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## Impacts of Mayan land use on Laguna Tuspán watershed (Petén, Guatemala) as seen through clay and ostracode analysis



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### ABSTRACT

Most of the cities built by the Mayas in the Petén area, in the Central Yucatán Peninsula, were abandoned 1200 to 1000 years ago. The phenomenon is sometimes un-appropriately called “the collapse of the Maya civilization”. Its main causes are still debated, ranging from climatic according to the occurrence of severe or modest droughts, to societal in the form of environmental mismanagement of the environment. In both processes, it is inferred that stress triggered the formation in many Petén lake sediments of erosional clay deposits, known as ‘Maya clays’.

This work presents a high resolution, multi-proxy study of ‘Maya clays’ in lacustrine sediments from Laguna Tuspán, near the archaeological site of La Joyanca. Micropaleontological (ostracodes), mineralogical (clay minerals) and geochemical (bulk elemental composition and stable isotopes in organic carbon) records reveal three different phases of soil erosion throughout the last 5300 years. The oldest phase from 5281 to 2998 cal yr BP (i.e. 3331 – 1048 BC) is characterized by successive natural and moderate soil erosion deposits which follow climatic variations recorded in the American tropical belt. The time interval between 2998 and 1281 cal yr BP (i.e. 1048 BC and AD 661) contains four distinct erosional layers which, according to clay mineralogy, are indicative of both increased erosion of the regolith and strong soil loss. The most recent, also the most massive, deposit of Maya clay ends around 1281 cal yr BP (AD 661), that is some 200 years before the so-called ‘Maya collapse’ in the Petén area. Recent archeological fieldwork studies indicate that a population mobility took place into the city of La Joyanca from its hinterland by the early Late Classic Period (ca. AD 600), that is, at the end or just after this erosion episode, and well before the occurrence of the Terminal Classic–Postclassic (AD 800–1250) drastic climatic changes. Shifts in environmental management by the local society and timing of urbanization may explain environmental changes better than droughts per se.

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### 1. Introduction

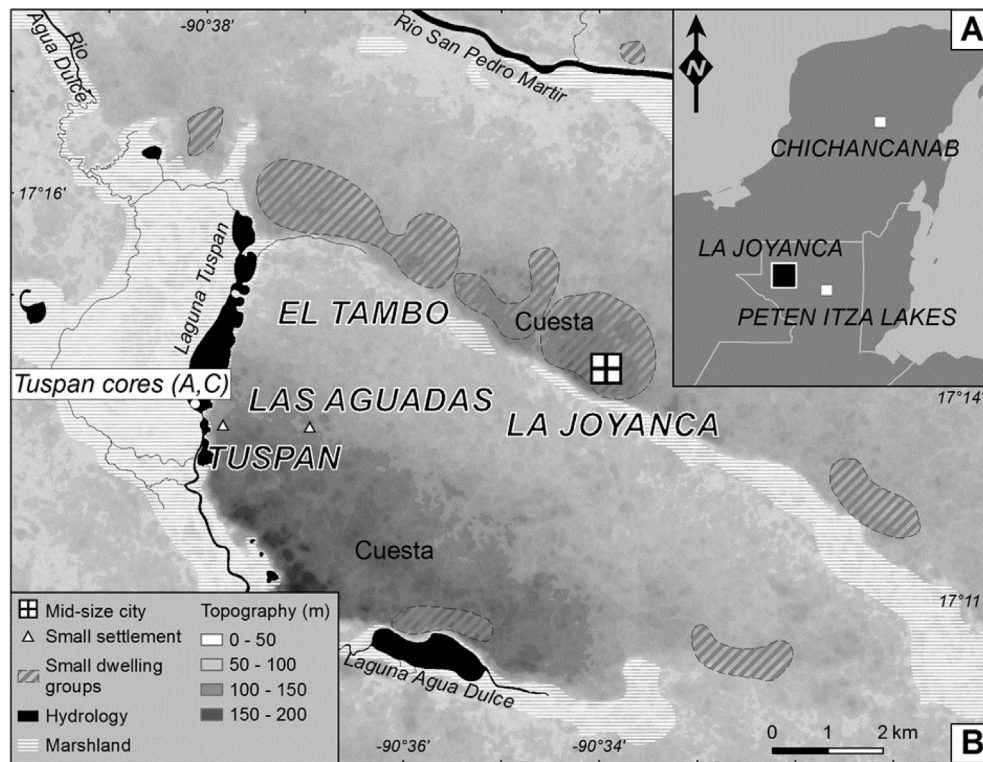
The past of the ancient Maya civilization is commonly divided into cultural periods spanning from the Early Preclassic Period starting ca. 4000 years ago, to the Postclassic Period ending with the Spanish conquest some 400 years BP. The chronology of the Classic interval (1750–950 yrs BP) is based on the rise and fall of political capitals, and thus slightly varies depending on the location

in the Yucatán Peninsula (Fig. 1). For the Petén lowlands, the Terminal Classic period is characterized by the abandonment of most of the cities between 1150 and 950 cal yr BP (AD 800–1000), a process known as the Classic Maya collapse.

Among the various theories attempting to explain this collapse, climatic changes are among the most frequently cited. Several studies on sediment archives collected in cenotes (karstic sinkholes) and lakes from the Yucatán Peninsula (Curtis et al., 1996; Hodell et al., 2005; Leyden et al., 1998; Luzzadder-Beach et al., 2012; Whitmore et al., 1996; Wilson, 1980) point to the occurrence of several droughts across the first millennium AD, the most severe occurring toward the end of the Classic Period (Stahle et al., 2011).

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**Fig. 1.** A: Location of La Joyanca city within the Maya cultural zone, including re-known climatic records location such as Chichancanab lake (Hodell et al., 2005) and Peten Itza lakes (Anselmetti et al., 2007; Mueller et al., 2009). B: Coring locations Tuspan-A and Tuspan-C and Maya settlements in the area, from small dwelling groups to mid-size cities (Carozza et al., 2007; adapted from Galop et al., 2004).

Medina-Elizalde and Rohling (2012) showed that water resources were reduced by 40% during the Terminal Classic period by studying speleothems from Tecoh Cave, in the northern part of the Yucatán. Another speleothem study by Kennett et al. (2012) indicates that reduced rainfall might have destroyed, or at least fragilized societies and polities of the main cities, which partly, or entirely, depopulated afterwards.

However, some cities located in the northern part of the peninsula, such as Uxmal and Chichén Itza, flourished during the collapse of the lowland cities (AD 800–1000), and lasted until AD 1100. This northern location corresponds to places where water resources are the most dependent on rainfall (Demarest, 2004). Several Northern Belize cities thrived throughout the Postclassic Period until the Spanish conquest. Also limiting the explanatory potential of droughts, several studies showed that the Mayas experienced and survived a series of crises throughout their history (Dunning et al., 2012), the worst of them being the Spanish conquest. Historical facts foster the development of alternative theories calling for severe mismanagement of the environment resulting from sociopolitical interactions. The Mayas conducted extensive deforestation as a way to increase land surface for agriculture (Carozza et al., 2007; Dunning et al., 2012; Galop et al., 2004; McNeil, 2012; Webster, 2002). Such a practice drastically increased soil vulnerability to erosion (Beach et al., 2006, 2009; Cabadas-Baéz et al., 2010). Long-term decreasing productivity of fields, with or without climate changes, might have triggered the abandonment of many Mayan cities.

Yet, the causality and relative role of climatic changes and/or Maya mismanagements of the environment are still debated issues (Aimers and Hodell, 2011). Detailed multiproxy studies have been conducted on numerous lake sediment cores in the Maya lowlands

but interpretations are generally hampered by the lack of discrete signals diagnostic of either human impact or climate changes (Leyden et al., 1998).

Major episodes of soil erosion which occurred during periods of extensive agriculture are recorded as thick detrital clay units known as ‘Maya clays’ (Anselmetti et al., 2007; Brenner, 1994; Deevey et al., 1979; Leyden et al., 1998; Mueller et al., 2009; Rosenmeier et al., 2002). Characteristic of the Preclassic Period, Maya clays are observed in many lake sediment records of the Peninsula as laminated layers (Anselmetti et al., 2007; Leyden et al., 1998). In the well-known Lake Petén Itza, Maya clays are present throughout 5 m of sediment record, spanning 2500 years (Mueller et al., 2009). In the neighboring Lake Salpetén, the 6.5 m thick Maya clays cover roughly 3000 years (Anselmetti et al., 2007). The average time resolution for records from Petén is about 500 years/meter. Such a high temporal resolution allowed Anselmetti et al. (2007) to precisely investigate the chronology of changes in erosion rate. The latter multi-proxies approach concluded in a decoupling between population density and soil erosion rate. The most rapid soil loss occurred early during initial land clearance, suggesting that even low numbers of people can have profound impacts on lowland tropical karst landscapes. This means that, for a relatively long time interval, Maya people had to live with fragile soils. Was this pattern common for the whole Petén area?

Here, we present a 5300 year sediment record from Laguna Tuspán in which several ‘Maya clay’ horizons are clearly identified. Previous studies conducted on a core extracted nearby indicate that sediments in this area accumulated at an average rate of 0.2 cm/year (Carozza et al., 2007; Galop et al., 2004). For the first time in Petén lake studies, a detailed analysis of clay fractions and assemblages is presented, completing micro-paleontological (ostracodes)

and geochemical (bulk elemental composition and stable isotopes in organic carbon) analyses on Maya Clay layers. These data set are interpreted in view of the history of human populations in the hinterland of a Classic city, La Joyanca, built five km east from Laguna Tuspán (Fig. 1).

## 2. Material and methods

### 2.1. Core location and geographical description

Laguna Tuspán is located in the Northwestern Petén, Guatemala (Fig. 1). The lake is bound by two successive limestone karstic cuestas in the north-east, and a large swamp area toward the west. It receives waters of Arroyo Tuspán at its northern tip, and is connected in its southern part to Laguna Agua Dulce through Río Dulce (Lemonnier and Michelet, 2004, Fig. 1). Laguna Tuspán is an exorheic basin and receives waters from three different origins (groundwater, rainfall and run-off). Its hydrological budget is complex and prevents the use of the stable isotope ratios of oxygen ( $\delta^{18}\text{O}$ ) measured in ostracode valves as a precipitation index. Oxygen isotopes of ostracode valves were successfully implemented in endorheic (hydrologically closed) basins such as Punta Laguna (Curtis et al., 1996) and Laguna Chichancanab (Hodell et al., 2005). The presence of rivers suggests that Laguna Tuspán cannot dry out and is less sensitive to droughts than Punta Laguna and Laguna Chichancanab. Maya populations that lived around Laguna Tuspán are not likely to have suffered directly from droughts and the natural site might even have been attractive during Preclassic drought times.

### 2.2. Archaeological context

The first signs of Maya settlement in the vicinity of Laguna Tuspán are dated around 2900 cal yr BP (i.e. 950 BC) (Galop et al., 2004). Most archaeological remains are found on La Joyanca uplands, i.e. on the eastern cuesta. The city was built around 1350 cal yr BP (i.e. AD 600) on the site of a Preclassic-early Classic village (Arnauld et al., 2004; 2013b). La Joyanca was a mid-sized city compared to Classic upper-rank cities as it covered 1.60 km<sup>2</sup> and included 635 structures, or visible mounds, with two 13 m-high pyramids and one stela with a glyphic inscription dated AD 485 in the Maya calendar. After its apogee, La Joyanca suffered a political collapse dated AD 800–850 (Arnauld et al., 2013a), then was gradually abandoned during the Terminal Classic (AD 850–1000) and the Early Postclassic (AD 1000–1100) (Arnauld et al., 2013b). Scattered populations must have resumed maize agriculture close to the city at least by 900 cal yr BP (i.e. AD 1050), as indicated by pollen records in the previous investigation by Galop et al. (2004) of Laguna Tuspán sediments. Maya occupation at this site and in its hinterland (including Laguna Tuspán) lasted at least two millennia, with recent reoccupation dating back to the 1990s (as found out by members of the initial research project).

In terms of the settlement total occupation, the apogee was reached early ca. 1350 BP (AD 600) when 63% of all its 185 dwelling units (most with less than three structures) were occupied simultaneously (Arnauld et al., 2013b). The excavated sample is 40%, with 35% effectively dated ( $n = 185$ ). Even if the time resolution of the La Joyanca chronology (based on ceramics and <sup>14</sup>C, Forné 2006) varies from Early to Terminal Classic phases, the data clearly indicate that there was more than a doubling (30–63%) of occupied units from 1450 to 1350 BP (AD 500–600), suggesting that the settlement population dramatically increased at the end of the Early Classic during a brief period. As no *in situ* natural growth can explain this increase, population influx into the settlement is probable. Then the occupation rate stabilized during Late Classic times, to decrease

gradually during the Terminal Classic and Early Postclassic Periods. Outside of the settlement, in the hinterland, occupation is dense on the eastern cuesta, less so on the Tuspán and Aguacate lakes margins (Fig. 1), but remains undated. Research efforts concentrating on hinterland-cities demography are still scarce (e.g., LeCount and Yaeger, 2010). The La Joyanca case study is highly suggestive of mobilities involving substantial farmers populations having resulted in what can be called “fluctuating cities” (Arnauld, 2013). So far, those dynamics have not been taken in account in paleoenvironmental records obtained in the Maya lowlands.

### 2.3. Lithological description

The present study is based on a 9.75 m-long sediment core, Core Tuspán C, recovered in 2006 using a Russian corer (type GYK) (Jowsey, 1966) at the southern tip of Laguna Tuspán (Fig. 1). It was taken a few meters away from a previous 6.5 m sediment core, Tuspán A, retrieved in 2001 (Fig. 1) and investigated by Galop et al. (2004). Both cores share a common stratigraphy (Fig. 2), and can be divided into two separate units. The lower unit is composed of alternating light and dark, thin (centimetric to subcentimetric) layers (Fig. 2). Continuous downcore changes in concentration of major elements, as measured by automated X-ray fluorescence core scanning (see part 2.5) on Core Tuspán C, indicate that dark (light) layers of this lower unit are mainly of terrigenous and biogenic origin. The upper unit encompasses the top ca. 4.5 m of the sedimentary section. This unit, composed of light colored sediments, is much more homogenous than the lower unit, but is interrupted by four 20 to 50 cm-thick organic-rich layers. These layers stand out with very high amounts of terrigenous particles. They correspond to the classical “Maya clays” or Clay Thick Layers and occur at similar core depths in both cores Tuspán C and A. For easier understanding, Maya clays are labeled CTL A, CTL B, CTL C and CTL D from the youngest to the oldest.

### 2.4. Chronology

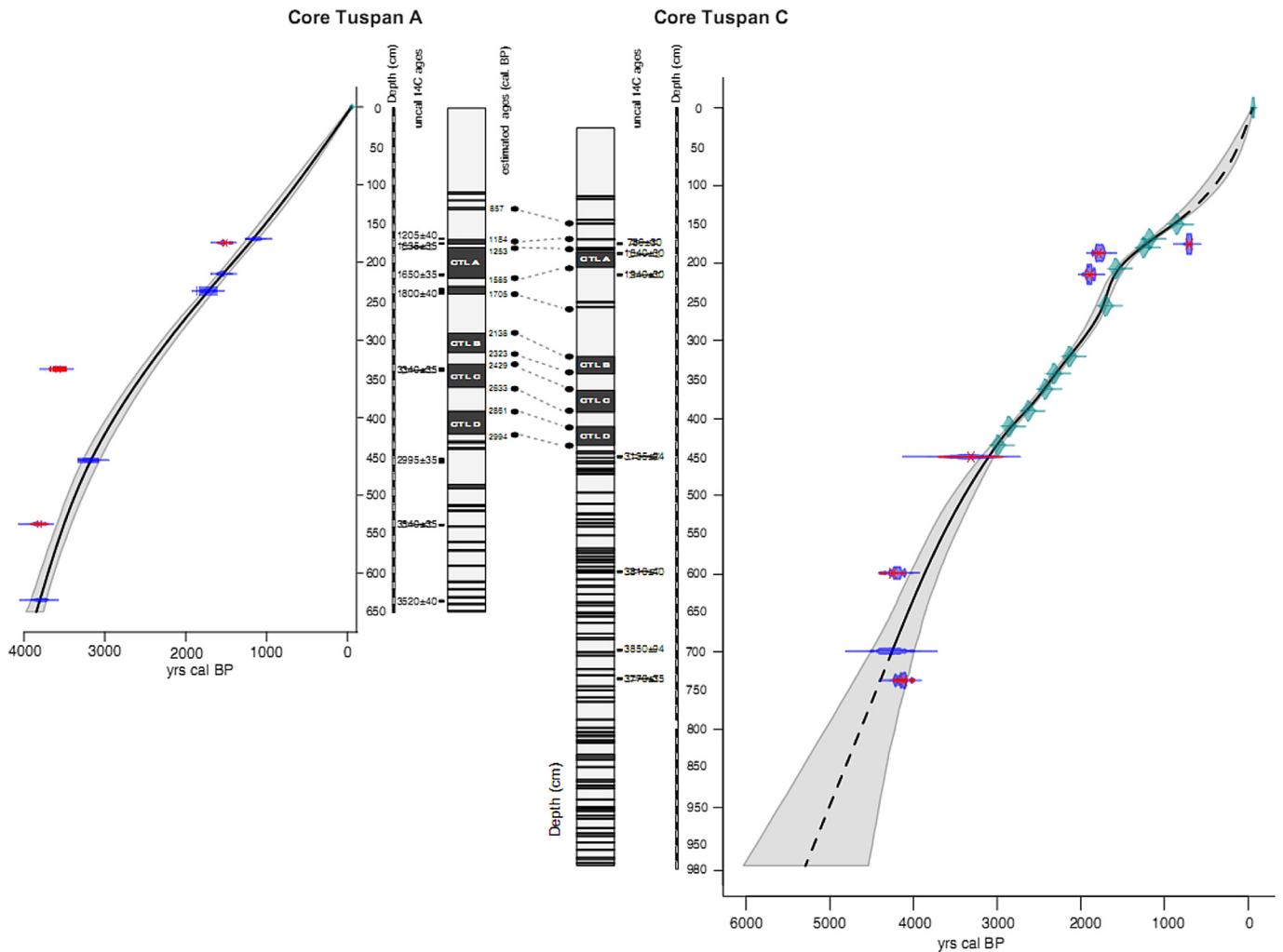
Seven AMS <sup>14</sup>C dates were obtained from vegetal macro-remains in Core Tuspán C (Table 1). Due to reworked material and reversed ages, most of those dates were rejected and the chronology of Core Tuspán C is based on both stratigraphic correlation and the age-depth chronology of Core Tuspán A (Fig. 2), which was established on eight AMS <sup>14</sup>C ages (Galop et al., 2004). The age-depth model of Core Tuspán C was built using the CLAM software (Blaauw, 2010) following the combined accepted AMS <sup>14</sup>C dates and estimated ages provided by the age model from Core Tuspán A (Table 1 and Fig. 2).

The majority of the dated levels are located between 180 and 450 cm, i.e. where the Clay Thick Layers are observed. The age model for the core is much less constrained in the upper and lower parts of Core Tuspán C, which means our interpretations on these parts of the record must be taken with caution. According to the age model, the studied core spans the last 5300 years of sedimentation. The boundary between the lower and the upper units is dated at around 2998 cal yr BP, when the deposition of CTL D starts. CTL D ends at 2846 BP. The three other Maya clays occur between 2640 and 2454 cal yr BP (CTL C), 2289 and 2141 cal yr BP (CTL B), 1544 and 1289 cal yr BP (CTL A). CTL A would correlate with the late part of the Early Classic (i.e., AD 400–600) and the early Late Classic Period (600–700).

### 2.5. Analyses

Prior to sampling, Core Tuspán C was subjected to a non-destructive analysis of its elementary composition using the





**Fig. 2.** Logs of cores Tuspan-A (Galop et al., 2004) and Tuspan-C (this study). Dated levels are shown in calendar ages (cal yr BP). The dark layers are organic matter-rich units, and the white layers are mainly made of authigenic and biogenic calcareous material. CTLs A, B, C, D are the so-called Maya Clay Thick layers. The age model for core Tuspan C (presented on the right panel) is based on dates previously obtained on core Tuspan A (in green) (Galop et al., 2004) and new dates obtained on core Tuspan C for this study (in blue). Red symbols underline rejected dates. The gray shading represents the uncertainty interval for this age model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

AVAATECH XRF core-scanner hosted at EPOC laboratory, Bordeaux University. Among several major elements, downcore changes in Ca and Ti content were selected as proxies of the relative contribution of biogenic vs. terrigenous sediments, respectively.

The core was then sampled every cm, with each sample being split into three subsamples: one for the analysis of ostracode assemblages and clay mineralogy, a second for organic carbon content and stable isotope composition of organic carbon, and a third being kept as archive.

For ostracode analyses, each sample was washed with water at sieve column from 63  $\mu\text{m}$  to 2 mm. The ostracodes were picked between 125 and 850  $\mu\text{m}$ . Census counts of fossil ostracode fauna are reported as number of valves per gram of dry sediment. Beside bulk ostracode abundances, we report on the concentrations of valves belonging to the dominant *Cytheridella* and *Candonopsis* genera. In addition, valves of *Cytheridella ilosvayi* species were selected for isotopic analysis. A minimum weight of 80  $\mu\text{g}$  (i.e.  $\sim 4$  individuals) was necessary for each analysis. After cleaning with distilled water, the ostracods were analyzed and the results were calibrated against PDB using international NBS19 standard. All the analyses were undertaken at the University of Bordeaux 1, using a

Micromass Multiprep autosampler associated with an Optima mass spectrometer. Standard deviation of multiple replicate measurements of the standard is 0.040 and 0.048 per mil for  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  respectively.

Organic carbon content ( $C_{\text{org}}$ ) was measured using a LECO C–S 125 analyzer with a precision of  $\pm 0.5\%$  after treatment of 80–100 mg of sediment with hydrochloric acid to remove calcium carbonate. The carbon isotope composition ( $\delta^{13}\text{C}$ ) of bulk organic matter was determined using a Carlo-Erba CN analyzer 2500 interfaced with a Micromass-Isoprime mass spectrometer available at EPOC laboratory, with a precision of  $\pm 0.3\text{‰}$ .

Clay mineralogy first involved an acid leach with 0.2 N hydrochloric acid. The excess acid was removed by  $\text{H}_2\text{O}$  washing and repeated centrifugations in order to enable clays to deflocculate. The clay-sized fraction ( $<2 \mu\text{m}$ ) was extracting following the method described in Holtzapffel (1985) : clay particles are isolated by settling, and oriented on glass slides (oriented mounts). Three XRD (X-ray diffraction) determinations were performed: (a) untreated sample; (b) glycosylated sample (after saturation for 12 h in ethylene glycol); (c) sample heated at 490  $^\circ\text{C}$  for 2 h. The analyses were run on a Philips PW 1749 X-ray diffractometer, between 2.49

**Table 1**

List of ages available for core Tuspan-A (previously published in Galop et al., 2004; Carozza et al., 2007) and new ages for core Tuspan C (this study).

Site/depths (cm)	Laboratory code	Material	<sup>14</sup> C age	Error	δ13C (‰)	Calibrated age BP (95%) (2σ)	
						Yr min	Yr max
<b>Core Tuspan A (Galop et al., 2004)</b>							
TuA (170)	Vera-2833	charcoal	1205	40	−18.5	1010	1261
TuA (175) <sup>a</sup>	Vera-2547	Vegetal remains	1635	30	−28.2	1417	1607
TuA (215)	Vera-2551	Vegetal remains	2945	35	−29.6	1417	1688
TuA (232–242)	Vera-2832	Vegetal remains	1800	40	−20.7	1613	1855
TuA (335–340) <sup>a</sup>	Vera-2549	Vegetal remains	3340	35	−28.2	3476	3681
TuA (452–458)	Vera-2548	Vegetal remains	2995	35	−34.8	3074	3326
TuA (537) <sup>a</sup>	Vera-2550	Unidentif. seed	3540	35	−26.9	3704	3911
TuA (635)	Beta-166918	Woof fragment	3520	40	−31	3693	3896
<b>Core Tuspan C</b>							
TuC (175–176) <sup>a</sup>	Poz-33644	Vegetal remains	780	30	−30	671	737
TuC (187) <sup>a</sup>	Poz-33643	Vegetal remains	1840	30	−27.6	1709	1864
TuC (214–215) <sup>a</sup>	Poz-33642	Vegetal remains	1940	30	−33.8	1822	1949
TuC (449) <sup>a</sup>	Vera-50874	Vegetal remains	3135	154	−54.1	2946	3699
TuC (598–599) <sup>a</sup>	Poz-33640	Vegetal remains	3810	40	−29.3	4087	4356
TuC (699)	Vera-50877	Vegetal remains	3850	94	−28.9	3985	4517
TuC (736–737) <sup>a</sup>	Poz-33641	Vegetal remains	3770	40	−30.3	3992	4243

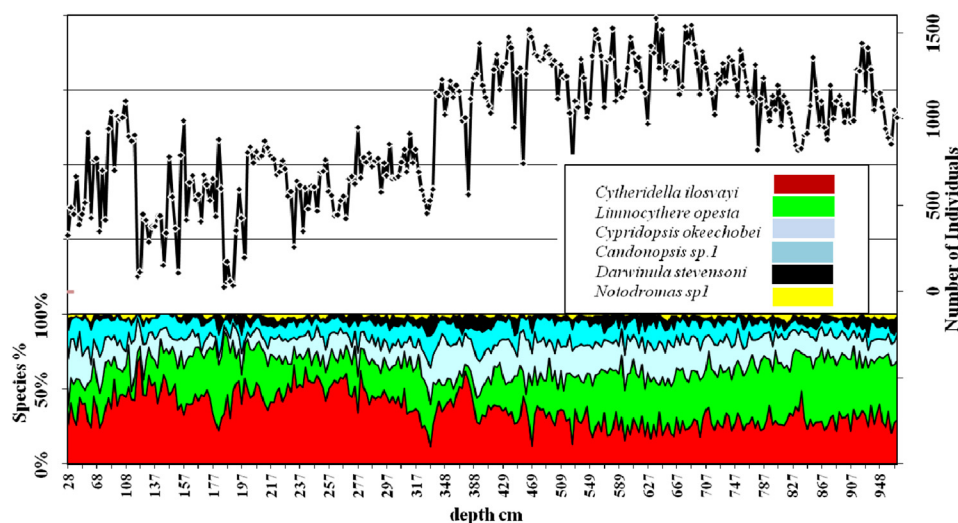
<sup>a</sup> Rejected.

and 32.5°theta hosted at the UMR8217 CNRS Géosystèmes, University Lille 1. Each clay mineral is then characterized by its layer plus interlayer interval as revealed by XRD analysis (Brindley and Brown, 1980). Smectite is characterized by a peak at 15Å on the untreated sample test, which expands to 17–18 after saturation in ethylene glycol and retracts to 10Å after heating. Halloysite-7A is characterized by peaks at 7.3Å, 4.43Å, 3.62Å on the natural and “glycosylated” runs, which disappear after heating. Semi-quantitative estimation of clay mineral abundances, based on the pseudo-voigt integration of the respective basal peaks was performed using the software MacDiff 4.2.5 developed by Petschick (2000).

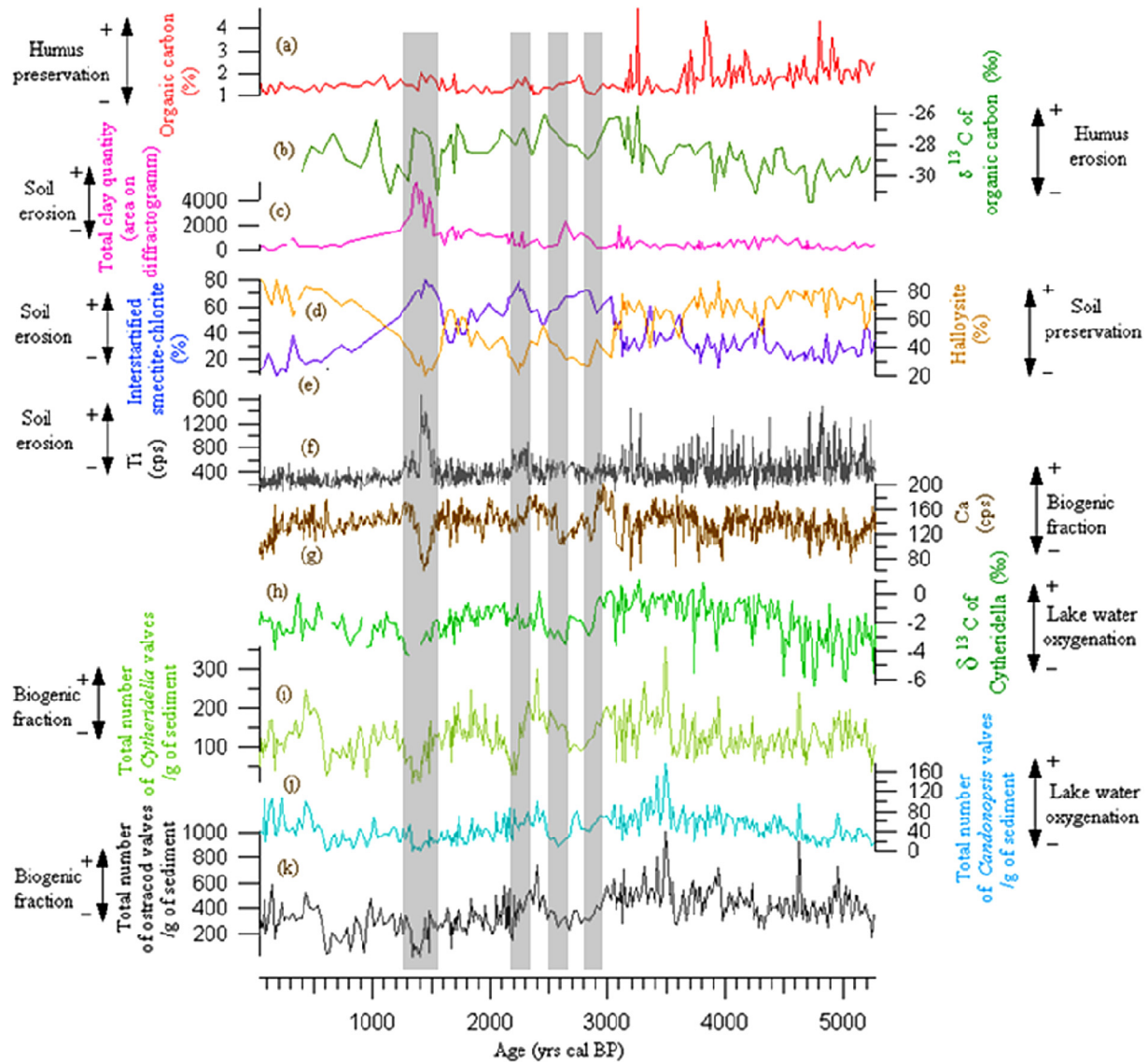
### 3. Results

As mentioned before, most of the proxies presented in our record show distinct patterns between the lower and upper sedimentary units, the last one including Maya clays (Figs. 3 and 4).

The diversity of the ostracode fauna in terms of number of species is relatively stable throughout the core, ranging from 5 to 8 genera. The average total abundance of ostracode valves is higher in the lower sedimentary unit (450 valves per grams) than in the upper one (300 valves per grams). The main ostracode species are *Darwinula stevensoni*, *Candonopsis* sp. 1, *Notodromas* sp. 1, *Cyprretta brevisaepta*, *Cypridopsis okeechobei*, *Limnocythere opesta*, *Cytheridella ilosvayi* (Fig. 3). *D. stevensoni* lives in weakly dynamic waters while *C. okeechobei* prefers dynamic waters. Their distribution appears as antiphasic. *Candonopsis* sp. 1, *Notodromas* sp. 1, *C. brevisaepta* are benthic, sometimes nectic species. *L. opesta*, *C. ilosvayi* are benthic, living in the first mm of the water–sediment interface. These two species live in permanent waters. The ostracofauna is very similar to these living in the laguna Peten-Itza, located about 300 km west from laguna Tuspan (Perez et al., 2010a and Perez et al., 2010b). *C. ilosvayi* is the most abundant species. The second abundant is *L. opesta*, but this species presents different morphologies, leading to a large range of interpretation. The third abundant species, *Candonopsis* sp. 1, is very stable



**Fig. 3.** Abundance (%) of the main ostracode species in core Tuspan C in the lower panel. Normalized number of individuals is represented on the right scale. Species: Tan: *Notodromas*; orange: *Darwinula stevensoni*; blue: *Candonopsis* sp.1; turquoise: *Cypridopsis okeechobei*; green: *Limnocythere opesta*; red: *Cytheridella ilosvayi*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 4.** Analysis performed on core Tusan-C: (a) Organic carbon content, (b)  $\delta^{13}\text{C}$  organic matter, (c) Total clay quantity, (d) Halloysite (%), (e) Interstratified smectite-chlorite (%), (f) Ca content (XRF, counts per sec), (g) Ti content (XRF, counts per sec), (h) Total number of *Cytheridella* valves (per gr of sediment), (i) Total number of *Candonopsis* valves (per gr of sediment) and (j) Total ostracod abundance (valves per g. of sediments). From 2998 to 1289 cal yr BP, four Maya Clay Thick Layers occur, as represented by gray bars in the figure. For each of these layers, proxies in core Tusan C show higher erosion of both soils and humus.

morphologically. Therefore, we have looked more carefully to both species, *C. ilosvayi* and *Candonopsis* sp. 1.

Over the whole sedimentary record, the total number of ostracode valves decreases within each dark lamina of the lower unit, as well as within each Maya Clay Thick Layer. A general decreasing trend in bulk ostracode abundance is observed in sediments earlier than 2998 cal yr BP. Both *Cytheridella* and *Candonopsis* show lower abundances within each dark lamina, as well as within each Maya Clay Thick Layer (Fig. 4). The preference of *Candonopsis* for oxygen-rich waters (Holmes, 1998; Mourguiart et al., 1986), suggests that dark laminae and Maya clays were deposited under oxygen-depleted bottom waters, but not anoxic conditions.

The isotopic signals measured on *C. ilosvayi* valves present different patterns. The isotopic composition of the oxygen in Ostracodes valves ( $\delta^{18}\text{O}$ ) has been successfully applied in previous works, done on some close lakes, for which the only possible changes are through the evaporation/precipitation budget (Curtis

et al., 1996; Hodell et al., 2005). For laguna Tuspán, the  $\delta^{18}\text{O}$  signal exhibits erratic fluctuations, which are complicated to interpret. Indeed, the hydrological setting is quite more complicated than for other Mesoamerican lacustrine environments, with possible inputs from the main river, but also from groundwater inflow coming out from the calcareous plateau. Therefore, although the  $\delta^{18}\text{O}$  signal has been performed, we have decided not to use it, neither to show it.

The  $\delta^{13}\text{C}$  values present mainly negative values all along the core (average  $-1.9\text{‰}$ ). For the lower sedimentary unit, i.e. from the bottom of the record until 3300 cal yr B.P., the  $\delta^{13}\text{C}$  record shows high amplitude variations, together with an increasing trend. For the upper unit,  $\delta^{13}\text{C}$  variations are smoother, and show  $^{13}\text{C}$ -depleted values within each Maya Clay Thick Layers (Fig. 4h).

High-frequency and high-amplitude changes in organic carbon content and Ti concentrations characterize the lower sedimentary unit. Significant increases of both constituents occur within each



darker lamina. These peaks become sparse within the upper sedimentary unit, with the exception of the intervals represented by the Maya Clay Thick Layers. While the organic carbon content within these layers is lower than the one reached in the lower unit, amplitude changes in Ti concentrations increase throughout the successive Maya clay layers, reaching its maximum value for CTL A (Fig. 4f). The Ca record shows a reverse pattern to the organic carbon content and Ti concentration within both the lower and upper sedimentary units (Fig. 4g). Such an opposite pattern may merely be induced by dilution. Meanwhile, the lower amplitude of organic carbon variations within the latest CTL A is at odd with the behavior of Ti and Ca for which the most prominent variability occurs within this terminal Maya Clay Thick Layer.

Stable isotope ratios of the organic fraction were measured in order to constrain the origin of the organic carbon.  $\delta^{13}\text{C}_{\text{org}}$  display low values ranging from ca.  $-25$  to  $-30\text{‰}$  (Fig. 4b). The organic matter is less  $^{13}\text{C}$ -depleted in sediments later than 3300 cal yr B.P. The  $\delta^{13}\text{C}_{\text{org}}$  reaches higher values of ca.  $-25\text{‰}$  close to or within Maya Clay Thick Layers. According to Powers and Schlesinger (2002) and Amiotte et al. (2007), isotopic ratios of  $-26\text{‰}$  and  $-28\text{‰}$  are characteristic of the carbon isotopic composition of soils and litters, respectively. Accordingly, the contribution of humic material to sediments in Laguna Tuspán is predominant during the time interval spanned by the lower, highly laminated sedimentary unit, while soil inputs characterize the sedimentation later than 3300 cal yr BP. Humus are made of terrestrial plant macro-remains, especially leaves, and cover soils over the uplands surrounding the lake. The less  $^{13}\text{C}$ -depleted values measured within the Maya Clay Thick Layers are probably indicative of stronger erosion in the uplands. Our results therefore indicate that the deposited organic matter is mostly allochthonous to Laguna Tuspán, being brought from the limestone cuesta uplands by river discharge or runoff. The recorded peaks in organic carbon downcore Tuspán C are interpreted as an increase in terrigenous input rather than an increase in biological production by lacustrine organisms. For the latest Clay Thick Layer (CTL A), the terrigenous material was depleted in organic carbon.

The total clay abundance is the highest within the four Maya Clay Thick Layers, peaking within the youngest one (CTL A) (Fig. 4c). The clay fraction is mostly composed of halloysite and interstratified smectite-chlorite. Halloysite is the dominant mineral species before 2998 cal yr BP, between 1830 cal yr BP and 1615 cal yr BP, and from 1240 BP to the top of the core (Fig. 4d). Interstratified smectite-chlorite dominate the clay assemblage between 3064 and 1240 cal yr BP (Fig. 4e), and peaks within each Maya Clay Thick Layer. Variations of interstratified smectite-chlorite abundance mirrors variations in both Ca concentrations and ostracode assemblages. As for Ti concentrations, discrepancies in clay abundance and composition can be observed between Maya Clay Thick Layers A and B, and Maya Clay Thick Layers C and D. Contrary to Clay Thick Layers A and B, Clay Thick Layers C and D do not coincide with a strong increase in clay abundance and organic carbon percentages. In addition, Clay Thick Layers C and D show higher halloysite percentages than in Clay Thick Layers A and B.

#### 4. Discussion

Drastic changes are observed in the vertical distribution of all investigated proxies in Core Tuspán C. Major transitions in sedimentary history are observed at ca 2998 cal yr BP (1048 BC), and, although to a minor extent, at ca. 1289 cal yr BP (AD 661). Our proxy records appear to be essentially affected by changes in the erosive process of the limestone cuesta uplands surrounding the lake. Rapid and extensive erosional events occurred frequently within the period spanning the earlier sedimentary unit of the core, with

no less than 36 events distributed between 5281 and 2998 cal yr BP. In contrast, the four Maya Clay Thick Layers are the only significant erosional intervals between 2998 and 1289 cal yr B.P.

##### 4.1. Record of natural climatic variability for the lower unit

The earlier sedimentary units can be divided into two different environmental settings by an age boundary at 3609 cal yr BP. Before 3609 cal yr BP, halloysite represents more than 60% of the clay fraction in all layers, with the exception of the one layer deposited around 4317 BP (Fig. 5a). High abundance of halloysite is often related to the presence of superficial soils under highly variable climatic conditions characterized by alternating episodes of high precipitation and severe drought (Cabadas-Baéz et al., 2010; Kleber et al., 2007; Niewenhuyse et al., 2000). Floods often occurred during this ca. 200 year-long period as confirmed by recurrent high values of Ti and organic carbon contents (Fig. 4c and f), revealing strong inputs of terrigenous material into the lake via runoff from the cuesta.

Between 3609 and 2998 cal yr BP, halloysite is still dominant but generally with a lower contribution to the clay mineral assemblage, therefore reflecting relatively drier climatic conditions. Less frequent peaks in Ti and  $\text{C}_{\text{org}}$  contents, an overall lower contribution of these constituents to the sediment, as well as increasing  $\delta^{13}\text{C}_{\text{org}}$  values can be related to less frequent flood events. A progressive decrease in humus thickness here indicates drier climatic conditions.

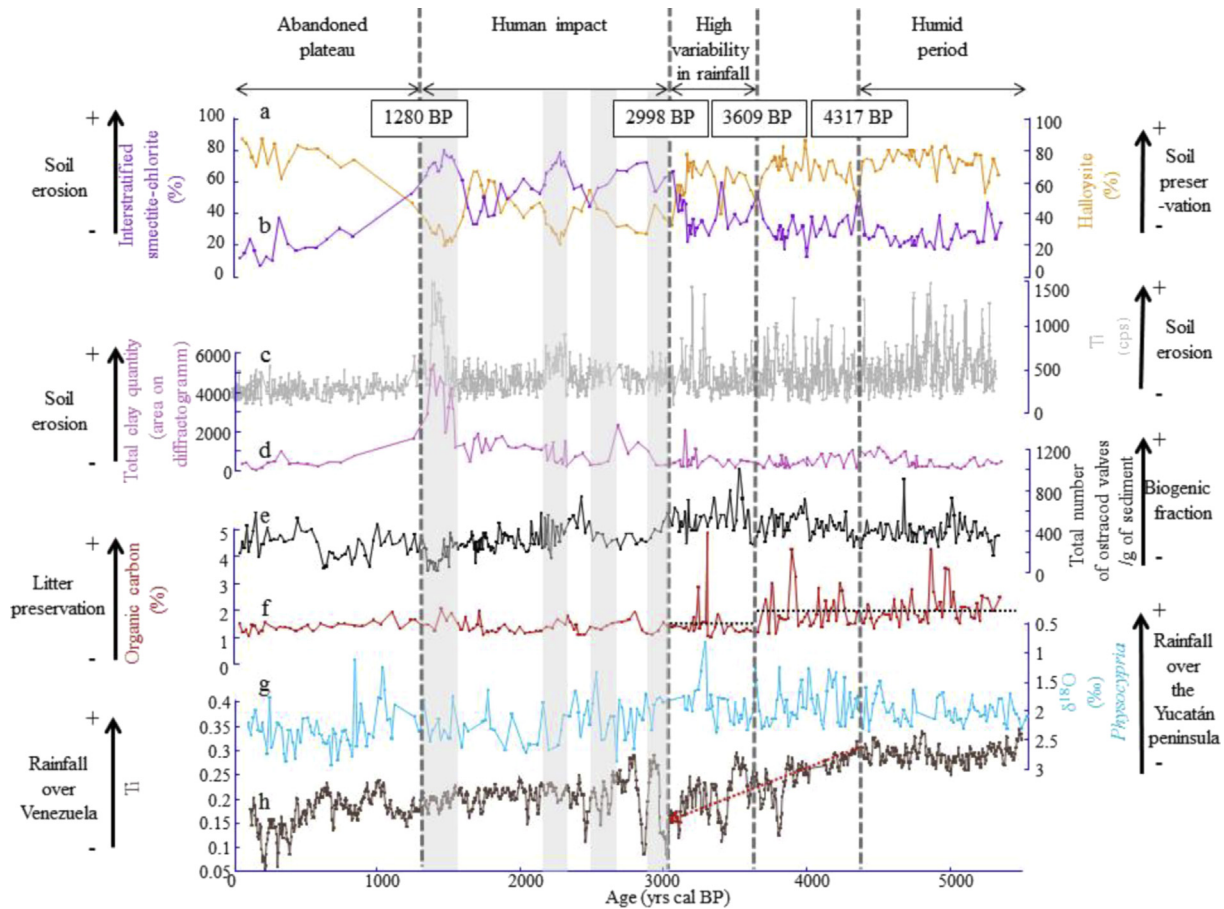
The climatic pattern inferred from our proxy records agrees with other paleoenvironmental records for the Yucatán peninsula. In particular, the  $\delta^{18}\text{O}$  measured in valves of the ostracode *Physocypria* from the endorheic Laguna Chichancanab (Hodell et al., 2005, Fig. 5g), a precipitation proxy associated with changes in lake level, are indicative of drier and more variable climate conditions over the Yucatán peninsula for periods younger than 3600 cal yr BP. Also, within the wider Caribbean Sea, some records are pointing to drier conditions between 3800 and 2800 cal yr BP (see Malaizé et al., 2011 for an overview). This is clear in the high-resolution elemental (Ti) record obtained in the Cariaco Basin record (Haug et al., 2003, Fig. 5h) where the continuous decrease between 3600 and 2800 cal yr BP reflects a drying trend related to lower influence of the Intertropical Convergence Zone which crosses both Cariaco Basin and Maya lowlands in boreal summer. Even though the main drying trend is observed between 3600 and 2800 cal yr BP, the Ti signal in Cariaco basin already started to decrease around 4300 cal yr BP (Fig. 5h), which corresponds to the first decrease in halloysite percentage seen in our record (Fig. 5a).

The apparent coherence from ca. 5281 to 2998 cal yr BP between sedimentary patterns in Laguna Tuspán and climate variability over the Yucatán Peninsula and the surrounding marine realm rules out the influence of human occupation on the sediment budget of the Laguna during this time period, and agrees with the proposed date for the earliest settlement of Maya populations in this area (i.e. 2900 cal yr BP (950 BC) (Galop et al., 2004).

##### 4.2. Imprints of human colonization

All proxy records obtained in Core Tuspán C point to a major change in sediment constituents and associated environmental settings of the lake area around 2998 cal yr BP. This time period corresponds to the occurrence of the earliest Maya Clay Thick Layer, CTL D.

The decrease in bulk ostracode abundance in sediments from Laguna Tuspán after 2998 cal yr BP, which is additionally expressed within each Clay Thick Layer (Fig. 5e), is thought to be induced by the dilution of the carbonate valves by terrigenous particles as well



**Fig. 5.** Comparison between core Tuspan-C, laguna Chichancanab (Hodell et al., 2005) and Cariaco basin (Haug et al., 2003). (a) Halloysite (%), (b) Interstratified smectite-chlorite (%), (c) Ti content (XRF, counts per sec), (d) Total clay quantity, (e) Total ostracod abundance, (f) Organic carbon content, (g)  $\delta^{13}\text{C}$  of Physocyprina (ostracod) valves ((Hodell et al., 2005), (h) Ti content in Cariaco basin (Haug et al., 2003). Gray bars correspond to Maya Clay Thick Layers. For ages later than 2998 cal yr BP, the climatic signal is erased by anthropic-induced erosion in core Tuspan C.

as by a deterioration of living conditions. Both causes are related to erosional events. Maya Clay Thick Layers can be interpreted as traces of erosional processes. Erosion locally induced oxygen depletion in bottom waters, as indicated by the record of the oxygen-sensitive ostracode genus *Candonopsis*. It implies also a reduction in the photosynthesis activity, as revealed by the  $\delta^{13}\text{C}$  signal of *C. ilosvayi* valves. Indeed, high photosynthesis strongly influences the isotopic composition of the dissolved inorganic carbon (DIC) pool, because of preferential incorporation of  $^{12}\text{C}$  in the organic matter. This is reflected by the composition of the ostracods which use the  $^{13}\text{C}$ -enriched DIC to build their shells. The  $^{13}\text{C}$ -depleted values observed within each Maya Clay Thick Layers can be interpreted as a reduction of photosynthesis, but also as oxygen depletion in bottom waters, which would increase bacterial decomposition of the organic matter, and subsequent release of low  $^{13}\text{C}$ -bearing carbon, clearly contributing to shift in the isotopic composition of the DIC.

High terrigenous input past 2998 cal yr BP are confirmed by the high contribution of the total clay fraction to sedimentation in Laguna Tuspán. Despite observed discrepancies for Clay Thick Layers C and D, clay abundance shows its highest values within Clay Thick Layers A and B, together with high Ti concentrations (Fig. 4c, d). The final Clay Thick Layer (CTL A) is characterized by the highest recorded contributions of clays and Ti to the bulk sediment. A drastic change in clay mineralogy after 2998 cal yr BP, from halloysite to interstratified smectite-chlorite (Fig. 4a, b), also calls for

the setting up of extensive erosional and alteration processes in the drainage basin of the lake (Guyot et al., 2007). Indeed, while halloysite usually derives from superficial soils (Kleber et al., 2007; Niewenhuyse et al., 2000), interstratified chlorite-smectite is either a product of calcite precipitation through palygorskite neoformation (Owliaie et al., 2006) or is formed through the underwater alteration of volcanic tephra (Hodder et al., 1993). The Petén area is mainly composed of limestones (Cosillo, 2008), which is in favor of the first hypothesis, but recent findings of ash layers in other aquatic environments in Central America (e.g. McNeil, 2012) show that the second process may also have been involved. Although erosional processes are the main candidates for the origin of Clay Thick Layers A and B, other mechanisms might be involved in the deposition of Clay Thick Layers C and D. Indeed, volcanic tephra have been found in some of these Clay Thick Layers. Unfortunately, these glass could not be chemically fingerprinted because most elements were already leached from the glass (Kees Nooren, personal communication). Further analyses are needed to investigate these observed lithological differences.

The  $\delta^{13}\text{C}_{\text{org}}$  record obtained from Core Tuspán C additionally suggests an overall loss of humus on the limestone cuesta during the Maya period, a loss which was particularly critical during the time periods spanning the Clay Thick Layers (Fig. 4b).

Vegetation changes induced by soil management by Maya populations during this critical period triggered the observed erosional process. In swidden agriculture (e.g. shifting, slash and

burn, milpa agriculture) even a slight increase in population density would have resulted in shifts like shortening of fallow time and more frequent burning, strongly impacting vegetation and soils (McNeil, 2012). In addition, pollen spectra obtained in the twin core Tuspán A by Galop et al. (2004) indicate that, starting around 2900 cal yr BP, when Maya people first settled the region, farming practices cleared more forest, with people seeking to expand cultivated surface in the La Joyanca uplands (Galop et al., 2004). The loss of trees would reduce humus thickness, and enhance runoff on destabilized soils (Barré et al., 2009). Soil management and forest clearance probably contributed to intensified erosion (Anselmetti et al., 2007).

Maya Clay Thick Layers A and B contain relatively high amounts of clays, even though Clay Thick Layer B was deposited well before the expansion of La Joyanca village by AD 600 (i.e. 1350 cal yr BP) (Arnauld et al., 2013b), indicating that erosion was intense before urbanization started. The most recent Maya clay (CTL A) stands out by its amplitude (Fig. 4c and d) and must be viewed as the most intense erosional event recorded in the Laguna Tuspán area. It was deposited between 1544 and 1289 cal yr BP (406–661 AD), i.e. just before and at the onset of the strong demographic growth and the construction of masonry buildings in La Joyanca city which took place from AD 600 on, as indicated by recent fieldwork (Arnauld et al., 2013b).

Following CTL A, halloysite contribution to the total clay assemblage recovers to levels similar to those of the period which preceded the settlement of Maya populations (>60% of the clay fraction) (Fig. 5a). This post 1289 cal yr BP interval was therefore characterized by a progressive soil recovery after the last Maya clay was deposited, a recovery which is explained by the local abandonment of swidden agriculture, or by drastic decrease in fallow rhythm and forest clearance. This change in human activity is confirmed by a local forest expansion, as revealed by pollen spectra obtained from the twin core Tuspán-A (Galop et al., 2004). This was made possible by intensive agricultural land use developed within the La Joyanca settlement and close fields on the eastern cuesta (Lemonnier, 2009) that accompanied urbanization (Arnauld, 2013).

A last peak of total and interstratified clay abundance is noted around 1007 cal yr BP (i.e. 943 AD), that is during the Terminal Classic phase of La Joyanca gradual abandonment. By that time, in many Maya cities, the population reverted to a rural way of life and must have settled back around the lakes (Arnauld et al., 2004).

#### 4.3. Erosion rates and population migration

Amidst results from the present study is the marked decrease in the human land use of Laguna Tuspán surroundings around 1289 cal yr BP (661 AD). It should be stressed that our sediment record, which bears a strong imprint of human activity, is hardly conclusive in terms of climatic changes during this period. Records such as the one obtained from Cariaco Basin, located more than 2000 km away, but depending on the same meteorological pattern, i.e. the latitudinal migration of the Inter-Tropical Convergence Zone (ITCZ) (Haug et al., 2003), suggest no drastic changes in precipitation budget over Central America ca. 1289 cal yr BP (Haug et al., 2003, Fig. 5h). The local abandonment or decrease in agricultural activities on lakeshores and slopes surrounding Laguna Tuspán was therefore not triggered by climatic changes, as originally suggested by Galop et al. (2004).

The Classic mobility from the lake surroundings could have been directed by the authorities of La Joyanca city. Indeed, the city saw a burst of monumental construction, which certainly required manpower, from 1350 cal yr BP (AD 600), during the Late Classic Period (Arnauld et al., 2004). By that time, the Maya hegemonic capitals, Tikal and Calakmul, were fighting for power in the Petén

area (Demarest, 2004; McAnany and Gallaretta, 2010; Yaeger and Hodell, 2009). Local populations may have looked for protection by gathering in the southeastern corner of La Joyanca plateau. The city also provided prosperity and better dwelling conditions (under the form of masonry houses), and may thus have attracted the population previously settled around Laguna Tuspán. Still open to debate and to further research is the issue of conscious action taken by Maya authorities to solve the soil erosion problem by concentrating population and agricultural land use into nucleated settlements. Urbanization is generally dated by early Late Classic times all over the Petén lowlands, or even earlier. In Western Petén not far from La Joyanca, similar mobilities into Piedras Negras and Yaxchilan from hinterlands have been dated AD 350 (Golden and Scherer, 2013).

Our paleoenvironmental record therefore shows a parallel evolution of soil erosion and human density around Laguna Tuspán. The earliest Maya Clay Thick Layer (CTL D) occurred synchronously with the first evidence of human agriculture (maize crops) (Galop et al., 2004). Erosional processes increased thereafter as evidenced by the increasingly higher contribution of clays to CTLs C, B and A, even with slight growth in local human density, as previously observed for other places in Petén, e.g. around Lake Salpetén (Anselmetti et al., 2007). However, as soon as the population left the surroundings of Laguna Tuspán, apparently to concentrate within the neighboring city, erosion ceased, and the environment returned to more natural conditions with reforestation and soil recovery. Soil recovery is seen as a consequence of a population movement towards the uplands in a local urbanization process that occurred at least 200 years before the general collapse of Maya cities. In turn, such a drastic variation suggests that this mobility of Maya farmers was associated with a marked shift in agricultural strategy during the Classic Period.

#### 5. Conclusion

The multi-proxy analysis of sediment Core Tuspán C shows three distinct periods spanning the past 5300 years.

A pre-human period, from 5300 to 2998 cal yr B.P., records natural climatic variations. Alternating droughts and precipitations prevailed for the earlier 1670 years. Droughts seem to have lasted longer and to have been more intense between 3609 and 2998 cal yr BP. Both periods are characterized by moderate erosion, owing to a dense forest cover producing thick litters and stabilizing soils. The Maya period (from 2998 to 1289 cal yr BP) illustrates the impacts of human presence on the environment, with the occurrence of four distinct Maya Clay Thick Layers dated to the Preclassic and Early Classic Periods of the Maya culture chronology. These layers are mainly composed of interstratified smectite-chlorite, revealing increased substratum weathering. Humus thickness and forest density were then much reduced, as previously reflected by pollen analysis (Galop et al., 2004), which enhanced soil destabilization. For each Maya Clay Thick Layer, Laguna Tuspán received much more detritic particles than during the pre-human period, and living conditions in the lake turned to oxygen-depleted waters. The most recent Maya clay deposit is the most massive one and ends at 1289 BP (AD 661). This drastic change is correlated with a population movement into the La Joyanca city, where monumental construction started by AD 600. Both processes have been independently assessed and dated through archaeological proxies (Arnauld et al., 2004, 2013a and b). Environmental recovery starts well before the abandonment of La Joyanca, that is, as soon as human land use strongly decreased in the immediate surroundings of the lake.

The erosion rate was directly linked to human activities around the lake. According to our record, the erosion rate increased with



human density in small settlements dispersed across the hinterland, the latest Maya Clay Thick Layer being the most erosive one, although the earlier clay layer already marked a drastic change in the environment around Laguna Tuspán. In other paleolimnological records, such as the one from Lake Salpetén, the early Maya settlement leads to the strongest erosive horizon in the neighboring lake, whereas erosion drops to reasonable levels while the population density reaches its maximum in nucleated settlements (Anselmetti et al., 2007). The comparison points out to land use and settlement variations in the Maya Lowlands that must be acknowledged to explain the diversity of responses by Maya societies to environmental constraints.

One of the most important results of the present study highlights and confirms the abandonment of Laguna Tuspán lakeshores at least two centuries before the abandonment of Maya cities in the Petén area. As originally suggested by our previous analysis (Galop et al., 2004), paleolimnological records must take into account the complex socio-ecological process linking urban developments and adjacent agrarian hinterlands that developed several centuries before the so-called “Maya collapse”. Rather than caused by a climatic change, population mobility from lakeshores to La Joyanca was probably linked to socio-political changes in the area, reflecting an increase in insecurity dragging the population to find protection in the La Joyanca nucleated settlement, a need for better life in masonry buildings, and a drastic shift in agricultural strategies. More sediment cores from the Central lowlands, especially from Petén, the region where the collapse was the most dramatic, are needed to fully understand the crisis that the lowland cities went through by AD 800–1050.

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