



Nixtun-Ch'ich' and its environmental impact: Sedimentological and archaeological correlates in a core from Lake Petén Itzá in the southern Maya lowlands, Guatemala

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ABSTRACT

Sedimentological information obtained from lake sediment cores has long been used to show how the Maya impacted their environment. Although general trends are usually observed, direct correlation of construction, deforestation, and abandonment of cities is hindered by poor chronological correlation between sedimentary and archaeological data. We report on findings from a 515-cm core covering the last ~7000 years of sedimentation that displays remarkable correlation between the two. The core was extracted from Lake Petén Itzá (Department of El Petén, northern Guatemala) immediately adjacent to Nixtun-Ch'ich', a long-lived (ca. 1300 BCE–1750 CE) southern lowland Maya site. Chronological precision for the core was achieved by an age-depth model based on Bayesian statistics and corroborated by dates from archaeological excavations. This model, based on six radiocarbon dates and integrated with physical (magnetic susceptibility) properties and scanning XRF analysis of elemental (Si, Fe, and Ti; also Sr and Ca) constituents, permits exceptionally precise correlations with independently dated constructional activity at Nixtun-Ch'ich'. Erosion resulting from the Middle Preclassic (800 to 500 BCE) creation of the site's atypical urban gridded landscape is prominently registered in the core. Other sediment changes at the end of the Late Preclassic period (ca. 50–200 CE) may be drought-related and reflect local expression of a "Late Preclassic Maya collapse," suggesting new avenues for archaeological exploration. This study highlights the potential of lake sediments, continuously recording human activities in the catchment, as faithful registers of subtleties unrecovered archaeologically. Detailed analyses of sediments deposited close to sites' drainage pathways may reveal intricate correlations such as those observed here, and shed light on cultural activities and environmental and living conditions undetected in the archaeological record.

1. Introduction

Paleolimnological investigations into long- and short-term climate changes and the impacts of human settlements on their environments are increasingly common in the Maya lowlands (the Yucatán Peninsula [Mexico], northern Guatemala, and Belize) and throughout the world. Chronological frameworks for interpreting climate changes from cored lake sediments are often rife with uncertainties resulting from radiocarbon error variations, indeterminacies in the calibration curve, hard-water error in some circumstances, and other factors. Such age uncertainties even beset cores sampling annual varves, which seemingly would reduce matters to a simple matter of counting (Fortin et al., 2019; Vandergoes et al., 2018).

In studies of human impacts on the environment, general

correspondences and trends are sought between gross changes in the physical properties and the biological and chemical constituents of cored sediments, and independently acquired archaeological dates on occupations and terrestrial events. Here we present data showing exceptionally precise chronological correlations between activities at the gridded lowland Maya lakeshore site of Nixtun-Ch'ich', in the Department of El Petén, Guatemala, and the deposition of eroded materials into Lake Petén Itzá.

1.1. Lake Petén Itzá and paleolimnology

Lake Petén Itzá is the largest (~100 km²) and deepest (165 m) of eight lakes in the "central Petén lakes region," an east-west line of variably sized closed basins at about 17.5° N latitude. These lakes were

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formed by the filling-in of karst depressions along a fault separating interbedded marine carbonates (limestone, dolomite, gypsum, marls) of Paleocene-Eocene age to the north, from Late Cretaceous to Tertiary age carbonates to the south (Brenner, 2018; Hodell et al., 2004). The second largest lake in Guatemala and the deepest in the Central American lowlands, Lake Petén Itzá receives about 1550 mm of highly seasonal rainfall annually. Its rich tropical forest surroundings attracted occupation to its islands and peninsulas and around its shores from the Late-Terminal Early Preclassic periods (ca. 1300–900/800 BCE) through the present day (Rice and Rice, 2018). Similar occupation histories characterize the other lakes, making them attractive targets for high-resolution studies of long-term human alterations of the environment.

Beginning in the mid-1960s, occasional paleolimnological studies were carried out in the Petén lakes district (Brenner, 2018: 43), first in tiny, shallow Lake Petenxil (0.5 km², $z_{\max}$ 4 m; Cowgill et al., 1966), then to the east in larger Lakes Yaxhá (7.4 km², $z_{\max}$ 27 m) and Sacnab (3.9 km², $z_{\max}$ 13 m; Deevey et al., 1980; Deevey et al., 1979), smaller Macanché (2.5 km², $z_{\max}$ 80 m; Vaughan et al., 1985), and Quexil (2.2 km², $z_{\max}$ 32 m) and Salpetén (2.9 km², $z_{\max}$ 38 m; Brenner, 1994; Leyden, 1984, 1987; Rosenmeier et al., 2016). Many of these projects sought environmental histories and tropical climate changes dating to Late Pleistocene times, long preceding human settlement. Coring of Lake Petén Itzá, for example, revealed sedimentation processes reaching back 85,000 years (Anselmetti et al., 2006; Hodell et al., 2006; Hodell et al., 2008; Hodell et al., 2012; Mueller et al., 2009). Other limnological studies focused on more recent—last 400 years—activity (Pérez et al., 2010; Rosenmeier et al., 2004). All were directed toward identifying general trends of environmental change and human impacts, including evidence of early forest removal for swidden agriculture and later deposition of thick, siliceous “Maya clay” resulting from heavy Classic-period (200–950 CE) construction. These and related studies (e.g., of lowland speleothems; Webster et al., 2007) typically do not seek or discuss direct correlations with specific, dated, cultural events aside from climatic (drought) causes of the Late Classic southern lowland Maya “collapse” (e.g., Douglas et al., 2016; Dunning et al., 2012).

1.2. Nixtun-Ch'ich' and its history

Nixtun-Ch'ich' is a medium-large (ca. 2 km²) Maya city on the western edge of the small southern body of Lake Petén Itzá. Occupying the mainland south of the steep escarpment that forms the lake's northern shore, the site also extends over the ~1 km-long Candelaria Peninsula to the east (Fig. 1).

Archaeological excavations and mapping at Nixtun-Ch'ich', carried out sporadically beginning in the middle 1990s and continuously since 2013, have revealed stratified occupation and construction dating from the Late and Terminal Early Preclassic periods through Middle and Late Preclassic (ca. 800 BCE–200 CE), and Classic times. The site's urban core (1.02 km²) is unusual for its strongly gridded layout created by multiple intersecting corridors that define 52 trapezoidal constructional blocks or sectors (Pugh, 2018; Pugh and Rice, 2017; Rice and Pugh, 2017). This grid, dense construction, and overall layout make Nixtun-Ch'ich' unique among Maya centers, which characteristically exhibit dispersed settlement, and the site plan has been proposed to resemble the dorsal surface of a crocodile, specifically a mythical “starry-deer crocodile” of world creation (Rice, 2018).

Occupation of Nixtun-Ch'ich' continued into the Postclassic (ca. 950 CE/1000–1525) period and through the next tumultuous century and a half of internal conflicts and unsuccessful Spanish pacification efforts in the region. Lake Petén Itzá and its surroundings were dominated by the Itza Mayas from their island capital Tayza (or Nojpeten), modern Flores Island in southern Lake Petén Itzá (Fig. 1; Jones, 1998; Rice and Rice, 2018). Nixtun-Ch'ich' was occupied by the Chak'an Itzas, a dissident western Itza faction allied with the Kowoj, the Itzas' enemies to the

east (Pugh et al., 2016; Rice and Rice, 2009). In 1697 the Spaniards finally conquered the Itzas through a waterborne attack on Tayza launched from Nixtun-Ch'ich' (Jones, 1998), and a mission community and church were established on the tip of the Candelaria Peninsula in the early eighteenth century (Rice, 2009). Thus Nixtun-Ch'ich', today the site of a cattle ranch, is one of the earliest and longest continuously occupied cities in Petén, its gridded sacred landscape maintained up to the present.

Several points about Nixtun-Ch'ich' are of particular interest with respect to sediment coring. First, the city was constructed on elevated limestone bedrock rising approximately 15 m above Lake Petén Itzá's notoriously fluctuating water level: current stage is about 115 m amsl but it has risen and fallen 4–5 m twice since the 1970s. The grid corridors, ten north–south “avenues” (named A–J west to east) and six east–west “streets” (First through Sixth, south to north), facilitated orderly movement through the community, as they do in ancient and modern cities in general (Pugh, 2018). Importantly, they also channel rainwater from heavy seasonal tropical downpours as well as detritus and erosional materials away from the city center. These are swept down to bodies of water lying to the northeast (Ensenada San Jerónimo) and south: an unnamed western “finger” of Lake Petén Itzá south of the Candelaria Peninsula. Second, radiocarbon dates from excavations to bedrock in these streets and avenues, particularly around the civic-ceremonial core of the site, revealed that the distinctive urban grid was put into place in the Middle Preclassic period, between 800 and 500 cal. BCE (Table 1; Pugh, 2018; Pugh and Rice, 2017). These points about the city's drainage and construction, plus its long occupation and location on a large lake, make it ideal for paleolimnological investigation.

2. Materials and methods

In July 2018, we visited Flores to take cores from Lake Petén Itzá in the vicinity of the site of Nixtun-Ch'ich'. Two coring sites were selected and two cores were extracted; the initial findings from one, PI-1, are reported here.

The PI-1 sediment core was collected using two modified piston corers—one specialized for mud-water interface sediments (Fisher et al., 1992) and the other for consolidated sediments—from a wooden platform mounted on two *lanchas* (motorized canoes). The core was taken immediately south of Nixtun-Ch'ich' in the waters of the narrow, fingerlike, western extension of the lake, 7 km long and 250–450 m wide. This extension originates as a small stream (Riachuelo Pixoyal) feeding into a low catchment west of Nixtun-Ch'ich' and moves sluggishly eastward, widening before joining the lake. The site for coring was positioned about 200 m south of the southern edge of the Candelaria Peninsula and about 300 m east of an imaginary southward continuation of easternmost Avenue J of the site grid (see Fig. 1). This location (UTM 16Q 187,675 m E, 1,875,639 m N; 16°56'37"/89°55'56"), in 8.4 m of water, was deemed appropriate for capturing erosional materials channeled into the shallow waters by the city's “avenues,” with minimal subsequent sediment movement by currents.

A mud-water interface core was first collected from the side of the platform to a depth of 72 cm. This core was extruded in the field, sectioned at 2.0 cm intervals, and the sections placed in Whirl-Pak bags to preserve water content. Next, a casing of PVC pipes was introduced through the center of the platform and lowered until it intruded the sediments to a depth of 50 cm. The 50 cm of sediments were cleaned using the modified piston corer to reduce friction during subsequent coring drives. Once this casing was set and cleaned, six sequential core sections were obtained to a measured depth of 515 cm. These sediments were kept inside polycarbonate tubes and transported to the field laboratory and then to the United States for further analysis. All analyses reported here were carried out on the core from 50 to 515 cm. [The first 50 cm were not analyzed as they were stored in plastic bags in the field to preserve water content for future analyses.]

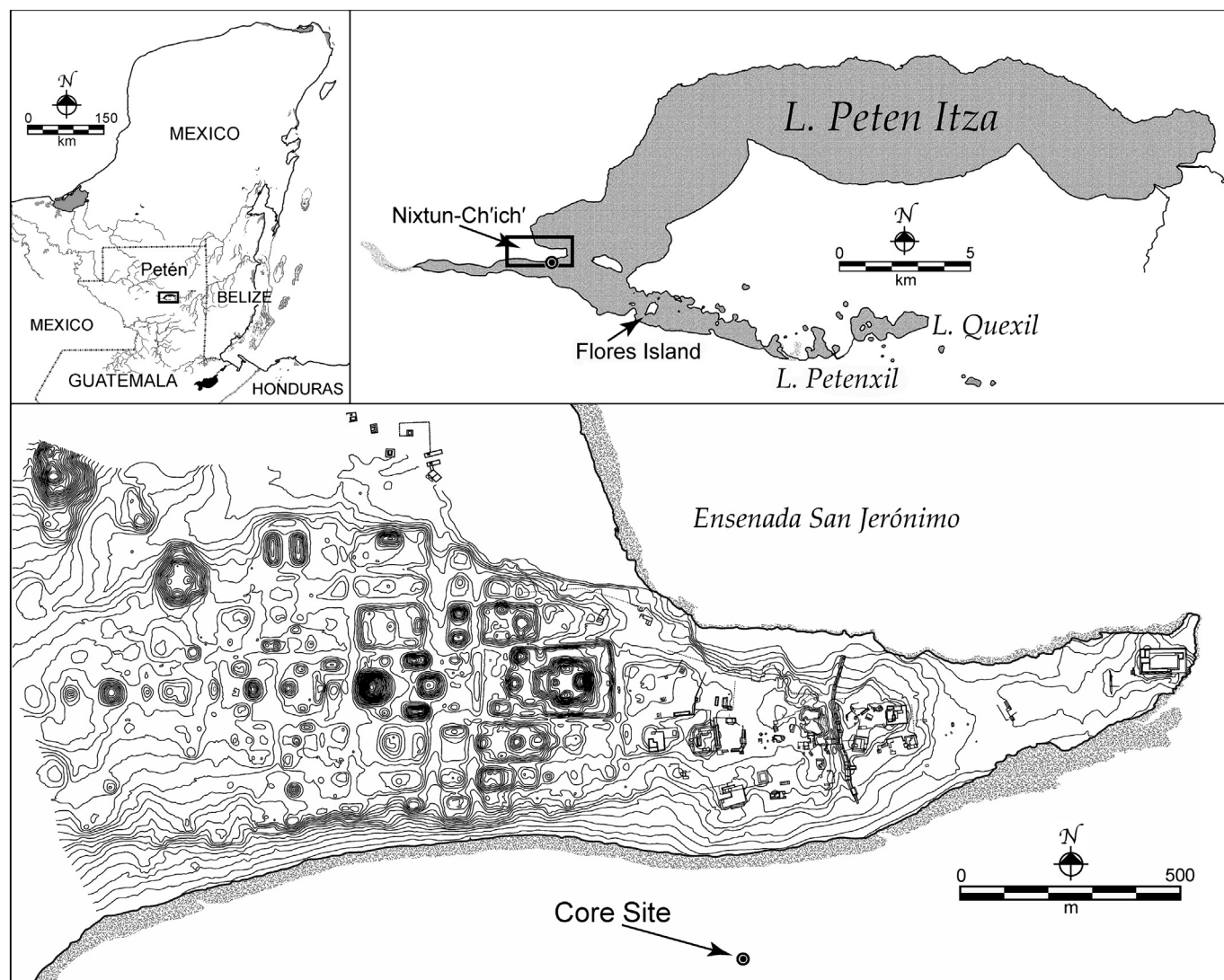


Fig. 1. Lake Petén Itzá and the site of Nixtun-Ch'ich' in Petén, Guatemala. The long north–south structure east of the base of the Candelaria Peninsula is the wall of a raised wall-and-ditch defensive complex; the rectangle on the tip of the peninsula is Mound ZZ1, a two-tiered mound with construction from Late Early Preclassic times into the early eighteenth century. Note location where sediment core PI-1 was extracted.

The PI-1 core was scanned by a GEOTEK Multi-sensor core logger at the University of Florida to measure density (gamma source and sensor) and magnetic susceptibility (loop sensor), and to obtain line scan photographs. The polycarbonate tubes were sliced lengthwise and the

core cleaned with a glass slide and scanned. Lithological description was carried out using the photographs and visual inspection of the cleaned surface at a cm scale.

Six samples (see below) of terrestrial organic matter (woody debris)

Table 1

Radiocarbon dates on charcoal from excavations of Nixtun-Ch'ich' streets.

(Source: [Pugh \(2018\)](#).)

Sample ID	Location		^{14}C age	Calibrated ^a date	
				Mean	Range (2 σ)
AA110389	4th St., N4089/E3790	Floor 15a	2631 $\pm$ 24	810 BCE	830–791 BCE
AA110393	4th St., N4089/E3790	Floor 12a	2454 $\pm$ 27	584 BCE	754–414 BCE
AA110394	4th St., N4089/E3790	Floor 10a	2472 $\pm$ 23	627 BCE	767–488 BCE
AA110390	4th St., N4089/E3790	Level 19a	2475 $\pm$ 22	639 BCE	767–511 BCE
AA110392	4th St., N4089/E3790	Level 15a	2418 $\pm$ 22	568 BCE	730–406 BCE
AA110391	4th St., N4089/E3790	Level 14a	2553 $\pm$ 23	682 BCE	801–562 BCE
AA107440	4th St., N4064/E4391	Level 14	2532 $\pm$ 31	671 BCE	798–543 BCE
AA107441	4th St., N4064/E4391	Floor 1	2492 $\pm$ 24	656 BCE	771–540 BCE
AA107442	4th St., N4074/E4391	Level 12	2472 $\pm$ 24	627 BCE	768–486 BCE
AA107489	6th St., N4279/E4074	Level 12	2515 $\pm$ 37	659 BCE	796–522 BCE
AA106865	3rd St., N3885/E4523	Floor 1	2457 $\pm$ 24	536 BCE	655–416 BCE

^a Dates calibrated with Oxcal 4.2.

for radiocarbon dating were removed, washed using deionized water and a 63 μm sieve to remove all sediments, and submitted to the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory. The resulting dates were calibrated using IntCal13 (Reimer et al., 2013) and an age-depth model constructed using the Bayesian software Bacon (Blaauw and Christen, 2011; see also Blaauw et al., 2018). The program Bacon (Blaauw and Christen, 2011) allows us to calibrate the radiocarbon dates and construct an age-depth model based on Bayesian statistics. The software divides the core into slices and conducts Markov Chain Monte Carlo iterations to estimate the accumulation rate of the sediments. The constructed model used the six radiocarbon dates plus an extra date (of core collection: 2018) at the top of the core. Dates are assigned to every centimeter of the core based on the weighted average of the model estimates, which allows us to correlate core observations and measurements with archaeological chronologies. This model partially compensates for the lack of sensitivity in radiocarbon dating between around 800/700 and 500/400 BCE, known as the “Hallstatt plateau” (Hajdas, 2008, p. 16), through a variant of “wiggle-match dating” (Blaauw et al., 2003).

The core was sent to the Large Lakes Observatory, University of Minnesota – Duluth, where the surfaces were again scraped and smoothed, then scanned by the ITRAX XRF Corescanner using a Cr source tube at 30 kV and 55 mA, at 5 mm resolution with a 15 second dwell time. Raw data were reprocessed to optimize peak-fitting using QSpec 8.6.0 software. X-radiographs of the core were collected using a Cr source tube run at 60 kV and 30 mA, with variable exposure times (275–575 ms) depending on the density of the sediments. All elemental data were smoothed using a 3-point running mean. Because we had to use two instruments to measure magnetic susceptibility and elemental composition of the core, slight variations with respect to the depth of certain peaks and troughs occur (1–2 cm). We believe those variations are a result of instrumental variability rather than real changes in the core composition.

3. Results and discussion

Our initial findings on core PI-1 reveal precise correspondences between human activities at Nixtun-Ch'ich' identified archaeologically, and sequenced constituents of the core. These findings pertain to dates, magnetic susceptibility, and elemental composition of the sediments. We are especially interested in the period from about ~800 BCE to ~100 CE. Results of further analyses including palynology will be integrated and reported upon their completion.

3.1. Core description

Core PI-1, from 515 to 220 cm depth, is characterized by gray, organic- and carbonate-rich silty clays with variable amounts of gastropod shells. Thin and thick laminations and thin beds are persistent throughout the core and are recognized by slight changes in color and organic debris (Fig. 2, left).

Laminae that contain a high percentage of organic matter are darker, while lighter laminae/beds contain a higher proportion of gastropod shells (although the shells are not abundant). At about 220 cm (788 BCE, see Section 3.2), a sharp change in color occurs, with a thin bed rich in organic debris (Fig. 2). Above this point, laminations persist for about 5 cm but then disappear, changing to homogeneous sediments that are dark gray, a color not common elsewhere in the core. A 1 cm-thick dark stratum at 206 cm (575 BCE) is rich in fragments of charcoal. Across a sharp boundary at 160 cm (132 CE, see Section 3.2), the laminations appear again and sediments return to gray carbonate-rich silty clays, similar to those present in the lower section of the core.

3.2. Dating

Six radiocarbon dates were obtained from the PI-1 core (Table 2).

Because they were based on wood samples, we are not concerned about hard-water error, which is a common problem in the Petén lakes owing to the presence of old carbon in the limestone outcrops surrounding the lakes (e.g., Curtis et al., 1998; Islebe et al., 1996).

The two lowest/oldest dates (sample IDs PI-1-5–6), with 2σ ranges between about 5000 and 3500 BCE, fall in the Middle Archaic (or Preceramic) period, a time when there is little to no archaeological evidence of human settlement (small, ephemeral camps) in Petén. The dates of core samples PI-1-3–4, spanning a narrow interval of about 2000 to 1300 BCE, represent the Late Archaic/Preceramic period (ca. 2500 to 1500/1000 BCE). This period has been sampled by numerous sediment cores in the southern Maya lowlands, which commonly include “disturbance pollen” from weedy plant taxa (e.g., Poaceae, Asteraceae) that flourish after high forests have been cut down for agricultural plots, beginning about 2200 BCE (Brenner et al., 2002; Islebe et al., 1996). Maize pollen in these same locales more directly supports the presence of early horticulturalists, although their settlement remains have not been identified archaeologically. These lowlanders were probably semi-sedentary cultivators who combined maize horticulture with hunting, foraging, and fishing subsistence activities (“forest agricultural tribalism”; Sahlin, 1968, p. 29; see also Clark and Cheetham, 2002), but who had not yet adopted fully sedentary village life.

The PI-1-3 date is of interest because, as discussed in Section 3.4, a peak in titanium, interpreted here as a proxy for soil erosion, around 1500 BCE might reflect the initial settlement of this locale by farmers. This date also immediately precedes the earliest evidence (beginning ca. 1300–1200 BCE) of occupation by people who made and used pottery (Rice, 2019b; South and Rice, n.d.). These early settlers likely resided in scattered small hamlets with permanent architecture, investigated archaeologically, and cultivated maize and other foodstuffs. Confirmation of pollen or other indicators of maize and other cultigens in the core awaits further analysis.

The considerably later date of PI-1-2, 887–1138 CE, corresponds to the Terminal Classic period in the Maya lowlands, the time of the protracted southern lowland Maya “collapse” (Aimers, 2007; Demarest et al., 2004; Turner II and Sabloff, 2012; Webster, 2002) and the beginning of the Early Postclassic. Analyses of excavated artifacts in Classic and Terminal Classic levels at Nixtun-Ch'ich' are not complete, but the site was occupied through this interval. Nixtun-Ch'ich' also experienced considerable Postclassic occupation, the typical low structures of perishable materials built atop earlier remains in the ceremonial core of the site and in other areas (Pugh et al., 2016). The PI-1-1 date, 1306–1452 CE, spans part of the Late Postclassic period, which lasts until 1525, and is a time of regional conflict leading to two centuries of open warfare between the Itzas and Kowoj until the Spanish conquest of the Itzas in 1697 (Jones, 1998).

The six radiocarbon dates we obtained from the core provide a robust age-depth model for our sedimentological interpretations and their correlation with known archaeological events at Nixtun-Ch'ich', although we recognize that uncertainties exist in the model. For example, the mean age at 220 cm—where we see a change in the sedimentological characteristics of the core—has a mean date of 788 BCE and a 2σ range of probable dates between 1097 and 447 BCE (Fig. 2). Similarly, the mean age at 160 cm—where the sedimentological characteristics suggest a return to “normal” conditions—has a mean date of 132 CE with probable dates ranging between 233 BCE and 458 CE (Fig. 2). Despite these age-depth ranges, all our results below use the weighted mean of the age-depth model (Fig. 2).

Fig. 3 illustrates the changes with age in magnetic susceptibility and elements Si, Fe, and Ti in the Lake Petén Itzá sediments. These curves reveal several peaks—periods of elevated erosion and sediment deposition—and troughs throughout the nearly 6000 years sampled by the PI-1 core. Given the lack of archaeological evidence of human occupation of the area before about 1300 BCE, however, we can only assume the earliest variations were caused by natural environmental

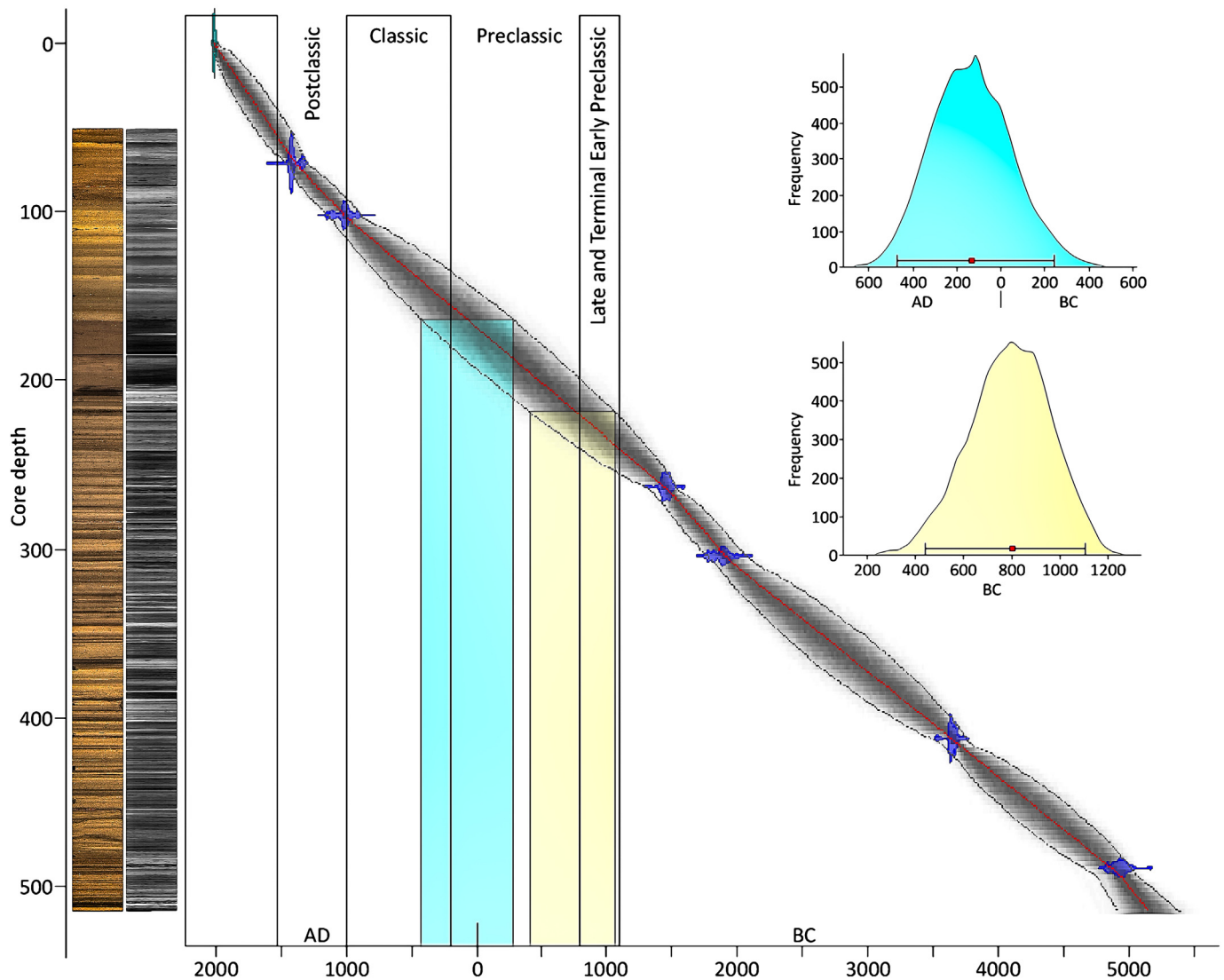


Fig. 2. Core PI-1 photographs, x-radiographs of density, and age-depth model based on six calibrated radiocarbon dates (dark blue), and the 2018 date when the core was retrieved (green). Gray areas in the age depth model indicate the likelihood of ages for a specific depth (darker gray is more likely), red line shows the best fit model based on weighted mean ages, and stippled gray lines show 95% confidence intervals. Light colored boxes and histograms show the age estimates for 220 cm (yellow) and 160 cm (light blue). The red box and black line in the histograms highlight the mean age and 95% confidence interval. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Calibrated radiocarbon dates on wood charcoal from Lake Petén Itza core PI-1.

Lab ID	Sample ID	Depth ^a	¹⁴ C age	Mean ^b	Range (2σ)
180,979	PI-1-1	71 cm	515 ± 30	1388 CE	1306–1452 CE
180,980	PI-1-2	102 cm	1020 ± 40	1008 CE	887–1138 CE
180,981	PI-1-3	263 cm	3190 ± 30	1447 BCE	1535–1303 BCE
180,982	PI-1-4	304 cm	3550 ± 35	1921 BCE	2082–1782 BCE
180,983	PI-1-5	412 cm	4875 ± 30	3654 BCE	3773–3508 BCE
180,984	PI-1-6	489 cm	6050 ± 35	4888 BCE	5038–4676 BCE

^a Depth from top of core.

^b Modeled age-weighted mean date calibrated with Bacon (Blaauw and Christen, 2011).

disturbances such as episodes of increased precipitation and runoff.

3.3. Magnetic susceptibility

Magnetic susceptibility is a first-order index of degree or magnitude of soil erosion. Most natural earthy materials have some degree of

magnetic strength, present particularly in ferromagnetic or iron (Fe)-based minerals. The “susceptibility” to magnetization of these materials in lake deposits is assessed by exposing a core to a weak magnetic current (mentioned in Section 2) and determining the resultant variations in magnetism. These variations are “proportional to the quantity of magnetic minerals present in the sample” (Thompson et al., 1975, p. 688). The magnetic minerals of interest are commonly magnetite and detrital titanomagnetite (Thompson et al., 1975, pp. 689, 690).

Of particular interest in core PI-1 is the sharp peak in magnetic susceptibility at 800 BCE, which begins to rise slightly earlier and is followed by a deep trough at 700 BCE (Fig. 4). This peak occurs at the beginning of the Middle Preclassic period and coincides with the implementation of the gridded site plan of Nixtun-Ch'ich' as established by dates from the street excavations (Table 1). These excavations revealed that the corridors and earliest platforms were built directly upon bed-rock rather than atop paleosols, which must have been cleared away. This removal is corroborated by the magnetic susceptibility peak, indicating that the initiation of construction of the city's streets and avenues was accompanied by significant disruption of soils and their redeposition in the lake waters.

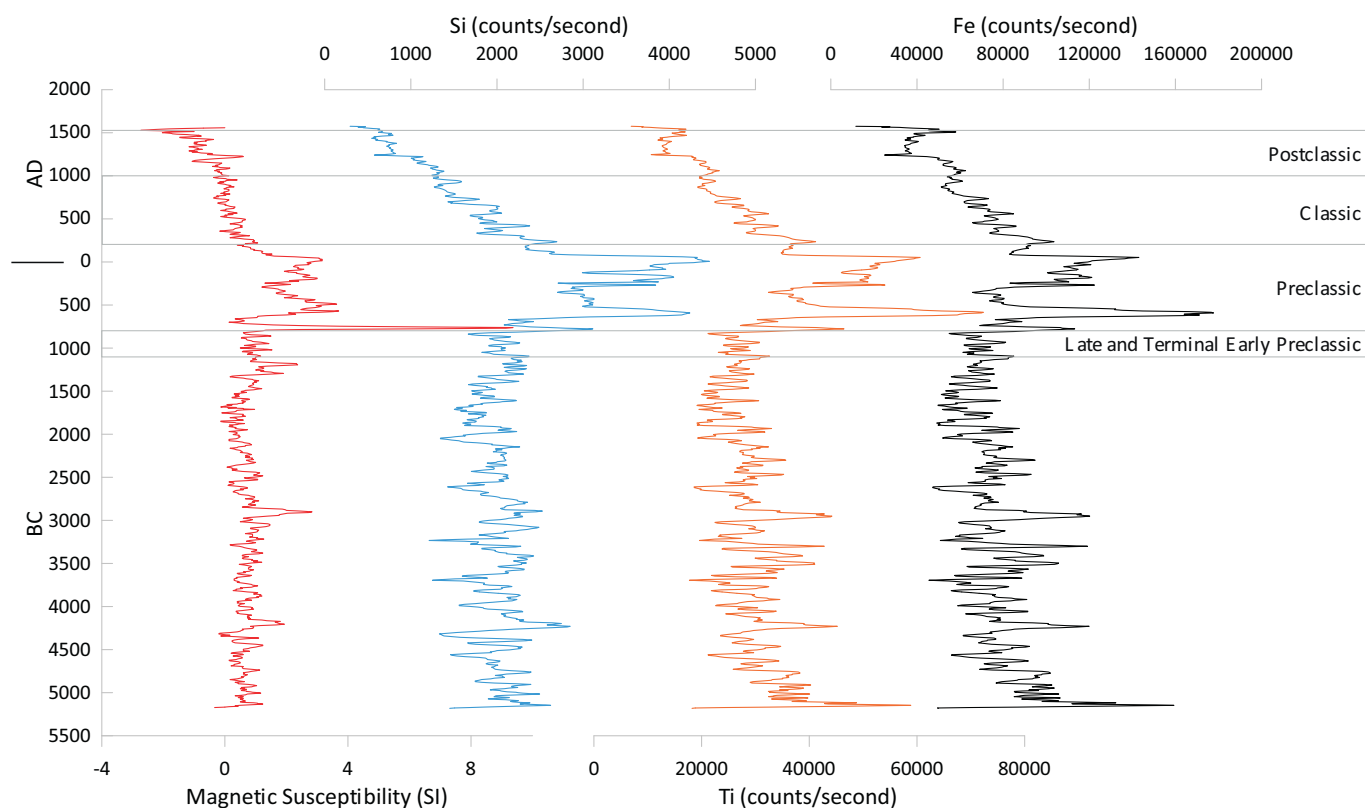


Fig. 3. Peak area versus age of (left to right) magnetic susceptibility, Si, Ti, and Fe in core PI-1.

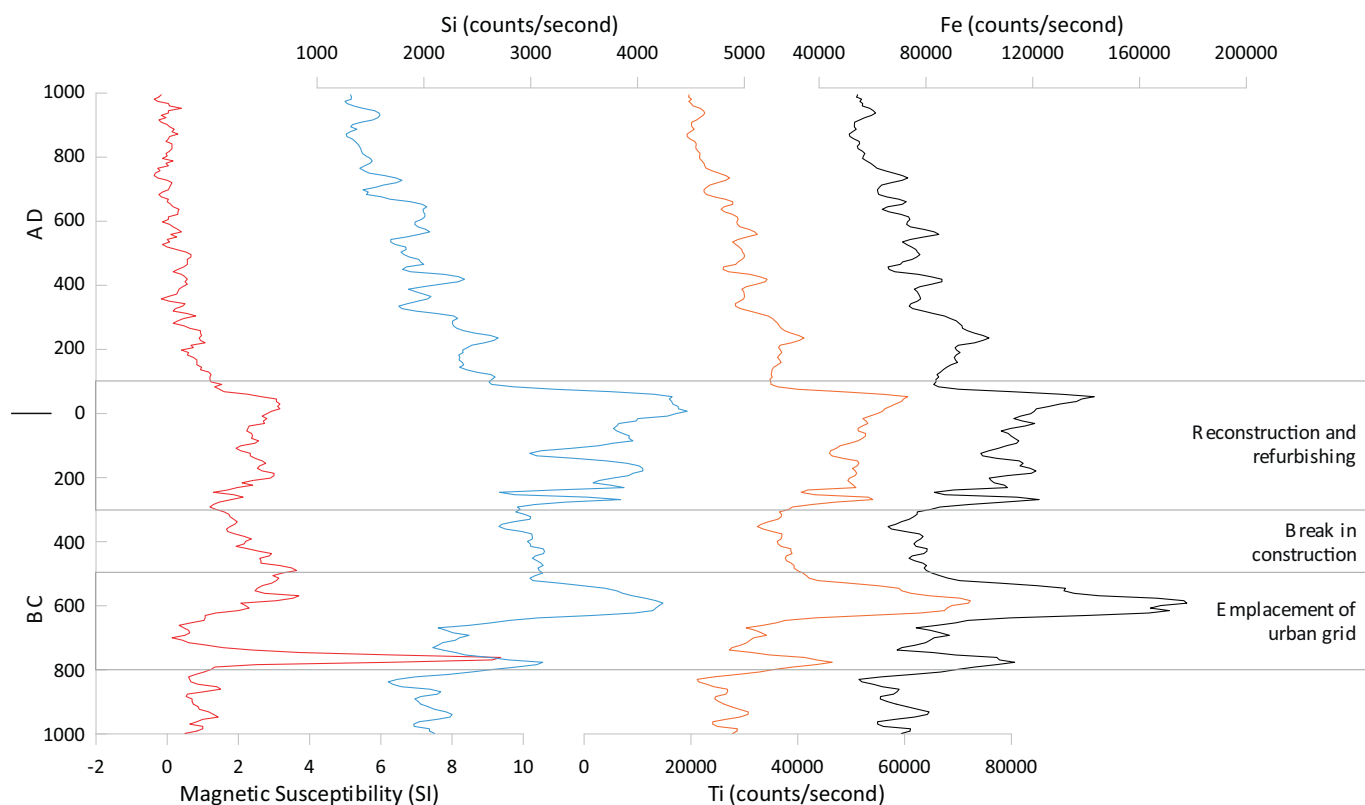


Fig. 4. Peak area versus age, 1000 BCE to 1000 CE, of (left to right) magnetic susceptibility, Si, Ti, and Fe in core PI-1.

The subsequent trough does not necessarily indicate a drop in construction or settlement; rather, there simply had been far less surface soil buildup by then to be eroded. Following the trough, susceptibility/erosion returns to moderately high levels for about 600 years (until around 100 CE or so), then drops off again. This elevated susceptibility probably registers continuing construction at the city followed by abrupt cessation, as discussed in Section 3.4. Throughout the Classic period (200–950 CE), susceptibility (as a proxy for new construction or reconstruction causing erosion) experiences minimal fluctuations and then declines sharply in the Postclassic period (Fig. 3).

3.4. Elemental data: Si, Fe, and Ti

Three element profiles (Figs. 3, 4) display a similar signature as that of magnetic susceptibility: silica (Si), iron (Fe), and titanium (Ti). Silica is a primary component of clays (hydrated alumina-silicates) and clay soils, and so it is typically abundant in sedimentary deposits. For example, silica is the main component of the heavy “Maya clay” deposits registering Classic-period deforestation and construction in many lowland lake cores (see, e.g., Anselmetti et al., 2007). Iron is a primary element contributing to the magnetic susceptibility of eroded sediments. Fe is a constituent of natural clays and soils that, in the Petén lakes region, is commonly seen in pottery: as finely particulate matter creating a red color, as small discrete red (ferruginous) lumps, or as magnetite nodules (see Cecil, 2001, Figs. 81–95). Titanium, the ninth most abundant element on earth, had a peak deposit here around 1500 BCE, corresponding to the late Early Preclassic period when we believe the locale that became Nixtun-Ch'ich' might have been initially settled by farmers (Rice, 2009, 2019b).

Titanium occurs in accessory minerals ilmenite, rutile, and sphene in clays and also in iron ores (hematite). Rutile, ilmenite, and sphene were not recorded in thin sections of pottery from the area because accessory minerals were not tallied for gross paste characterization. However, the presence of Ti in the sediment core can be compared with the findings of recent compositional studies of pottery from Nixtun-Ch'ich' and nearby sites. In LA-ICP-MS analysis of Postclassic pottery, Ti was grouped with Al and Fe in a principal components transformation of the raw data (Cecil, 2001, pp. 454–467, Fig. 115). In neutron activation analysis (INAA) of Preclassic artifacts, Ti was absent in a distinct group of figurines made from white- or cream-firing clay lacking iron impurities and thought to have been produced at Nixtun-Ch'ich' (Cecil, 2017; Rice, 2019a). This supports the association of Ti with hematite or other iron-bearing minerals in central Petén sediments.

Si, Ti, and Fe remain fairly constant for the lower part of the core, increase from about 800 BCE to 100 CE with associated peaks and troughs (see below), and then decrease to a minimum in the upper part of the core (Fig. 3). It is not surprising that the peaks and troughs in the abundances of Si, Fe, and Ti in the PI-1 core sediments closely track magnetic susceptibility. A dramatic increase in these elements occurs almost simultaneously with the 800 BCE peak in susceptibility, beginning at the same time and with the steep dropoff slightly before 700 BCE. More dramatic peaks in these elements—higher and wider (longer lasting) than that of magnetic susceptibility—are registered at 600 BCE, with another sharp decline lasting until close to 500 BCE. These increased elemental inputs suggest renewed construction or amplification of the grid between about 650 and 500 BCE, details not captured archaeologically because of the radiocarbon dating plateau.

The trough—lowered erosional inputs—between approximately 500 and 300 BCE appears to mark the end of major Middle Preclassic construction efforts. A corresponding break was noted in northern Petén in the Mirador Basin, where pollen analyses suggested ecological disturbance and possible depopulation (Dunning et al., 2014, p. 120). The reduced sediment inputs coincide with a significant increase in calcium (Ca) and strontium (Sr) and a Ti decrease (see Ca/Ti and Ti plots in Fig. 5). Rises in Ca and Sr typically signal increased aridity and a decrease in precipitation (or in microfossils, not a significant component

of the core), but a speleothem from northern Yucatán suggests that 500–166 BCE was a period of high precipitation (Medina-Elizalde et al., 2016). In any event, we have detected no clear corresponding cultural changes in the archaeological record at Nixtun-Ch'ich'. The lull in sediment deposition seems to suggest a lull in construction activity before the major rebuilding and refurbishing efforts evident in the Late Preclassic period (300 BCE–100 CE).

The PI-1 core suggests an abrupt reduction of erosion (and construction?) beginning around 100 CE, earlier than the commonly accepted date for ending the Late Preclassic. In addition, the color and characteristics of the sediments in the PI-1 core change around 132 CE, signaling some thus far unknown major alteration in activities (partial abandonment?) at Nixtun-Ch'ich'. Again, similar phenomena are evident in the Mirador Basin around 130–225 CE (Dunning et al., 2014, p. 120) and also elsewhere in the lowlands. These developments are associated with drier climatic conditions and a “Late Preclassic collapse”—cessation of monumental architecture and depopulation—of large sites such as El Mirador, Cuello, and others (see, e.g., Beach et al., 2015; Douglas et al., 2016; Dunning et al., 2012; Ebert et al., 2017; Inomata et al., 2017; Medina-Elizalde et al., 2016; Wahl et al., 2007; Webster et al., 2007). In the PI-1 core, the abrupt shift observed at 100 CE corresponds to another increase in Ca and Sr, further supporting correlations between Late Preclassic lowland site abandonments and aridity. These changes might be associated with the peculiar and thus far unexplained sparse Early Classic (200–600 CE) occupation long noted in the western Petén lakes region.

Elemental abundances and magnetic susceptibility in PI-1 display irregular peaks and troughs during the Early and Late Classic periods, although with a general decline indicating reduced erosion and possible vegetation regrowth, but not necessarily depopulation. A small peak occurs in the early 900s CE 900 CE (Fig. 4), when Nixtun-Ch'ich' and the western Lake Petén Itzá basin are thought to have experienced an influx of immigrants from the north and west (Rice, in press). An abrupt decline around 1200 CE cannot be explained archaeologically at present, although a slight increase in Si and Fe might reflect low-level disturbance associated with Late Postclassic (Chak'an Itza) settlement activity.

4. Conclusions

A 515 cm-long sediment core, labeled PI-1, was extracted from shallow waters of Lake Petén Itzá south of the Maya archaeological site of Nixtun-Ch'ich', Petén, Guatemala. Six wood charcoal samples yielded calibrated date ranges from about 5000 BCE to 1450 CE. Analyses of magnetic susceptibility and the elements silica, iron, and titanium in the sediments over this temporal range revealed a complex series of peaks and troughs strongly corresponding to erosional inputs resulting from terrestrial processes, both natural and, after about 1500 BCE, anthropogenic. Input peaks at about 800 BCE and 600 BCE, with elevated levels continuing until around 500 BCE, correlate with radiocarbon dating of construction of the distinctive Middle Preclassic urban grid of Nixtun-Ch'ich' between around 800 and 500 BCE (Pugh and Rice, 2017). This was followed by reduced sediment deposition for two centuries, until around 300 BCE when it rose again, coinciding with major Late Preclassic reconstruction and remodeling.

Erosional inputs declined abruptly starting around 100 CE accompanied by an abrupt change in core characteristics at 132 CE. These may correspond to the reduced occupation of the west-central Petén lakes region noted in the Early Classic period, a poorly understood phenomenon that may relate to a Late Preclassic “collapse” of cities elsewhere in the lowlands. Variable but generally low-levels of sedimentation continued through the Late Classic and Postclassic periods, possibly as a result of vegetation regrowth in the area.

The PI-1 core exhibited striking correlations with archaeologically known activities at Nixtun-Ch'ich', but it also suggested some subtleties that have not yet been identified. One is the apparent massive burning

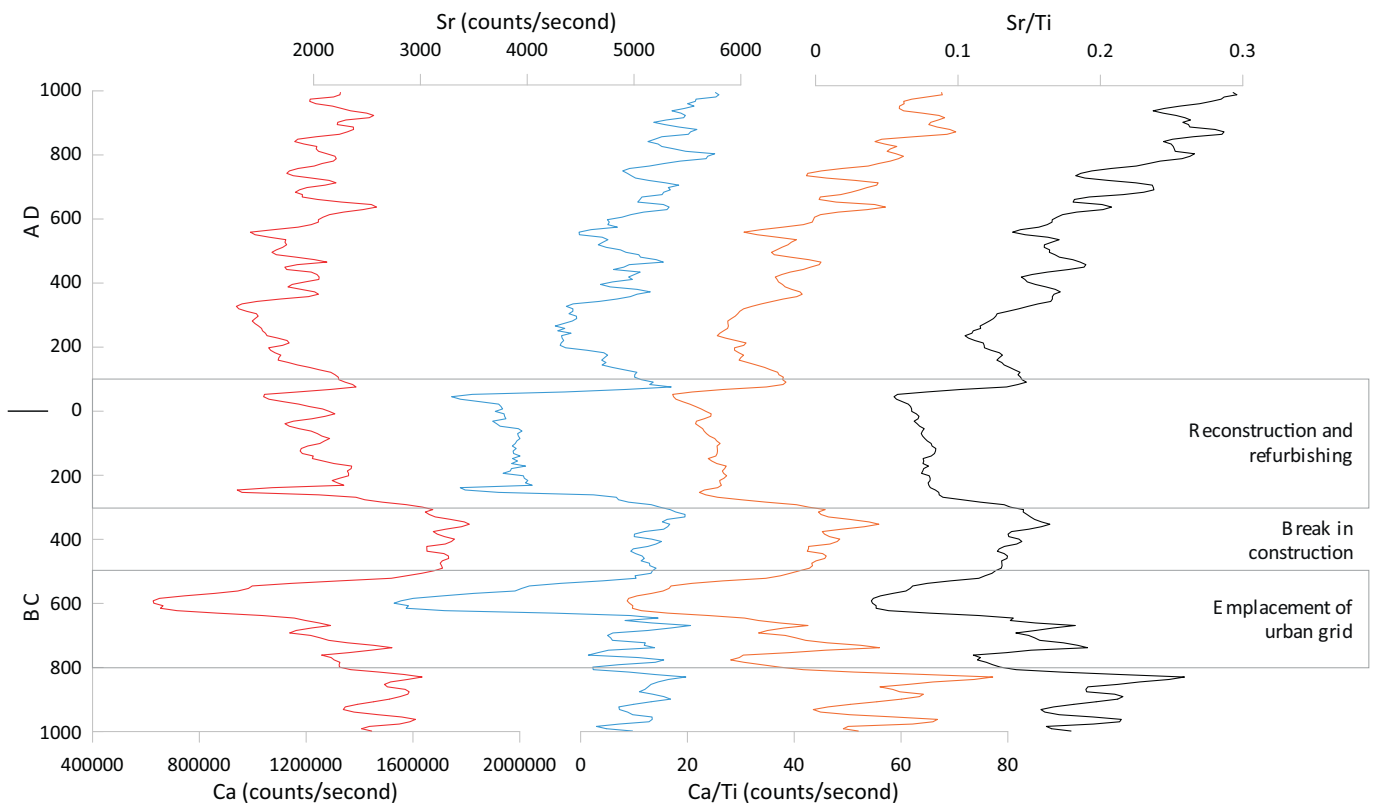


Fig. 5. Peak area versus age, 1000 BCE to 1000 CE, of (left to right) Ca, Sr, Ca/Ti, and Sr/Ti in core PI-1.

near the end of the Middle Preclassic period around 575 BCE. Was this from clearing and burning new agricultural fields, or from a conflagration in the city? Another event or set of events marked by changes in core sediments begins around 100 CE, and might be connected to drought and region-wide changes in settlement—perhaps abandonments? These intriguing possibilities indicate that paleolimnology and sediment cores reveal not only large-scale climatic and terrestrial processes, but also complex intersections with smaller-scale cultural activities and previously undetected conditions.

Declaration of Competing Interest

None.

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