the mineral fraction and carbon content due to loss of mass by calcination loss on ignition (LOI, 105-550-950°) (**Santisteban *et al.***, 2004) and qualitative (visual estimation) ones to differentiate mineral and organic components (continental-marine), according to **García-M. *et al.*** (2022).

For the palynological analysis, we processed 3 cm^3 samples of sediment at 6 cm intervals along the entire column. The physicochemical analysis followed the guidelines of the Palynology and Paleoecology laboratory at the Institute of Natural Sciences, National University of Colombia (**García-M. *et al.***, 2022). The final extraction of pollen was done by flotation (zinc chloride, $ZnCl_2$) with a density of 1.96 g/ml. One or two drops of glycerin were added to the final residue, which was then placed in the oven at 40°C for 24 hours, and then the slides were mounted using glycerinated gelatin as a support. The palynological analysis was performed with an optical microscope. We counted 300 pollen grains, also including spores of ferns, fungi, and other palynomorphs in the count. For the palynological determination, we used pollen atlases (**Roubik & Moreno**, 1991; **Herrera & Urrego**, 1996; **Fernández & García**, 2008) and reference collections from the palynology library of the Palynology Laboratory of the Institute of Natural Sciences, National University of Colombia.

According to **Rangel and Suárez** (2022) and **Cortés and Rangel** (2023), the palynomorphs of the "sum of pollen" group were segregated into phytoecological groups, as follows:

Mangrove: *R. mangle, A. germinans, Conocarpus erectus*, and *Acrostichum aureum*.

Aquatic marsh: *Pontederia* (*Eichhornia*) *crassipes, Typha dominguensis, Eclipta prostrata, Scoparia dulcis*, and *Cyathula, Sagittaria, Paspalum, Hydrocotyle,* Cyperaceae, Amaranthaceae, and *Althernanthera* species.

Playón: Sand beach (playón) *A. peruviana* and *Solanum* and *Cestrum* species.

Lowland plain forest: *S. paniculata*, *Euphorbia hirta*, *Bombacopsis quinata, Iriartea deltoidea, T. rosea, Allophyllus occidentalis, M. frutescens, Lonchocarpus sericeus, A. excelsum, S. mombin, B. simarouba, C. platanifolia, Pouteria, Senna, Uribea* cf. *tamarindoides, M. montana, Acalypha villosa*, and *Sapium, Cassia, Eugenia, Myrcia, Byrsonima, Ficus, Euphorbia, Protium, Acacia, Cecropia, Miconia, Paullinia,* and *Warszewiczia* species.

Other palynomorphs, fern, and fungal spores, together with *Hippomane mancinella, Ludwigia helminthorrhiza, T. geniculata, P. caucanum, H. indicum, Phyllantus, Casearia, Macfadenya, Malphigia glabra, Faramea*, with very low relative frequency values, were grouped under the heading of elements not included in the pollen sum.

We constructed general and ecological diagrams with detailed counts using the Tilia program, version 2.0.4.

Results

Dating - sedimentation

Figure 2A shows the chronological sequence according to depth. Radiocarbon dating yielded the following results: at a depth of 80 cm, the calibrated age was 70+/-30 BP and the sedimentation rate, 1.14 cm/year; at 295 cm, the calibrated age was 4760+/-40 BP and the sedimentation rate, 0.046 cm/year, and at 657 cm, the calibrated age was 5960+/-40 BP and the sedimentation rate, 0.3 cm/year. The estimated age of the base was 6185 years BP.

Stratigraphy

Quantitative analysis

Figures 2B and **3A** show the general description of the sediment column and the curves for organic carbon, inorganic carbon, total carbon, residual moisture, and mineral fraction according to the quantitative analysis. **Table 1S,** https://www.raccefyn.co/index.php/raccefyn/article/view/3179/4585, shows the values according to the subzones.

The variation along the column showed the following:

Organic carbon (LOI 550°C). The highest average value (13.26%) was found in subzone IIa, the lowest (6.64%) in subzone Ic. The minimum extreme value (0.02%) was found in subzone Ib, and the maximum extreme (48.22%) in subzone Ia.

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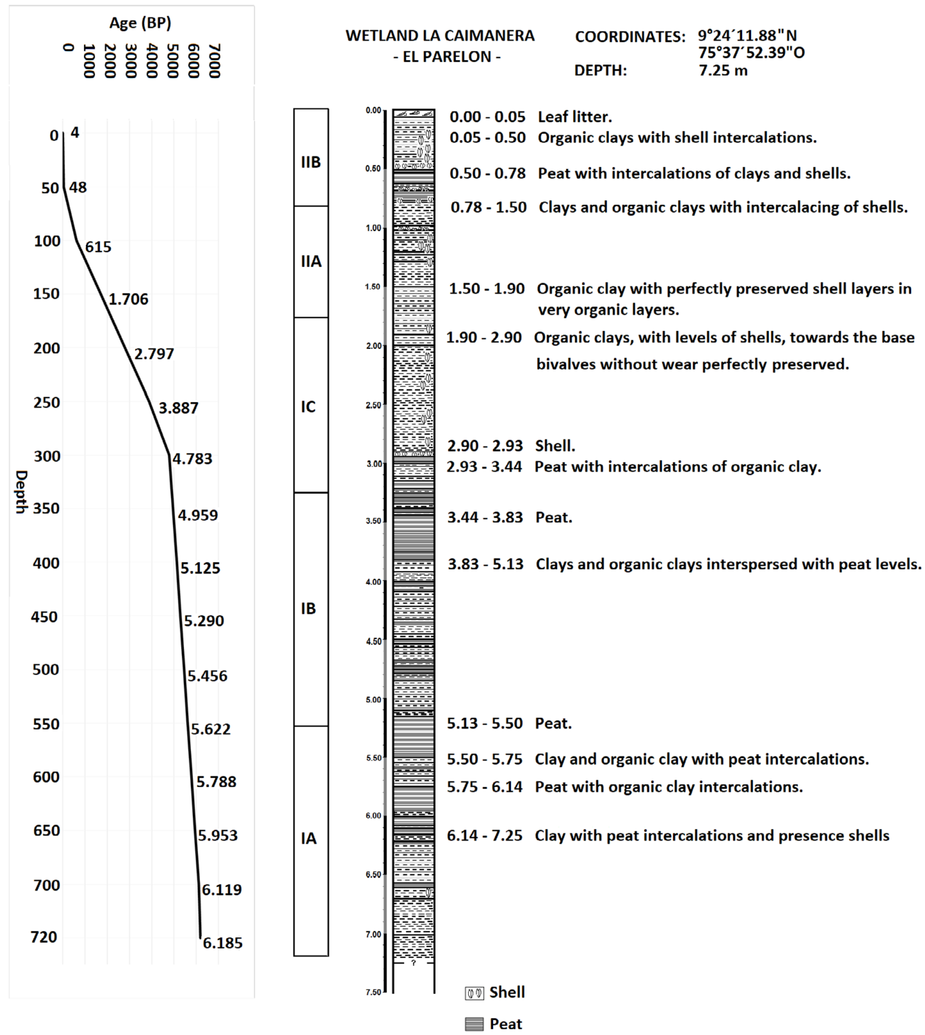

Figure 2. A. Age vs depth curve. **B.** Stratigraphy

Inorganic carbon (LOI 950°C). The highest average value (18.66%) was found in subzone Ic, and the lowest (11.58%) in subzone Ib. The lowest extreme value (0.05%) was found in subzone Ib, and the highest (24.24%) in subzone Ia.

Total carbon. The highest average value (28.42%) was found in subzone IIa, and the lowest (21.90%) in subzone Ib. The lowest extreme value (2.33%) was found in subzone Ib, and the highest (48.77%) in subzone Ia.

Residual moisture (LOI 105°C). The highest average value (16.11%) was found in subzone Ib, and the lowest (1.46%) in subzone Ic. The lowest extreme value (0.03%) was found in subzone Ic, and the highest (82.30%) in subzone Ib.

Mineral fraction. The highest average value (73.24%) was found in subzone Ic, and the lowest (62.01%) in subzone Ib. The minimum (11.52%) and maximum (96.69%) extreme values were found in subzone Ib.

Qualitative analysis

Mineral component. **Figure 4** shows the variation of the mineral fraction along the column (differentiated phenocrystals and fine undifferentiated phenocrystals) and the integrated organics. The mineral fraction (especially fine undifferentiated phenocrystals) predominated with an average value of 63% and a maximum expression of 77% in

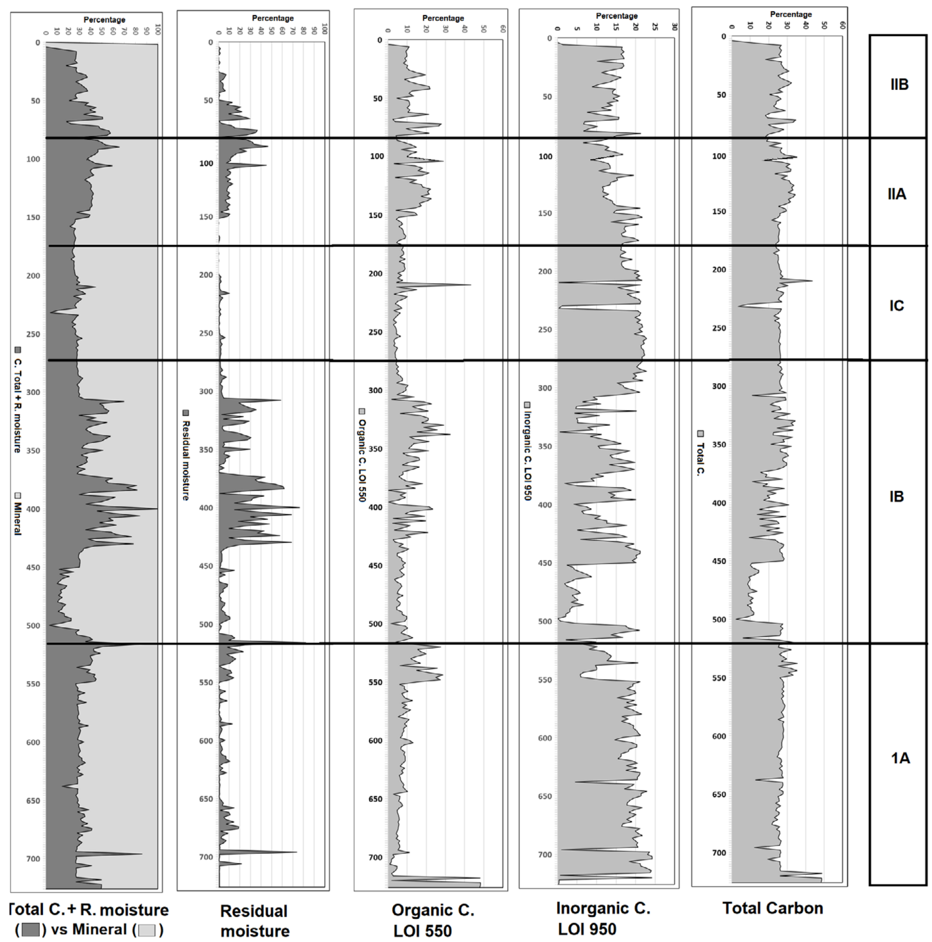

Figure 3. Quantitative analysis. **A.** Carbon content and mineral fraction. **B.** Carbon percentage (LOI 550). **C.** Inorganic carbon percentage (LOI 950). **D.** Total carbon.

subzone IIa and a minimum of 53% in subzone Ib (**Table 2S,** https://www.raccefyn.co/index.php/raccefyn/article/view/3179/4585). Among phenocrystals, there was a significant presence of iron oxide, ferromagnesians, anhydrite, feldspars, and sulfides. Malachite, rhodochrosite, calcite, sulfur, and halite, together with quartz, rock fragments, and other salts, were gathered in the "other mixed phenocrystals" group. The highest value in the phenocrystals group was in subzone Ia with 31.5%, while the lowest was in subzone Ib with 17.2%; anhydrite predominated in subzone Ia with 4.3%; iron oxides in subzone IIa with 3.4%; sulfides reached the highest value (4.1%) in subzone IIa, and ferromagnesians in subzones IIa and IIb with 2%.

Organic component. The average value was 37%, reaching its maximum expression in subzone Ib (47%) and the minimum one in IIa (23%). We registered the highest average value (40.9%) of marine component (shells) in subzone Ic and the lowest (5.5%) in Ia. In terms of peat, the highest value (26.7%) was registered in subzone Ib, and the lowest (1.6%) in IIb. The highest level of coal (5.3%) was found in subzone Ia, and the lowest (1%) in IIa, while it was not found in IIb. Organic remains (seeds, wood, tissues) reached the highest average value (11.7%) in subzone Ib and the lowest (3.6%) in IIa. The column showed a clear segregation in terms of the origin of the organic components, as follows: between the base, 725-290 cm, the continental ones dominated, and from there to the top (0 cm) the marine ones, except for the section 128-118 cm, where the continental component predominated.

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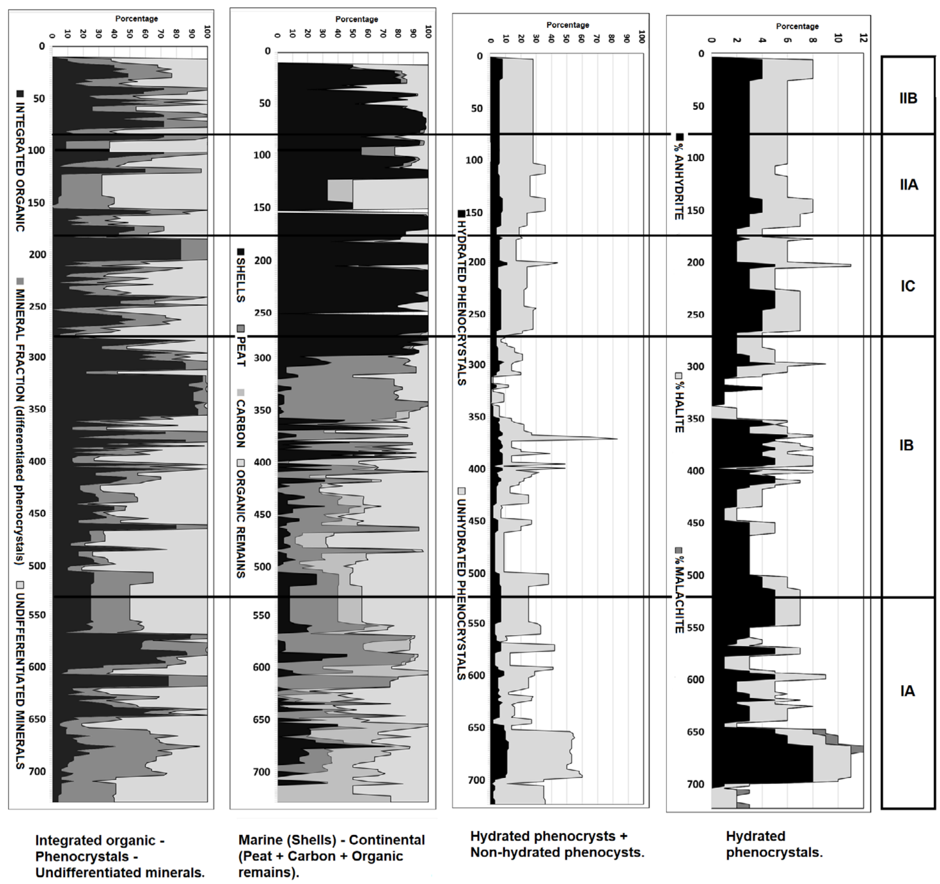

Figure 4. Organic components and mineral fraction of the sediment (qualitative, percentage estimated by using a stereoscope)

Palynological diagrams (changes in vegetation).

Two global trends in the vegetation of the site can be distinguished in the general diagram (**Figure 5**). Between the base, 727 cm and 175 cm, continental wetland conditions predominated, and estuary elements (mangroves) were absent. From 175 cm onwards, we recorded the presence of elements associated with the mangroves.

The segregation based on the predominance of one type of vegetation in the zonation showed the following:

Zone I. Depth 725-175 cm. Approximate age, 6185-2142 years BP. This is the typical setting of a composite zonation in a freshwater wetland surrounded by a lowland plain forest vegetation, whose representation in the palynological spectrum predominated. Based on the values of the ecological groups and the dominant species, it is feasible to consider the following zonation:

Subzone Ia: Depth 725-525 cm. Approximate age, 6185-5522 BP. It is characterized by the dominance of plain forest representation, particularly by the mainland forest, with *M. montana* (4-17%), *A. villosa* (1-7%), *S. mombin* (1-11%), *L. sericeus* (1-13%), *Ficus* sp. (1-9%), *Miconia* sp. (5-20%), and *Warszewiczia* (1-9%). In the flooded forest, *S. paniculata* (common name "freshwater mangrove", 2-11%) and *B. quinata* (1-13%) were present with important values. The values of the aquatic-swamp group characterized the subzone, with the species associated with the water mirror, such as *Sagittaria* sp. (1-18%), *Hydrocotyle* sp. (2-5%), and *Paspalum* sp. (1-13%), reaching the highest representation. In the swamp group, *S. dulcis* (1-13%), Cyperaceae (1-6%), and *T. dominguensis* (1-7%) showed high values. Among the elements of the sand beach, *Solanum* sp. (4-20%) predominated, and among the elements not included (**Figure 6A**), the records of warty and psilated triletes had values close to 20%.

Subzone Ib: Depth 525-275 cm. Approximate age, 5522-4323 BP. Plain forests continued to dominate, particularly the terra firme forest with *Uribea* cf *tamarindoides* (1-9%), *Acacia* sp. (1-7%), and *I. deltoidea* (1-11%), which replaced the dominance of *M. montana* (1-3%). *S. paniculata* (1-16%) representation in the flooded forest persisted. The

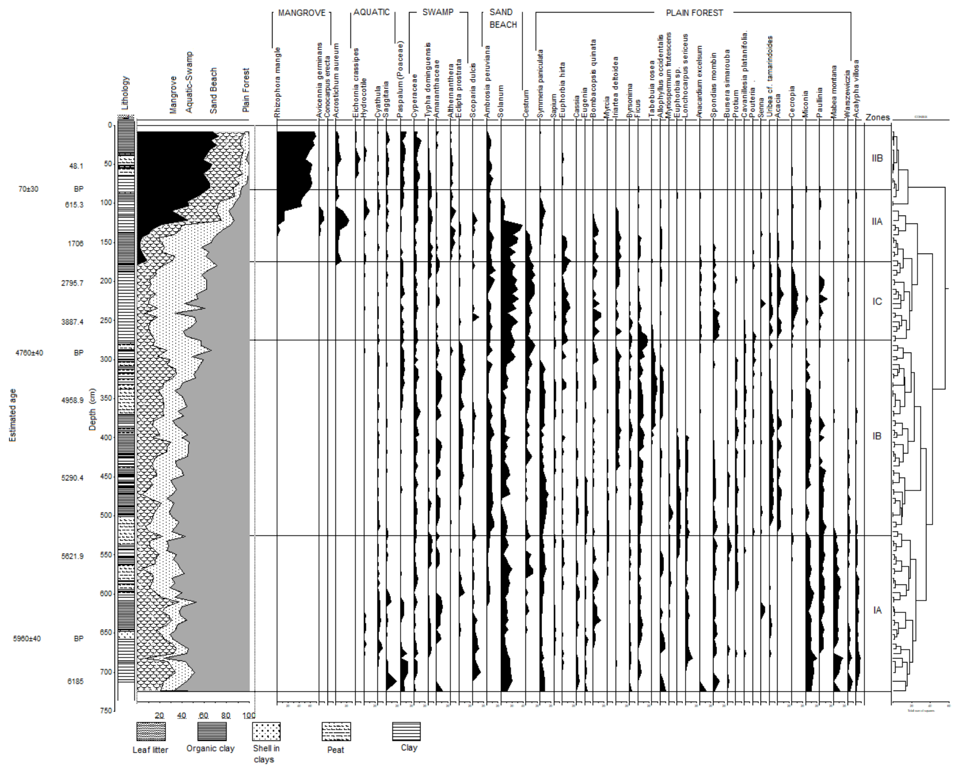

Figure 5. General palynological diagram elements included in the pollen sum

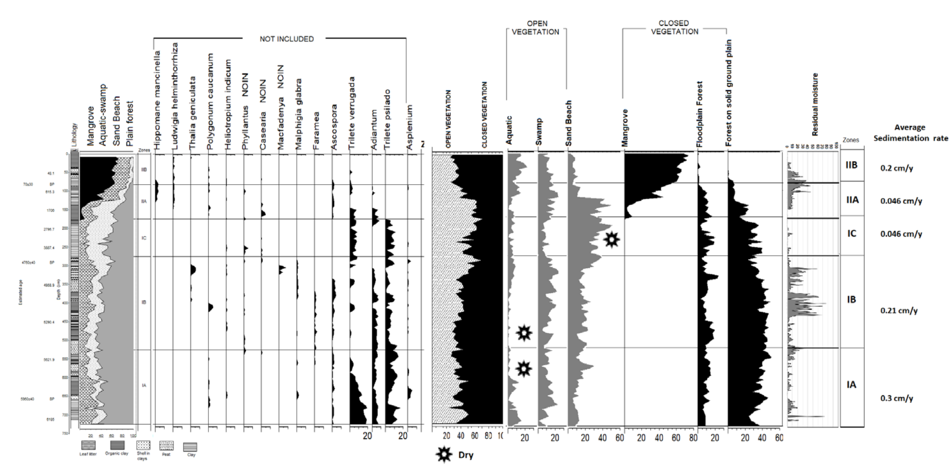

Figure 6. A. Palynological diagram of “not included” elements. **B.** Ecological segregation between open and closed vegetation

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values reached by the swamp elements were the highest of the whole diagram, especially those of Cyperaceae (1-11%), Amaranthaceae (1-10%), and *E. prostrata* (1-13%). The values of species associated with the water mirror, such as *Sagittaria* sp. (1-3%) and *Hydrocotyle* (1-2%), decreased. Among the sand beach elements, besides *Solanum* sp. (2-26%), *A. peruviana* (2-13%) was important. Among the "not included" elements, trilete psilado and *Adiantum* records were important, as well as *T. geniculata*, *P. caucanum, Phyllanthus* sp., and *M. glabra*.

Subzone Ic: Depth, 275-175 cm. Approximate age, 4323-2142 B.P. Here, plain forest representation decreased, particularly due to the absence of records of *S. paniculata*. Instead, *E. hirta* increased (2-15%). The terra firme forest representation also decreased, and now, it is represented by *S. mombin* (2-12%), *Acacia* sp. (1-11%), *A. excelsum* (1-4%), and *Cecropia* sp. (1-11%). The values of the species associated with the water mirror increased, particularly those of *Paspalum* sp. (1-7%) and *Hydrocotyle* sp. (1-4%). Wetland representation decreased due to the low values of Amaranthaceae (2-5%), *E. prostrata* (1-3%), and *T. dominguensis* (1-6%). The subzone is characterized by the increase in the values of species typical of sandy beaches, such as *Solanum* sp. (11-32%), *A. peruviana* (1-15%), and *Cestrum* sp. (4-17%). Among the "not included" elements, psilate and warty trilete records were significant.

Zone II. Depth, 175-0 cm. Approximate age, 2142-present. This zone reflects an estuarine environment with an initial phase of low mangrove representation that ultimately becomes dominant. Based on the values of the ecological groups and the dominant species, it is feasible to consider the following zoning:

Subzone IIa: Depth, 175-80 cm. Approximate age, 2142-70 B.P. Plain forest representation strongly decreased, especially due to the low values of the terra firme forest of *Cecropia* sp. (1-2%), *Acacia* sp. (1-3%), *Uribea* cf. *tamarindoides* (1-2%), and *Ficus* sp. (1-6%). The representation of *I. deltoidea* increased (4-11%), and that of *A. excelsum* remained the same (1-2%). In the flooded forests, *B. quinata* (2-10%) and *S. paniculata* (1-11%) records were significant in the final area of the subzone. The values of species associated with the water mirror increased, particularly those of *Hydrocotyle* sp. (1-11%) and *Sagittaria* sp. (1-4%), but decreased for *Paspalum* sp. (1-6%). The representation of the swamp increased, especially with *T. dominguensis* (1-9%), Amaranthaceae (1-2%), *E. prostrata* (1-4%), and *S. dulcis* (1-8%). The representation of the sand beach remained up to the middle part of the subzone, decreasing towards the end with *Solanum* (40-5%). The subzone evidences the beginning of low records for those elements associated with the mangrove, such as *A. aureum* (3-25%) and *A. germinans* (2-9%). *R. mangle* was recorded for the first time (1-47%). Among the "not included" elements, *Casearia* and *Adiantum* spores records were significant.

Subzone IIb: Depth, 80-0 cm. Approximate age, 70-present. The representation of mangroves predominated, especially due to *R. mangle* recorded values (50-70%); *C. erectus* (1%) and *A. aureum* (1-10%) were also found, while *A. germinans* was not recorded. The values of the species associated with the water mirror increased, particularly those of *Sagittaria* sp. (1-6%), *Paspalum* sp. (4-11%), and *Eichhornia crassipes* (1-9%) appeared. The representation of the swamp decreased with *T. dominguensis* (1-6%) and *Alternanthera* sp. (1-5%). The representation of the sand beach with *A. peruviana* (2-11%) decreased drastically, and the records of *Solanum* sp. (1%) and *Cestrum* sp. practically disappeared. The decrease in the representation of lowland forests was accentuated by the low values of *S. paniculata* (1%) and the absence of *B. quinata* in the flooded forests, while the terra firme forests were scarcely represented by *Cecropia* sp. (1-2%), which practically disappeared towards the end. The subzone is characterized by the predominance of mangroves. Among the "not included" elements, *H. mancinella* and *L. helminthorrhiza* records were significant.

Changes in vegetation dominance (physiognomy)

According to the general palynological diagram and to the segregation of the phyto-ecological groups (**Figure 6B**), in subzones Ia and Ib, the representation of closed vegetation predominated (flooded and terra firme forests); the poor representation of the aquatic group in some subzone Ia sections (500-430 cm) is quite peculiar, and it is related to the low values of residual water in the sediment. In subzones Ic and IIa, the representation of open vegetation increased due to the high values of sand beach elements, which reached their highest values in Ic, while the value of residual water in the sediment was the lowest of the entire column. In subzone IIb, the closed vegetation dominated, represented by mangroves, as the representation of the forests of the plain decreased drastically. This, together with the increase in residual water, is associated with the consolidation of the mangrove environment. In brief, during periods of low expression of aquatic vegetation and high expression of sand beach vegetation, the residual water values decrease, a condition that is associated with the decrease of the water column in the basin of the wetland, either due to a decrease in the flow of the tributaries or due to low values in local and regional precipitation.

Palynological associations in the sediments and affinities with current vegetation types

Table 1 describes the palynological associations based on the pollen spectra in the sediment by subzones and the floristic affinity with current vegetation types. The correspondences between the types of tropical dry forests, such as those dominated by *M. montana, S.*

Table 1. Relationship between palynological associations detected in the sediment analysis and similar current vegetation types (Caimanera wetland)

Sub-zones	Dominant taxa in sediments and pollen zones	Vegetation types in the Caribbean (Cortés & Rangel, 2023; Rangel-Ch. & Suárez, 2022)
Ia	*Mabea montana*	Forests dominated by *Mabea montana* in very humid sites around wetlands in the Caribbean
Ia	*Lonchocarpus sericeus*	Forests dominated by *Lonchocarpus* species (*L. fendleri, L. punctatum*), common in hills and dry and stony sites in La Guajira and Cesar
Ib	*Tabebuia rosea*	*Tabebuia rosea*, dominant in floodplain forests around Caribbean wetlands such as the *Phyllantho elsiae-Tabebuion roseae* formation (alliance), and in humid flat areas such as the *Tabebuio roseae-Samaneetum samanis* forests
Ib	*Protium* sp.	*Protium* species, particularly *P. heptaphyllum*, dominant in forests and low terraces in very humid locations such as southern Córdoba in the Caribbean
Ib, Ic	*Uribea* cf. *tamarindoides*	Characteristic dominant species in the forests of the *Erythroxylo amazonici-Anacardion* excelsi alliance of the *Spondiado mombinis-Anacardetalia excelsi* order and the *Cratevo tapiae-Spondietea mombinae* class. These forests are established in flat areas along streams and channels (riverine vegetation).
Ia, Ic	*Spondias mombin*	Dominant species with a wide distribution in different types of vegetation, from forests such as those of the *Cratevo tapiae-Spondiadetea mombinis* class established around the wetland; mixed palm groves such as those of the *Spondiado mombinis-Attaleetea butyraceae* class, dominant in the plains and terraces around the Caribbean wetland, particularly the Cesar wetlands. Also dominant in dry areas, where it is associated with typical species of very dry tropical forests such as those of the *Spondiado mombinis-Handroanthetea ochracei* class.
Ib, Ic, IIa	*Symmeria paniculata*	Dominant in the tall scrub forests such as the *Symmerio paniculatae-Tabebuietum roseae* association around the Caribbean wetland
IIb	*Rhizophora mangle* y *Avicennia germinans*	*Rhizophora mangle* is a characteristic species of the *Rhizophoretea mangle* class. It includes various types of mangroves, such as the *Avicennio germinantis-Rhizophoretum manglis* association, in locations with high salinity.
Ic, IIa	*Ambrosia peruviana* y *Solanum* sp.	Characteristic dominant species of the *Heliotropio indici-Solanion campechiense* formation, with maximum expression in the *Ambrosietum peruvianae* association, dominant in the sand beaches of the Caribbean wetland
Ic, IIa	*Anacardium excelsum*	Dominant in several types of vegetation with wide distribution in the Caribbean, such as the forests grouped in the *Huro crepitantis-Anacardietalia excelsi* order on terraces-hills in dry areas, and in the *Spondiado mombinis-Anacardietalia excelsi* order in flat, humid sites.

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mombin, A. excelsum, and *Protium heptaphyllum*, are very important, and the distribution area of most of them concentrates in the Caribbean wetlands. The sediments also reflect the presence of tall forest scrublands dominated by *S. paniculata* on the flood plain and the *A. peruviana* and *Solanum* sp. (*Solano campechiensis- Ambrosietum peruvianae*) scrubs dominating the sand beaches during low water periods. Among the mangrove types, some are dominated by *R. mangle* and *A. germinans* (*Avicennio germinantis-Rhizophoretum manglis*) and are associated with salinity conditions in the water column.

Paleoenvironmental reconstruction

Zone I. (725-175 cm) Approximate age, 6185-2142 years BP. The paleo-environment was a freshwater wetland with the characteristic zonation of the hydric ecological series: from rooted-emergent aquatic vegetation (*Sagittaria - Hydrocotyle*) and swamps with plant communities such as *T. dominguensis* and Cyperaceae species "grasslands", to the lowland with *S. paniculata* flooded forests and the dry tropical forest formations (terra firme) dominated by *M. montana* and *S. mombin*. According to the zonation of the palynological diagram, the following is the environment reconstruction in the subzones (**Figure 7**):

Subzone Ia. (725-525 cm) Approximate age, 6185-5522 BP. The wetland reached its greatest surface area and water volume; the aquatic vegetation was represented by *Sagittaria* and *Hydrocotyle* species; the grassland by *Paspalum* sp., and the swamp vegetation by dense formations of *T. dominguensis*, where Cyperaceae species and *S. dulcis* predominated. On the plain, in flooded areas, *S. paniculata* tall scrub forests were established, and on dry-land forests, *S. mombin* and *M. montana* dominated. Compared to current climate conditions in the study area, this was a period with slightly higher precipitation values.

Subzone Ib. (525-275 cm). Approximate age, 5522-4323 BP. In the wetland, the water surface was reduced, and swamp vegetation coverage increased, showing its maximum development. The representation of the S. *paniculata* flooded forest was maintained. The area covered with mixed palm groves dominated by *I. deltoidea* increased, replacing the *M. montana* forests (terra firma), and the sand beach vegetation increased its representation. Compared to the previous subzone, it was a period with less precipitation.

Subzone Ic. (275-175 cm). Approximate age, 4323-2142 BP. The surface area with water mirror and areas covered with swamp vegetation, *S. paniculata* flooded forests, and terra firme forests of *A. excelsum* and *S. mombin* decreased. The sand beach vegetation with *A. peruviana* and *Solanum* sp., spread over these areas. As in the previous subzone, it was a period with low precipitation values.

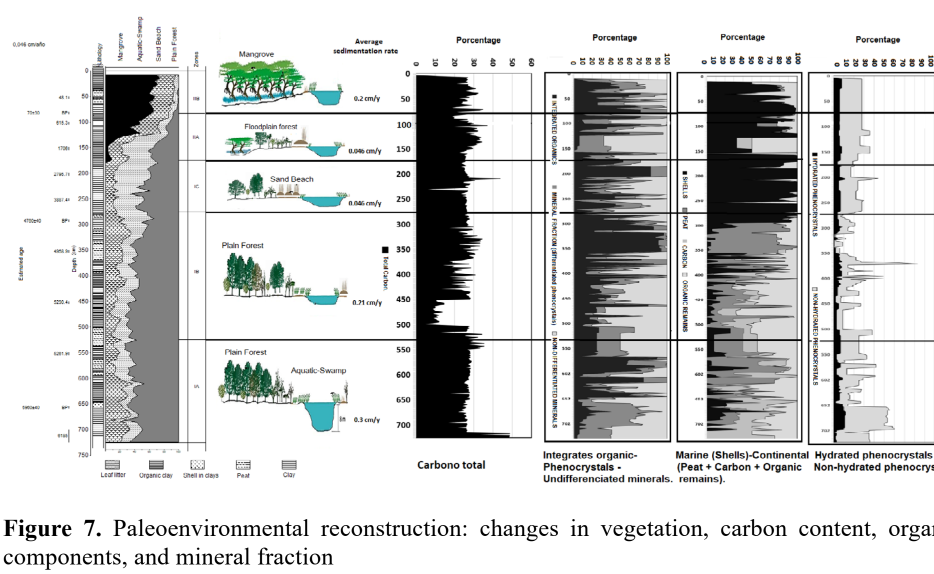

Figure 7. Paleoenvironmental reconstruction: changes in vegetation, carbon content, organic components, and mineral fraction

Zone II. (175-0 cm). Approximate age, 2142-present. In the lower part (IIa), a paleoenvironment landscape of freshwater wetland persisted with emergent rooted aquatic vegetation (*Sagittaria - Hydrocotyle*); in the swamp, plant communities such as the *T. dominguensis* and Cyperaceae and *Alternathera* species "grasslands" were established. *A. aureum, C. erectus*, and *A. germinans* records indicate an increase in the marine influence. The representation of the sand beach increased, and that of the dry-land forest decreased drastically. In the upper part (IIb), mangrove dominance is evident. The following is the environment reconstruction in the subzones:

Subzone IIa. (175-80 cm). Approximate age, 2142-70 BP. The surface area with a water mirror (aquatic vegetation) increased; the areas covered with swamp vegetation and the *S. paniculata* floodplain forest also increased; the extension of the dry land vegetation decreased and was replaced by the mixed *I. deltoidea* palm grove. The representation of the sand beach remained high. The precipitation was slightly higher compared to the previous subzone.

Subzone IIb. (80-0 cm). Approximate age 70-present. It reflects an estuarine wetland with typical mangrove vegetation dominated by *R. mangle.* Although brackish water conditions predominated, the representation of aquatic vegetation was maintained, but that of the swamp and sand beach decreased. The representation of forests on the flood plain and dry lands was very scarce. Precipitation conditions were similar to the present, but greater than those of the previous subzone.

Discussion

Sedimentation rate

Two contrasting environments were differentiated in the sediment column and the palynological diagram (**Figure 5**): between 725-175 cm (subzones Ia, Ib, Ic), the palyno-logical spectra showed a continental wetland environment (without mangroves), and between 175-0 cm (subzones IIa and IIb), an estuary (marine) environment with mangroves.

The sedimentation rate in subzone Ia (725-525 cm) was 0.3 cm/year, and 0.21 cm/year in subzone Ib (525-275 cm). These values surpassed the limit (0.038-0.10 cm/year) for wet periods (maximum level in the water column). In subzone Ic (275-175 cm), according to **Lazala *et al*.** (2010), the value of 0.046 cm/year was quite close to the variation limits in the Caribbean wetlands for dry periods (0.011-0.037 cm/year).

In subzone IIa (175-80 cm), with a mangrove in a regular state of development, the sedimentation rate of 0.046 cm/year was below the limit (0.09-0.12 cm/year) proposed by **Rangel-Ch.** (2024) for mangroves' degree of development (vigor) in the Colombian Caribbean.

In subzone IIb (80-0 cm), characterized by a vigorous mangrove development according to the palynological diagram (**Figure 5**), the sedimentation rate (accretion) was 1.14 cm/year, a value that follows the pattern of vigorous mangrove development in the Colombian Caribbean (0.52-1.14 cm/year).

The sediment column reflects two contrasting environments in sedimentation rates and the establishment of the vegetation dominant formations in the basin and surrounding areas. The lower part of the diagram depicts a freshwater wetland environment with no seawater input. Sedimentation rates fluctuated between 0.3 and 0.21 cm/yr. In the freshwater wetland-mangrove transition phase (subzone Ic), the sedimentation rate was close to the variation limits for "dry" periods in the Caribbean wetlands. In the upper part, the sedimentation rate in an estuarine environment was 1.14 cm/yr, which reflects the marine influence and a vigorous mangrove development influencing substrate accretion through the production and accumulation of organic matter and the retention of mineral elements (**Krauss *et al*.**, 2014).

Quantitative analysis: mineral and organic fractions (carbon)

The mineral fraction predominated throughout the column; the highest average (73.24%) was found in subzone Ic, and the lowest one (62.01%) in subzone Ib. The minimum (11.52%) and maximum (96.69%) extreme values were found in subzone Ib.

The highest values of carbon content were reached in subzone Ia. Except for sections with low values and an extreme minimum of 2.33%, in subzone Ib, the behavior of the curve was very similar. The inorganic carbon values were higher than those of organic carbon, particularly in subzones Ia and Ic. However, the mineral fraction domain was differentiated by sections: between 544-504 cm, the upper part of subzone Ia, and the lower part of Ib, the representation of total carbon increased, with an average of 27% and a maximum of 35.5% at 538 cm. In the section at 428-306 cm and in the middle and upper parts of subzone Ib, the total carbon average value increased to 25%, with a maximum of 34.4% at 330 cm. In the section at 146-6 cm, upper part of subzones IIa and IIb, the average value of total carbon was 27%, with a maximum of 36.9% at 104 cm.

In summary, the average values of organic carbon (6.64 to 13.26%) were lower than those of inorganic carbon (11.58 to 18.66%), and total carbon fluctuated between 21.9 and 28.42, with sections in which its representation increased (544-504 cm, 428-306 cm).

As for residual water, the highest expression (16.11%) was reached in the lower part of subzone Ib. The lowest value (1.46%) was found in subzone Ic, probably related to the disappearance of aquatic vegetation representation.

Qualitative analysis

Here, the mineral fraction also predominated along the column. The organic fraction (continental and marine) had a high representation in subzone Ib, section 350-312 cm, with an average of 94%, and in subzone Ic, section 200-180, with an average of 83%. In the marine component (shells), the maximum value was reached in subzone Ic, and a very low value in Ia. In the continental component, peat and organic remains showed the highest value in subzone Ib. A clear segregation was evident: between the base and 725-290 cm, the dominance of continental organic components was evident, and from there to the top (0 cm), the marine component dominated, represented by mollusc shells (*Anomalocardia brasiliana* and *Mytilopsis sallei*) and crustacean remains (*Balanus* species). In the mineral fraction, the group of undifferentiated fines predominated, while in the phenocrystals, anhydrite predominated with a higher value in subzone Ia; iron oxides, sulfides, and ferromagnesians reached a higher representation in subzone IIa. The hydrated phenocrystals (anhydrite, halite, and malachite) registered a higher value in sections of subzones Ia, Ib, and Ic (**Figure 4**), related to the low representation of aquatic elements in the palynological diagram. Phenocrystals (hydrated + non-hydrated) showed higher values in some sections of sub-zones Ia, Ib, and Ic; the values of hydrated phenocrystals, such as anhydrite, halite, and malachite, were very significant. These periods with higher values are related to periods in which the water level in the basin decreased (drought).

Paleoenvironmental changes and their relationship with other areas of the Colombian Caribbean

The oldest records reporting the presence of mangrove vegetation in coastal wetlands are those of Navío Quebrado (La Guajira) and Boca de López I (**Figure 8**). In Ostional (Córdoba), La Caimanera (Sucre), and Neguanje (Magdalena), mangrove records begin approximately at 1200 years BP. The changes detected show the following patterns: between 6500-4400 years BP, the oldest record of Navío Quebrado (La Guajira) reflects an initial phase in the formation of the mangrove vegetation, with very low values of *R. mangle*, and the sporadic presence of *A. germinans.* In Boca de López I, with an age at the base of 4585 years BP, the two mangrove species also register low records. Between 4400-3400 years BP, *R. mangle* representation increased, although from 3700 years BP, in Boca de López I, mangrove records disappeared. Between 3400-2000 years BP, the mangrove developed vigorously in Navío Quebrado, while in Boca de López I, vigorous mangrove only appeared at the end of the period. Between 2000-1200 years BP, the mangrove developed vigorously in Neguanje (Tayrona) and the CGSM (Boca de López I), while in Navío Quebrado, the presence of the mangrove decreased. Between 1200-500 years BP, vigorous mangrove grew in Neguanje and Ostional, but in Navío Quebrado and

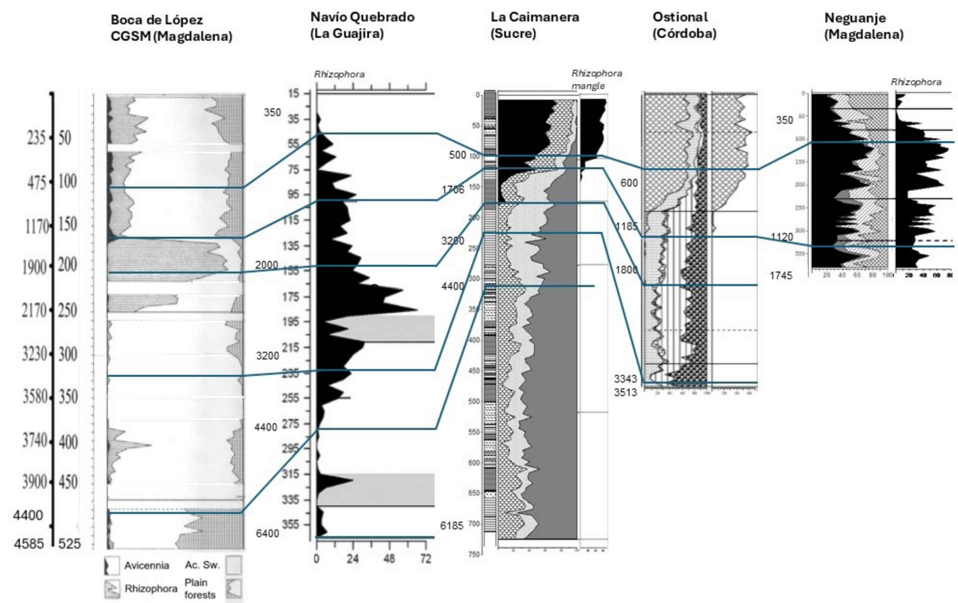

Figure 8. Correlation of vegetation changes over time in several locations in the Colombian Caribbean

La Caimanera, mangroves were greatly reduced. Between 500 years BP and the present, there has been a vigorous development of mangroves in La Caimanera and Ostional, and a slight decrease in Neguanje and CGSM (Boca de López I).

The changes detected do not allow for defining a repeating pattern in the estuarine and deltaic environments of the Colombian Caribbean. There were periods of vigorous mangrove development (between 3400 and 2000 years BP at Navío Quebrado and CGSM), which were associated with changes in the sea level during that time (**Robertson & Martínez**, 1999). However, other periods of significant mangrove development, such as between 1800 and 500 years BP (Boca de López I, Neguanje), and between 500 years BP and the present (La Caimanera and Ostional), cannot be linked to previously documented sea level changes.

A detailed analysis of the Caimanera situation suggests a complementary explanation for these changes. The analyzed sediment column presents two contrasting periods: between the base and 175 cm, when the environment was dominated by continental freshwater wetlands, and between 175 and 0 cm, before the transition, when the environment was estuarine. What changes occurred during the freshwater-brackish water transition? To answer this question, we must review the conditions in subzone Ic, at a depth of 275-175 cm, with an approximate age of 4323-2142 years BP. During this period, the vegetation was dominated by sandy beach elements, which had the highest representation in the entire diagram (**Figure 5**), while the representation of aquatic vegetation was the lowest in the entire column. The stratigraphy was characterized by organic clays; the sediment was consolidated, and no peat remains were found. The average values (%) of inorganic carbon (18.66%) and the mineral fraction (73.24%) were the highest in the entire column, while the residual moisture content was the lowest (0.03%). The highest average values (3.34%) were observed for anhydrite (differentiated phenocrysts) and shell content (40.98%). These biophysical conditions support the classification of subzone Ic as “dry,” in terms of moisture (precipitation, water column level), compared to the other subzones in the column. Under these climatic and stratigraphic conditions, it is plausible to recreate a scenario in which subduction occurred in the basin, facilitating the influx of seawater. This interpretation would therefore be more closely related to local variations than to global (or regional) sea level fluctuations.

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Conclusions

The natural history of changes in the vegetation and environmental conditions of La Caimanera wetland revealed two well-defined and contrasting periods: between the beginning or base of the sediment column analyzed (725 cm, 6185 years BP, and the middle-upper part at 175 cm, 2142 years BP), when the environment was that of a continental freshwater wetland. The hydric series began with aquatic vegetation dominated by *Sagittaria* and *Hydrocotyle* species, and *Paspalum* sp., probably towards the shore, where they formed a belt ("gramalotal"). In the wetland vegetation, Cyperaceae species and *S. dulcis* were present. On the lowland plain, the low *S. paniculata* scrub-forest took root, and in the surroundings, in the final phase of the ecological series, on continental land, forests dominated by *M. montana, S. mombin*, and *A. excelsum* were arranged. The mineral component dominated the sediment; hydrated phenocrystals reached significant values at two points, a feature related to periods when the water level in the wetland dropped. In the organic component of continental origin, peat and plant remains were significant. In the upper part (subzone Ic), a drastic change occurred: the transition to a brackish environment, related to the considerable extension of the area covered by beach vegetation (*A. peruviana*) and the greatest expression of components of marine origin (shells). In this subzone, the lowest value (1.46%) of residual water was registered, a condition that is closely related to the disappearance of the representation of aquatic vegetation. Under these conditions, in this segment of the paleoenvironmental history, the wetland reached its greatest surface and volume of water, and the sedimentation rates varied between 0.3 and 0.21 cm/year. In the upper part (transition zone), the sedimentation rate was 0.046 cm/year, which is close to the upper limit of sedimentation rate variation in the Caribbean wetlands for dry periods (0.011-0.037 cm/year).

From 2142 years BP to the present (175 cm to 0 cm), the conditions for an estuarine environment (brackish water) were established. In the last 1000 years BP, the mangrove wetland (closed vegetation) developed vigorously, an event that is expressed in the palynological spectrum; the representation of marine remains (shells) is high, which is evidenced by the high representation of *A. brasiliana* and *M. sallei* mollusk shells and remains of crustaceans, species of *Balanus*, and a sedimentation rate (accretion) of 1.14 cm/year.

Supplementary information

See the supplementary information in https://www.raccefyn.co/index.php/raccefyn/article/view/3179/4585

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Author contributions

JBP: palynological and stratigraphic analysis and writing of the document; **AJJ**: field work, stratigraphic analysis, and writing of the document; **ORCH**: field work, comprehensive information analysis, and writing of the document.

Conflicts of interest

The authors declare that they have no personal or institutional conflicts of interest.

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