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Original article

How lake sediment records inform archaeology: examples from the Americas and potential future applications in Colombia

Aporte del estudio de los registros sedimentarios lacustres a la arqueología: ejemplos de las Américas y posibles aplicaciones futuras en Colombia

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Abstract

Paleolimnology, the study of lake and wetland sediments, provides a powerful means of reconstructing long-term interactions among climate, environment, and human societies. Drawing on examples from across the Americas, where sediment records have clarified the environmental contexts and ecological consequences of agriculture, deforestation, hydraulic engineering, and demographic change, this paper examines how such archives can strengthen archaeological interpretation. Sediment sequences preserve stratified, independently dated evidence of hydroclimatic variability, vegetation change, fire history, erosion, nutrient loading, and other indicators of anthropogenic disturbance that are often inaccessible through archaeology alone. Focusing on Colombia, this note argues that paleolimnological data can significantly enhance interpretations of pre-Hispanic societies such as the Tairona, Zenú, Muisca, Calima, Quimbaya, Tierradentro, San Agustín, and Tumaco-La Tolita. Although Colombia has a long tradition of paleoecological research, most previous studies emphasized natural Holocene climate and vegetation change rather than explicitly addressing archaeological questions. The paper therefore proposes an integrated research agenda using multiproxy sediment records to investigate land use, water management, fire, soil erosion, metallurgy, and the environmental dimensions of social change. Colombia's rich prehistory and abundant sediment archives make it an exceptional setting for this interdisciplinary approach.

Keywords: Paleolimnology; Archaeology; Americas; Colombia; Climate and environmental change.

Resumen

La paleolimnología, es decir, el estudio de los sedimentos de lagos y humedales, proporciona un medio poderoso para reconstruir las interacciones a largo plazo entre el clima, el medio ambiente y las sociedades humanas. A partir de ejemplos de las Américas, donde los registros de sedimentos han aclarado los contextos ambientales y las consecuencias ecológicas de la agricultura, la deforestación, la ingeniería hidráulica y el cambio demográfico, examinamos cómo dichos archivos pueden fortalecer la interpretación arqueológica. Las secuencias de sedimentos preservan evidencia estratificada e independientemente fechada de la variabilidad hidroclimática, el cambio de vegetación, la historia de incendios, la erosión, la carga de nutrientes y otros indicadores de perturbación antropogénica que a menudo son inaccesibles solo a través de la arqueología.

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Enfocándonos en Colombia, planteamos que los datos paleolimnológicos pueden mejorar significativamente la interpretación de sociedades prehispánicas como la Tairona, Zenú, Muisca, Calima, Quimbaya, Tierradentro, San Agustín y Tumaco-La Tolita. Aunque Colombia tiene una larga tradición de investigación paleoecológica, la mayoría de los estudios previos enfatizaron el cambio natural del clima y la vegetación del Holoceno en lugar de plantear preguntas explícitamente arqueológicas. Por lo tanto, el artículo propone una agenda de investigación integrada que utiliza registros de sedimentos de múltiples indicadores (multiproxy) para investigar el uso de la tierra, la gestión del agua, el fuego, la erosión del suelo, la metalurgia y las dimensiones ambientales del cambio social. La rica prehistoria de Colombia y sus abundantes archivos de sedimentos la convierten en un escenario excepcional para este enfoque interdisciplinario.

Palabras clave: Paleolimnología; Arqueología; América; Colombia; Cambio climático y medioambiental.

Introduction

During the Holocene (11,700 years before present (yr BP) to the present), human societies evolved through long-term, regionally diverse processes of demographic expansion, subsistence agriculture intensification, and institutional elaboration. Rather than a simple linear progression from hunting-gathering to farming to urbanizing, archaeological evidence indicates repeated reorganization of human-environment relations under changing climate, environmental, and social conditions (**Bevan *et al.***, 2017; **Freeman *et al.***, 2024). In the Early Holocene (11,700 to 8,200 yr BP), postglacial warming and hydrological reorganization created conditions favorable to human population growth and the emergence of plant cultivation and animal management, leading to increasing sedentism at many sites across the globe (**Bocquet-Appel**, 2011; **Zeder**, 2011). Holocene societies became agents of environmental transformation through forest clearance, plant and animal translocation, and modification of soil and hydrological systems (**Roberts *et al.***, 2018).

Paleolimnology, i.e., the study of lake and wetland sediment cores, provides a powerful way to investigate long-term climate-environment-human interactions because the accumulated deposits in those aquatic ecosystems preserve high-resolution, stratigraphic records of past climate change, environmental variability, and human disturbance (**Frey**, 1988; **Smol**, 2010; **Escobar *et al.***, 2020; **Escobar *et al.***, 2025). Such sediment sequences contain pollen grains, charcoal particles, diatoms, chironomids (non-biting midges), geochemical tracers (mineral material, organic biomarkers [e.g., pigments, *n*-alkanes, cyanobacterial toxins]), and stable isotope information (e.g., $\delta^{13}C$ and $\delta^{15}N$) that can be used to infer, for example, past vegetation changes, fire regimes, soil erosion intensity, water-column salinity, nutrient loading, aquatic primary productivity, and hydrologic balance. Paleolimnological data from reliably ^{14}C-dated sequences can thus provide a climate/environmental context for archaeological projects, enabling investigators to gain insights into the histories of agricultural intensification, demographic growth, land-use expansion, and political transformation, tracked using measurable changes in aquatic systems and their watersheds. Many paleolimnological studies show that aquatic ecosystems preserve evidence in their accumulating sediments of ancient human activities and their consequences, including, among others, land clearance, enhanced soil erosion, and cultural eutrophication (**Dubois *et al.***, 2018; **Salgado *et al.***, 2019). Paleolimnology can thus be used to establish climate conditions during the emergence and development of cultures but also to document how expanding human societies increasingly affected landscapes and freshwater ecosystems throughout the Holocene.

Application of paleolimnology in archaeological studies has proven to be especially important for periods of the Middle (8,200 to 4,200 yr BP) and Late Holocene (4,200 yr BP to the present) characterized by intensifying societal complexity and vulnerability. As forest clearance for farming, pastoral land use, and urban growth increased, lake sediments often registered these developments through changing pollen spectra, enhanced charcoal deposition, greater detrital inputs, nutrient enrichment, and shifts in aquatic community

composition. Thus, paleolimnology has provided an empirical means for testing hypotheses about past environmental dimensions of societal "development" and "collapse" (**Haug *et al.***, 2003; **Chen *et al.***, 2023). It can reveal whether periods of cultural florescence coincided with intensified landscape modification, whether times of demographic decline or settlement reorganization corresponded with droughts or environmental degradation (e.g., soil loss, lake salinization, water contamination), and whether reduced human pressure led to ecological recovery or a persistent state of environmental degradation. Case studies in different regions revealed that the consequences of multiple human-mediated environmental stressors were often synergistic, and that lake sediments recorded the effects of interactions between climate forcing and land use, which could not have been determined from archaeological evidence alone (**Giguet-Covex *et al.***, 2014; **Dubois *et al.***, 2018; **Palmisano *et al.***, 2021; **Velez *et al.***, 2024).

When integrated with archaeological or historical data, paleolimnological findings shed light on cultural resilience and/or collapse (**Bell & Blais**, 2020). Sediment records have been used to identify past drought intensity and frequency, flood episodes, soil erosion pulses, local/regional fire history, salinity shifts, and trophic state change, enabling researchers to distinguish between natural (climate) fluctuations and human-caused environmental degradation and to better understand how the two societal stressors worked in combination. Such archives, in some cases, revealed continued environmental exploitation, in spite of political fragmentation, supporting the argument that "collapse" is better understood as cultural reorganization than complete demise (**Middleton**, 2017; **Kohler & Rockman**, 2020). Sediment records have also shown that ecological impacts can persist long after episodes of political crisis, meaning that the legacy of societal growth and breakdown became materially inscribed in lakes, wetlands, and their watersheds. High-resolution studies of floodplain deposits and varved (annually laminated) lake sediments have shown that such sequences can track the tempo of human impacts over centuries to millennia, making them indispensable for linking long-term climate change, land-use intensification, and social transformation (**Cole *et al.***, 2019; **Żurek *et al.***, 2020). Thus, paleolimnology expands the archaeological study of Holocene societies beyond the "reconstruction" of ancient settlements and institutions, enabling inferences about climate and environmental feedbacks during which societal development, expansion, vulnerability, and decline occurred.

Three examples from the Americas

Mississippian culture

Paleolimnological records from Cahokia (southern Illinois, USA) and the broader Mississippian region of North America provide clear evidence for how human land-use change reshaped floodplain environments through time. The study of sediment cores from Horseshoe Lake and Avery Lake, in Illinois, indicates that anthropogenic landscape transformation began centuries before Cahokia's apogee (~1050-1350 CE, Common Era) and intensified through the Late Woodland Period (ca. 500-1050 CE) (**Muñoz *et al.***, 2014, 2015; **Bird *et al.***, 2019a). At Horseshoe Lake, pollen and organic carbon stable isotope ($\delta^{13}C_{org}$) data provided evidence of rapid forest clearance beginning around 450 CE, followed by the expansion of Eastern Agricultural Complex crops and, later, maize (corn) cultivation, with peak land-use intensity between about 900 and 1200 CE (**Muñoz *et al.***, 2014). Diatom assemblages independently support this interpretation by documenting a shift toward planktonic taxa associated with shallow, productive lake conditions during periods of dense human occupation, suggesting sustained nutrient enrichment and cultural eutrophication (**Brugam & Muñoz**, 2018). Stratigraphic records of fecal stanols (stable lipid biomarkers produced in the gut) from the same watershed indicate that the human population rose sharply to a maximum around 1000–1100 CE and declined thereafter (**White *et al.***, 2018; **White *et al.***, 2019). Paleolimnological data from Avery Lake, near the Kincaid Mounds archaeological site, include declines in arboreal pollen, increases

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in disturbance plant taxa such as *Ambrosia*, presence of maize pollen, and elevated $\delta^{15}N$ values, demonstrating that the limnological consequences of intensive land use and concentrated populations were not unique to Cahokia, but were rather characteristic of Mississippian floodplain occupation more broadly (**Bird *et al.***, 2019a).

Lake sediment geochemistry also demonstrated that Mississippian land use led to metal pollution, especially lead (Pb) contamination. Sediments from Avery Lake showed distinct Pb concentration peaks associated with both Baumer (300 BCE-300 CE) and later Mississippian occupation, but Pb isotope analyses indicated that the Mississippian-period peaks came from galena (lead sulfide) processing and use, rather than simple erosion of lead in local bedrock and soils (**Bird *et al.***, 2019b). Isotope mixing models linked this lead primarily to ore sources in southeastern and central Missouri, with a smaller contribution from the upper Mississippi Valley, and suggested that ~1.5 metric tons of galena-derived Pb were deposited in Avery Lake during the Mississippian occupation (**Bird *et al.***, 2019b). Earlier Pb enrichment during the Baumer phase is best explained by local biomass burning and highlights that different occupation phases yielded different geochemical signatures (**Bird *et al.***, 2019b). Coeval increases in Pb concentration and $\delta^{15}N$ values in sediment cores collected near Cahokia suggest that lead enrichment was just one of many indicators of human disturbance tied to occupation intensity (**Pompeani *et al.***, 2018; **Pompeani *et al.***, 2021). These findings show that lake sediment archives can capture evidence not only of land clearance and nutrient loading, but also of the environmental consequences of ritual practice, material processing, and long-distance trade (**Bird *et al.***, 2019b).

The paleoclimate literature associated with Cahokia consistently indicates that the site developed under favorable hydroclimate conditions and declined during a period of increasing climate instability, though whether decline was a consequence of deteriorating climate factors remains debated (**Benson *et al.***, 2009; **Bird *et al.***, 2017; **Pompeani *et al.***, 2021). Oxygen isotope data ($\delta^{18}O$) from Horseshoe Lake indicate relatively wet conditions during Cahokia's rise, followed by a substantial shift toward lower effective moisture after 1200 CE and persistent drought conditions through much of the period of abandonment, with particularly severe dry conditions between 1350 and 1450 CE (**Pompeani *et al.***, 2021). Stratigraphic data for fecal stanols, flood deposits, and stable oxygen isotopes ($\delta^{18}O$) suggest that declining warm-season precipitation reduced agricultural reliability at the same time that social reorganization was underway (**White *et al.***, 2019). Stable carbon isotope ($\delta^{13}C$) data from paleosols in Cahokia's North Plaza show that low-elevation wetland settings remained moist, or at least seasonally moist, even during intervals of regional drought, indicating that local floodplain microenvironments did not respond uniformly to broader climate fluctuations (**Rankin & Mueller**, 2024). These findings demonstrate that regional paleoclimate trends must be interpreted along with evidence of local environmental conditions, and that vulnerability at Cahokia likely depended on the spatial distribution of productive and resilient environments, in addition to the broader climate condition (**Rankin & Mueller**, 2024).

Hydrologic change emerged from the paleolimnological record as a critical factor that linked climate, land use, and human demographics in the Mississippian region. Grain-size records from Horseshoe and Grassy Lakes suggest that the time from approximately 600 to 1200 CE was marked by the absence of major Mississippi River floods, a hydrologic regime that likely facilitated agricultural intensification, settlement expansion into the lower floodplain, and the establishment of Cahokia as a regional center (**Muñoz *et al.***, 2015). This long interval of reduced flood frequency apparently ended with a major flood *ca*. 1200 CE, interpreted as having been the first event in centuries large enough to inundate croplands, settlements, and stored food across much of the American Bottoms, a 145-km stretch of floodplain that lies along the eastern shore of the Mississippi River (**Muñoz *et al.***, 2015). Fecal stanol data indicate that demographic decline followed this event, strengthening arguments that hydrologic disturbance played a direct role in Cahokia's reorganization (**White *et al.***, 2019). Similar work on sediments from Avery Lake showed that prior to Euro-American deforestation, sedimentation rate tracked flood regime changes more

closely than it did local land clearance, underscoring the dominant role of hydroclimate in shaping floodplain-lake sediment accumulation (**Bird *et al.***, 2019). Collectively, these studies show that lake sediment archives provided an integrated framework for interpreting Mississippian prehistory by preserving sediment-based evidence of past deforestation, eutrophication, demographic fluctuation, lead pollution, droughts, and floods, thereby revealing the multiple environmental stressors that influenced the trajectory of Cahokia and related Mississippian societies.

Tiwanaku culture

Paleolimnological research in the Lake Titicaca basin (Bolivia/Perú) showed that Tiwanaku culture emerged and thrived during a period of increasing Late Holocene moisture and rising lake levels, rather than under static environmental conditions (**Abbott *et al.***, 2003; **Guédron *et al.***, 2023). Analysis of multiple variables in sediment cores from Lake Titicaca and adjacent Andean basins showed a prolonged Early-Middle Holocene lowstand that reflected an arid interval, followed by a stepwise hydrologic recovery that transformed the southern basin of Titicaca, Lago Menor, into an increasingly productive lacustrine and wetland landscape (**Abbott *et al.***, 2003; **Guédron *et al.***, 2023). The paleolimnological data indicate that lake-level rise, combined with periodic flooding of vast riparian areas, created ideal conditions for intensified agro-pastoralism, settlement nucleation, development of raised-field agriculture, and the eventual consolidation of major Tiwanaku centers around the basin (**Binford *et al.***, 1997; **Guédron *et al.***, 2023).

Tiwanaku land-use change in the Titicaca Basin must therefore be interpreted against the backdrop of this evolving hydrologic history. Archaeological studies emphasize that intensive raised-field agriculture, canalized wetlands, terrace farming, and pastoral production were all contingent on the reliable availability of shallow groundwater and the seasonal dynamics of the South American Summer Monsoon (**Binford *et al.***, 1997; **Janusek & Kolata**, 2004; **Arnold *et al.***, 2021). The sediment records document the shifting water-level history in the lake and the changing littoral ecology and detrital inputs that likely reflect both hydrologic and human landscape modification. In Lago Menor (Huiñamarca), Titicaca's shallow southern Basin, decadal- to centennial-scale lake-stage declines coincided with increases in the concentrations of titanium (Ti) and characeae (macroalgae) remains, reflecting the fluctuating position of macrophyte communities with shifting water depths in the littoral zone, changing salinity, and, in some intervals, potentially enhanced clastic input from expanding agro-pastoral land use during the emergence of Tiwanaku (**Guédron *et al.***, 2023). The same study noted that by the final centuries of the Formative Period (1500 BCE-400 CE), and even after 500 CE, lake-level rise inundated large areas on the adjacent flat *pampas*, likely forcing settlers to move upslope, a process that probably concentrated populations and reconfigured access to wetlands and cultivable land in ways favorable to Tiwanaku political growth (**Guédron *et al.***, 2023). Earlier syntheses argued that the wetter Late Holocene promoted conditions that favored the spread of agriculture and, eventually, the development of the highly managed and very productive raised-field systems of the Tiwanaku core area (**Binford *et al.***, 1997; **Abbott *et al.***, 1997, 2003). A recent study of a core from Lake Orurillo used two independent isotope proxies for past hydroclimate, $\delta^2H_{leaf\ wax}$ and $\delta^{18}O_{calcite}$, to identify a severe drought, including a phase of nondeposition or erosion between 915 and 1025 CE that indicates an extreme lake lowstand, followed by continued aridity into the 13th century (**Arnold *et al.***, 2021). The authors argued that the century-long interval was the longest and most severe period of reduced precipitation in the last 4000 years at the site, and that it overlapped temporally with the cessation of monumental construction, political fragmentation, and subsequent abandonment of major Tiwanaku centers (**Arnold *et al.***, 2021).

For the Tiwanaku, hydroclimate fluctuation emerged as a key variable that affected social change. Tiwanaku's agricultural yields were not dependent on rainfall amount alone, but on a combination of factors related to rainfall. Periodic high lake stands flooded and enriched riparian soils and created sufficiently high water tables to maintain spring flow

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that flushed canals between raised fields, thereby protecting crops against freezes, keeping soils from becoming too saline, and providing sites for cyanobacteria to fix nitrogen, giving local farmers a reliable source of N-rich "fertilizer" that accumulated in the shallow canals. Paleolimnological data were central to understanding Tiwanaku prehistory, showing that the wetter conditions that began about 3500 years ago enabled agricultural intensification and political florescence, whereas prolonged drought and lake regression about 1100 years ago undermined the water-based infrastructure on which Tiwanaku power depended.

Maya culture

Paleolimnological research across the Maya Lowlands of Mesoamerica showed that human occupation was prolonged, spatially variable, and tightly linked with hydroclimate (**Brenner *et al.***, 2002, 2003, 2023). Foundational syntheses emphasized that stratigraphic changes in pollen grains, diatoms, minerals, and stable oxygen isotopes in sediment cores from lowland lakes preserved continuous records of human-mediated forest loss, soil erosion, changing lake trophic state conditions, and changing climate in the Late Holocene (**Brenner *et al.***, 2002, 2003, 2023). In Petén, northern Guatemala, sediment cores from multiple lakes documented the long period of prehistory during which the ancient Maya altered regional landscapes through their agro-engineering activities. Evidence came in the form of declining arboreal pollen percentages, increases in disturbance taxa, presence of *Zea mays* (corn) pollen, and deposition of the thick inorganic "Maya Clay," a distinctive erosional product of hillslope destabilization and sediment transfer into lakes from about 3000 to 1000 years ago (**Deevey**, 1979; **Rosenmeier *et al.***, 2002; **Mueller *et al.***, 2009; **Schüpbach *et al.***, 2015; **Brenner**, 2023). At Lake Salpetén, forest clearance and enhanced soil erosion may have begun as early as 1700 BCE, and persisted through the Late Classic, *ca*. 850 CE, after which there was a demographic decline and forest recovery (**Rosenmeier *et al.***, 2002). At nearby Lake Petén Itzá, however, earliest Holocene forest decline began ~4500 yr BP, preceding archaeological evidence for sedentary settlement or intensive maize agriculture, implying that initial dry tropical forest decline was climate-driven rather than human-mediated (**Mueller *et al.***, 2009). Paleo-fire studies further clarify this picture. Charcoal particles and molecular fire markers show that ancient Maya agriculture relied heavily on slash-and-burn techniques, but fire regimes shifted from being predominantly climate-driven in the highly seasonal Early Holocene to being largely human-caused at the onset of agriculture, with biomass-burning peaks around 3700 and 2700 yr BP linked to early land clearance (**Schüpbach *et al.***, 2015).

Hydroclimate also proved to be a key variable in the rise, persistence, and eventual fall of ancient Maya culture. Most Maya lowland lakes are effectively hydrologically "closed," and in some cases, their water levels and chemistry responded rapidly and strongly to changes in the evaporation-to-precipitation ratio. Lake Chichancanab, northern Yucatán Peninsula, México, was the first waterbody in the Maya Lowlands where stable oxygen isotopes and mineral content of the lake sediment were used to infer relative wet/dry climate conditions in the past (**Covich & Stuiver**, 1974; **Hodell *et al.***, 1995; **Brenner *et al.***, 2002, 2003). During dry periods, preferential evaporation of the light isotope of oxygen (^{16}O) in water left the lake water with relatively more ^{18}O than during wet episodes. Furthermore, the lake became supersaturated with dissolved gypsum ($CaSO_4 \cdot 2H_2O$) as the lake volume shrank in dry times, ultimately leading to mineral precipitation of gypsum on the sediment surface. The sediment record from Chichancanab shows the lake first filled with water about 8000 years ago, probably associated with a wetter climate after the dry late Pleistocene and rising sea level that accompanied deglaciation and forced the freshwater aquifer in the region upward. After a period of Early Holocene dry climate conditions and saline waters that probably lasted less than a millennium, lake level rose and fresher conditions were maintained for some four thousand years. About 3000 BP, coincident with initial sedentary human settlement in many areas of the Maya Lowlands, $d^{18}O$ values on snail and ostracod shells and gypsum concentrations in sediments rose, indicating drying (higher evaporation/precipitation) in the region. Peak sulfur and oxygen

isotope values, i.e., the driest times since the earliest Holocene, occurred in the Terminal Classic Period (800-1000 CE), coincident with archaeological evidence for Classic Maya cultural decline (**Hodell *et al.***, 1995, 2005).

Farther east on the peninsula, Lake Punta Laguna provided a higher-resolution record for the last 3500 years and showed repeated wet/dry episodes during the Classic and Postclassic Periods (250-1500 CE), with especially severe drought pulses around the Terminal Classic Period (**Curtis *et al.***, 1996; **Escobar *et al.***, 2010). Isotope measurements on single ostracod valves and gastropod shells demonstrated that not only were Terminal Classic conditions dry on average, but also persistently dry, with low within-stratigraphic-sample isotope variability, indicating sustained precipitation deficits rather than brief anomalies (**Escobar *et al.***, 2010). Those persistent, dramatic droughts, documented through study of lake sediment sequences, were corroborated by high-resolution analyses of speleothems (stalagmites) from caves in southeastern México and Belize (**Medina-Elizalde *et al.***, 2010; **Medina-Elizalde & Rohling**, 2012; **Kennett *et al.***, 2012; **James *et al.***, 2025). In the Southern Maya Lowlands of northern Guatemala, paleo-hydrologic interpretation is more complicated because human-mediated deforestation substantially altered watershed hydrology. At Lake Salpetén, lower carbonate $\delta^{18}O$ values during intervals of strong human disturbance may reflect, in part, greater input of isotopically light surface runoff and groundwater, rather than increased rainfall amount, illustrating the difficulty of separating the effects of climate versus land clearance on lake hydrology (**Rosenmeier *et al.***, 2002; **Brenner *et al.***, 2002). This revealed that paleolimnological records from the densely occupied, once-forested, southern lowland watersheds encode both climate forcing and anthropogenic hydrologic modification.

Climate change nevertheless emerged as a major driver of long-term environmental stress for the ancient Maya, especially when multiple lake records were compared regionally and new isotope methods were employed. As mentioned, Lake Chichancanab was the first waterbody to provide strong evidence linking the Terminal Classic Maya "collapse" to drought, revealed by gypsum layers and higher $d^{18}O$ values in snail and ostracod shells, which marked some of the driest Holocene conditions on the northern Yucatán Peninsula (**Hodell *et al.***, 1995). Subsequent work in the same lake refined this interpretation, showing that droughts in the northern lowlands recurred through the last 2600 years and that the driest late Holocene interval occurred between about 800 and 1000 CE, approximately coincident with the Classic Maya collapse (**Hodell *et al.***, 2005). A major advance came from isotope analysis of gypsum hydration water in sediments from Chichancanab, which was used to estimate the reduction in rainfall during Terminal Classic droughts. The data suggested that annual precipitation declined by 41–54% during dry times, with short intervals of up to 70% reduction and a 2–7% decrease in relative humidity (**Evans *et al.***, 2018). Plant-wax hydrogen isotope (δD) records from lake sediment cores taken along a N-S transect on the peninsula, however, showed that drought impacts were not spatially uniform. Those compound-specific δD records from Lake Chichancanab in the north and Lake Salpetén in the south demonstrated that drying during the Terminal Classic was more severe in the Southern Maya Lowlands than in the north, perhaps explaining the more profound, archaeologically documented sociopolitical decline in the south (**Douglas *et al.***, 2016). Those records also identified an earlier drying interval from ~200 to 500 CE in the south, suggesting that the Classic Period Maya had already faced times of hydrologic stress long before the Terminal Classic collapse (**Douglas *et al.***, 2016).

The Terminal Classic Maya "collapse" (or reorganization) is best understood not as a simple response to recurrent droughts or socio-political failures. More likely, it was the outcome of multiple, interacting factors, which probably included climate stress, loss of soil fertility, contamination of water sources (**Lentz *et al.***, 2020), and inter-site competition for increasingly scarce resources. Paleolimnological evidence shows that by the onset of the Early Classic Period (250 CE), many southern lowland watersheds had already been subjected to centuries of forest clearance, soil erosion, altered runoff, and changing agricultural strategies (**Curtis *et al.***, 1998; **Rosenmeier *et al.***, 2002; **Mueller**

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et al., 2009). Plant-wax stable carbon isotopes ($\delta^{13}C_{wax}$) indicated that during droughts of the Early Classic (~250-550 CE), Maya land use shifted away from extensive C4-rich (*milpa*) swidden cultivation toward more intensive, water-conservation strategies for maize production, probably concentrated near wetlands and other perennial water sources (**Douglas *et al.***, 2016). This suggests that ancient Maya farmers were able to adapt to moderate, temporary drying. Yet paleolimnological records indicate that the later, Terminal Classic droughts were drier, more persistent, and widespread, and came after prior landscape transformation that likely reduced the capacity of the ancient Maya to resist or be resilient in the face of such climate stress (**Hodell *et al.*,** 1995; **Rosenmeier *et al.***, 2002; **Evans *et al.***, 2018).

Reviews of paleolimnology in the Maya region have stressed that lake records capture the potential effects of both natural climate deterioration and human-driven environmental impacts on ancient Maya society, cognizant of the fact that human activities in watersheds can "mimic" and, therefore, obscure interpretation of climate shifts, especially when using sediment records from southern lowland lakes (**Brenner *et al.***, 2002). Paleolimnology revealed a coupled climate/environment system in the tropical Maya Lowlands that played a role in the rise, long-term persistence, and ultimate demise of ancient Maya culture. Archaeology has shown that sedentary settlement in the region persisted for nearly two millennia, testimony to the vast traditional ecological knowledge and resilience of ancient Maya people. However, by the Late Classic, population densities were high, in some areas much higher than they are today (**Canuto *et al.***, 2018). When persistent, severe rainfall declines occurred in the Terminal Classic Period, at a time when forests and soils had been exploited for nearly two millennia, the socio-political system was overwhelmed (**Douglas *et al.***, 2016). To be clear, however, despite a large demographic decline, the ancient Maya did not "disappear." Instead, they reorganized into smaller, more nucleated and defensive postclassic sites, and their descendants are spread throughout the region today.

Paleolimnology and pre-Columbian cultures in Colombia

Colombia is one of the most intensively studied countries in Latin America for paleolimnology and palaeoecology, largely because of its long tradition in palynology, initiated in the 1960s by van der Hammen (**Flantua *et al.***, 2015; **Hooghiemstra & Flantua**, 2019; **Roldan**, 2020; **García-M *et al.***, 2021; **Beltrán-P *et al.***, 2025; **Palma-Silva *et al.***, 2025). Most of the "paleo" work to date has focused on natural climate/environmental changes. The Holocene record from the Andes, however, is especially rich (**Hooghiemstra & Flantua**, 2019), and there are also archives from the Caribbean lowlands (**Vélez *et al.***, 2014; **Serna *et al.***, 2020), the Pacific lowlands (**Berrío *et al.***, 2000a; **Vélez *et al.***, 2001; **Jaramillo *et al.***, 2021), the inter-Andean valleys (**Vélez *et al.***, 2003; **González-Carranza *et al.***, 2012), the Amazon (**Behling *et al.***, 1999; **Berrío *et al.***, 2003), and the eastern lowlands (**Berrío *et al.***, 2000b; **Wille *et al.***, 2003) (**Figure 1**). Most of the cited studies were pollen-based, whereas a few used diatoms or testate amoebae, and others emphasized sediment geochemistry, grain size distributions, stable isotopes, or trace metals (**Bird *et al.***, 2017; **Liu *et al.***, 2019; **Kamenov *et al.***, 2020; **Vélez *et al.***, 2021). The relative paucity of non-pollen-based investigations highlights the fact that the Holocene history of Colombian aquatic ecosystems has often been inferred indirectly from terrestrial vegetation change. Studies of limnological responses to climate and environmental change inferred from diatoms, aquatic macrophytes, or geochemical variables remain sparse.

An important potential application of Holocene paleolimnology in Colombia, not yet fully exploited, is the relationship between long-term aquatic ecosystem change and the protracted history of Indigenous societies in the country. In the Eastern Cordillera, paleolimnological records show that major shifts in limnological conditions often coincided with phases of agricultural intensification, population growth, and sociopolitical transformation among Herrera and Muisca societies. At Lake Pedro Palo, which lies at ~2000 masl in the sub-Andean forest belt on the western slope of the Eastern Cordillera, increased fire frequency, higher terrestrial organic matter input, and a switch to more

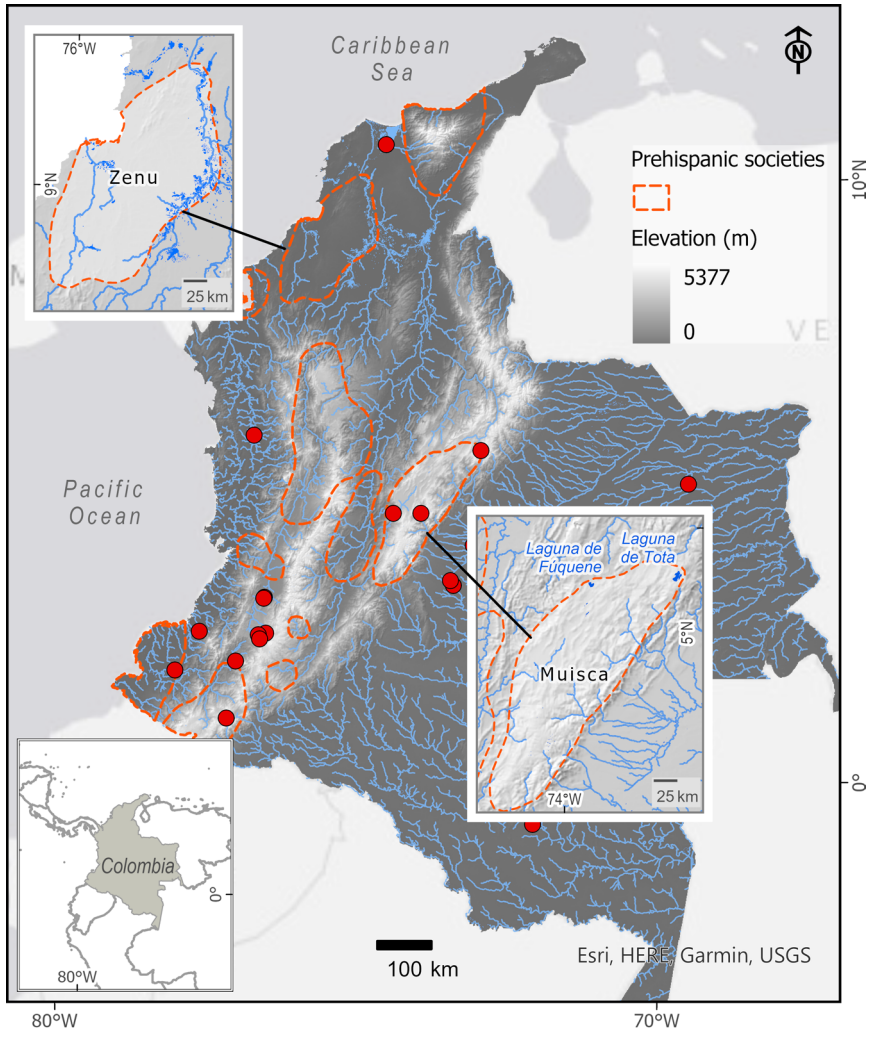


Figure 1. Map of Colombia. Red dotted lines delineate the areas of influence of the pre-Columbian cultures in Colombia. The red dots represent the paleolimnological studies cited in the document.

nutrient-tolerant planktonic diatoms between about 4110 and 2050 cal yr BP were interpreted as having been the result of anthropogenic burning, deforestation, and nutrient loading associated with expanding horticulture and increasing social complexity on the high plains near Bogotá (**Vélez *et al.***, 2021). At Lake Tota (3015 masl), in the Department of Boyacá, limnological shifts *ca*. 1200, 1500, and 1900 CE coincided, respectively, with the transition from Herrera to Muisca occupation, Spanish colonial transformation of the watershed, and recent agro-industrial intensification. These shifts included changes from more planktonic to more benthic and littoral diatom assemblages, increased detrital input, altered nutrient dynamics, and evidence for greater ecological stress (**Vélez *et al.*,** 2024). Regional archaeological projects indicated that the limnological changes occurred during periods of increasing population density, terrace and *camellón* (raised field) agriculture, intensified craft production, ritual use of the lake, and, later, colonial deforestation and wetland drainage (**Delgado**, 2017, 2021; **Langebaek**, 2019; **Vélez *et al.***, 2024). Sediments from other lakes in the Muisca region, including Fúquene and Ubaque, preserve evidence of human impacts, including cultural eutrophication, altered hydrology, and increased soil erosion and fire documented through stratigraphic changes in diatom and/or pollen assemblages. The findings showed that Colombian paleolimnological archives not only

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record climate changes of the past but also archive information about how pre-Hispanic and Colonial-period peoples influenced aquatic ecosystems throughout the Late Holocene (**Vélez *et al.***, 2003; **González-Carranza *et al.***, 2012; **Flantua *et al.***, 2016; **Bird *et al.***, 2017; **Vélez *et al.***, 2021).

In the high Andes (~2500–3200 m), particularly in the Eastern Cordillera, sediment sequences from large lakes record coupled climate and floristic changes during the Late Holocene. Lake Tota (~55 km^2) is the largest natural lake in Colombia and has yielded multiple Holocene paleoclimate and paleoenvironmental records. Pollen and geochemical data from the last millennium indicate warm and relatively dry conditions during the Medieval Climate Anomaly (*ca*. 950-1250 CE), followed by colder and relatively wetter conditions during the Little Ice Age (ca. 1300-1850 CE), with major floristic turnover involving upslope and downslope movement of Andean forest and sub-Páramo elements (**Correa-Metrio *et al.***, 2022; **Bird *et al.***, 2024). Recent paleolimnological work in Lake Tota showed the strong influence of recent human-generated nutrient loading, associated with agriculture and manure applications, and illustrated how modern cultural eutrophication can be viewed against the backdrop of long-term Holocene limnological conditions (**Aranguren-Riaño *et al.***, 2018; **Muñoz-López & Rivera-Rondón**, 2022). Sediments from nearby Laguna Siscunsí also possess a record of Late Holocene hydroclimatic and limnological change, including evidence for episodes of lower water levels at times during the last two millennia (**Bird *et al.***, 2024). These high-Andean records show that both climate and long-term cultural occupation shaped limnological conditions in lakes of the Eastern Cordillera.

In the upper montane forest and páramo belt (>3200 m), Holocene lake-sediment records highlight environmental sensitivity to moisture balance, fire, and human impact, even where human occupation was relatively limited. Deposits from the Santurbán-Berlín region and other páramo sites were used to document long-term fluctuations between lacustrine and mire (wetland) conditions and shifts toward more aerophilous or disturbance-tolerant diatom floras in the Late Holocene, driven largely by hydroclimate change but modified locally by human activities (**Vélez *et al.***, 2021). In a sediment core from Laguna La Cocha (2780 masl), the last ~1400 years of the record contain evidence of forest disturbance, logging, fire, and changes in diatom assemblages related to both climate fluctuations and human land use (**González-Carranza *et al.***, 2012; **Flantua *et al.***, 2016). Syntheses of the numerous Colombian pollen records demonstrated that human impact became increasingly evident in the Late Holocene - first in the lowlands of northern Colombia, by ~5 ka BP, then expanding into the Llanos and high Andes during the last 3000 years, as reflected by the occurrence of maize pollen, grains of disturbance taxa, charcoal, and declines in the relative abundance of pollen from arboreal taxa (**Marchant *et al.***, 2001, 2002; **Flantua *et al.***, 2016). Across Colombia's full elevation gradient, Holocene paleolimnology revealed a mosaic of climate- and human-driven environmental transformations, with most inferences based on pollen analyses but increasingly complemented with information from diatoms, geochemistry, stable isotopes, aquatic macrophyte remains, and measures of trace metal concentrations.

Proposed future work in Colombia

Archaeology in Colombia has shown that pre-Hispanic societies sometimes modified the local environment through settlement constructions, agricultural activities, landscape adjustments, and water management rather than passively adapting to existing natural conditions (**Henderson & Ostler**, 2005; **Rodríguez-Gallo**, 2019; **Posada-Restrepo *et al.***, 2023). The Tairona of the Sierra Nevada de Santa Marta constructed terraced settlements, with paved roads, stone stairways, retaining walls, and drainage features on steep slopes, suggesting they exercised careful control of water runoff and soil erosion in mountain watersheds (**Rodriguez-Osorio *et al.***, 2023; **Soto-Rodríguez & Vargas**, 2025). The Zenú provide a clear case of sophisticated, large-scale hydraulic engineering

in lowland South America, through their construction of canal networks and raised fields in the Sinú and San Jorge floodplains, which evidences their deep knowledge of seasonal inundation, wetland productivity, and hydrologic variability (**Plazas *et al.***, 1993; **Posada-Restrepo *et al.***, 2023). In the eastern Andes, the Muisca occupied a landscape characterized by lakes, wetlands, highland valleys, and cultivated fields. In the west, the Calima and Quimbaya peoples developed in ecologically heterogeneous valleys and slopes, where land use, craft production, and social complexity were closely linked to the environmental setting (**Salgado-Lopez**, 1986; **Henderson & Ostler**, 2005; **Perea *et al.***, 2013).

The diverse, archaeologically documented pre-Hispanic cultures in Colombia offer particularly tantalizing opportunities for paleolimnologists because of the abundant lakes, marshes, wetlands, abandoned channels, flood basins, and sediment-trapping hollows capable of preserving long records of climate and environmental change. Sediment cores from such contexts would likely contain pollen, phytoliths, charcoal particles, diatoms, and geochemical information that could be used to infer deforestation, soil erosion, burning, plant cultivation, metallurgy, and climate and hydrological change through time. In the Muisca area, paleolimnological work on high-Andean lakes and wetlands could identify when forest clearance and agriculture intensified, whether population growth coincided with increased soil erosion, and how occupation histories related to paleoclimate, e.g., droughts, cold phases, or fluctuations in water level. In the Tairona region, sediments from small mountain basins and wetlands could be studied to clarify whether terrace construction and/or settlement on slopes reduced erosion through stabilization, or, on the contrary, increased it through forest opening and intensified land use at different elevations. In southwestern and southern Colombia, geoarchaeological and archaeological studies have already revealed a link between human occupation and alluviation, colluviation, and other basin processes. Paleolimnology has the potential to expand such studies both spatially and temporally.

Zenú culture lends itself to the combined archaeological and paleolimnological study because the society existed in a wetland environment where climate variability, sedimentation, avulsion, seasonal flooding, and water control were critical to both cultural resilience and vulnerability. Sediment core records from ancient canals, marshes, oxbow lakes, and floodplains in the Sinú and San Jorge systems could reveal when hydraulic infrastructure was constructed, whether its use corresponded to wetter or drier intervals, how vegetation changed in and around managed wetlands, and whether these engineered landscapes served as buffers against climate variability requiring constant labor under unstable hydrological conditions. Comparable approaches could also transform our understanding of the Calima and the Quimbaya, where lake and wetland sediments could record shifts in agriculture, burning, forest clearance, and soil erosion associated with changing occupation density, metallurgical activity, and inter-regional interactions. In Tierradentro and San Agustín, upland sediment archives could test whether monumentality, funerary elaboration, and settlement expansion coincided with phases of population growth, intensified cultivation, or climatic stress in the upper Cauca and upper Magdalena River regions. Along the Pacific coast, “paleo” data from estuaries could be useful for addressing questions about Tumaco-La Tolita, as they might reveal past changes in salinity, river migration, sea-level influence, extreme rainfall, and anthropogenic burning in a region where water dynamics are fundamental to human occupation.

The Sibundoy Valley, an ancient Pleistocene lacustrine basin perched in the Colombian Southwestern Andes-Amazon transition, should hold an extraordinary sedimentary record of Neotropical biodiversity dynamics, paleoclimate shifts, and human ecological adaptation. Because the valley operates as an ecotone between high-altitude Andean paramos and the Amazonian piedmont, its dense, organic-rich histosols and fluviolacustrine terraces could serve as a natural archive to reconstruct variations in precipitation and temperature, as well as vertical migrations of vegetation belts, directly altering local biodiversity and forest compositions throughout the Quaternary. When cross-referenced with regional

archaeological data, these paleoenvironmental datasets could offer critical insights into how ancient societies interacted with a fluctuating landscape and climate on the strategic corridor between the highlands and the Amazonian lowlands.

Conclusions

Studies of lake and wetland sediment cores from across the Americas have shown that paleolimnology can greatly enhance our understanding of archaeological records by providing a climate and environmental context for interpreting past cultural changes. These paleoclimate/paleoenvironment archives shed light on the local conditions faced by people in prehistory, including the magnitude and frequency of shifts in hydroclimate conditions, e.g., droughts. Paleolimnology can also be used to document and explore the impacts of human activities on the local environment, e.g., deforestation and consequent soil erosion, cultural eutrophication of water bodies, and contamination from metallurgy. The analysis of multiple variables in lake and wetland deposits may also lead to new perspectives on the decline of past civilizations, providing information about climate stress and excessive resource exploitation. It is likely that, in many cases, cultural decline was far more nuanced than a "single bullet theory," and was likely a consequence of a complex combination of factors, some of which can be explored using sediment records. The Colombian cases suggest that there is exceptional potential for using paleolimnology to supplement archaeological data. The country already has a rich tradition of research in Holocene paleoecology, though most previous work focused on climate-driven vegetation changes rather than using the information-rich sediment archives to address questions about pre-Hispanic societies. Expansion of paleolimnological research into regions of Colombia that were occupied by the Muisca, Tairona, Zenú, Calima, Quimbaya, Tierradentro, San Agustín, and Tumaco-La Tolita could reveal how urban settlement, residential construction, agricultural practices, hydraulic engineering, and other human activities affected Colombia's landscapes and aquatic ecosystems in the Late Holocene. Given Colombia's rich prehistory and abundant lakes and wetlands, the country is an optimal location for integrating archaeological and paleolimnological research.

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