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High resolution stalagmite climate record from the Yucatán Peninsula spanning the Maya terminal classic period

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ABSTRACT

The decline of the Classic Maya civilization was complex and geographically variable, and occurred over a ~150-year interval, known as the Terminal Classic Period (TCP, C.E. 800–950). Paleoclimate studies based on lake sediments from the Yucatán Peninsula lowlands suggested that drought prevailed during the TCP and was likely an important factor in the disintegration of the Classic Maya civilization. The lacustrine evidence for decades of severe drought in the Yucatán Peninsula, however, does not readily explain the long 150-year socio-political decline of the Classic Maya civilization. Here we present a new, absolute-dated, high-resolution stalagmite $\delta^{18}O$ record from the northwest Yucatán Peninsula that provides a much more detailed picture of climate variability during the last 1500 years. Direct calibration between stalagmite $\delta^{18}O$ and rainfall amount offers the first quantitative estimation of rainfall variability during the Terminal Classic Period. Our results show that eight severe droughts, lasting from 3 to 18 years, occurred during major depopulation events of Classic Maya city-states. During these droughts, rainfall was reduced by 52% to 36%. The number and short duration of the dry intervals help explain why the TCP collapse of the Mayan civilization occurred over 150 years.

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1. Introduction

In the beginning of the ninth century, the Maya Classic socio-political system characterized by kingdoms ruled by 'divine' kings, the *k'ul ajawob*, began to express the first symptoms of deterioration in the southern lowlands. By C.E. 909 the system of divine kingship had practically vanished in the southern lowland sites, after major depopulation in this region occurred (80–85% from its population peak) (Schele and Miller, 1986; Webster, 2002; Demarest et al., 2004). The Maya Classic socio-political system, however, persisted until ~C.E. 950 in the northwestern region of the Yucatán Peninsula, represented by the Puuc sites, such as the city-states of Uxmal and Oxkintok (Fig. 1). The lowland Maya population, which reached four million people by C.E. 800, plummeted to a few hundred thousand over the following 150 years (Culbert and Rice, 1990).

Previous studies have suggested that a "megadrought" lasting between 50 and 130 years, which extended across the Yucatán Peninsula, played a fundamental role in the socio-political events that led to the demise of the Classic Maya civilization (Hodell et al., 1995; Curtis et al., 1996; Gill, 2000). According to the megadrought hypothesis, the negative impacts of intense drought on the carrying capacity of the environment, food production, and human health, resulted in drastic depopulation, social unrest, warfare and, ultimately, the disintegration of the political system (Gill, 2000). As revealed by a wealth of archaeological evidence, however, the Classic Maya civilization declined over a 150-year period, and not abruptly, as would be expected if it had been significantly vulnerable to drought. Furthermore, the cultural history of the northern Puuc cities do not match environmental trends which imply that the lowlands were experiencing peak aridity during the time when regional population and monumental construction was growing rapidly (Carmean et al., 2004).

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[2] SJB and DWL helped planned the research, participated in the field work, data analysis, interpretation and writing.

[3] YA and VP helped developed the speleothem chronology.

[4] LvG helped creating the temperature correlation maps and participated in the statistical analysis, discussion and interpretation of the data.

[5] M.V. contributed his expertise to improving the climate/stable isotope relationship and its discussion in the manuscript.

[6] AK helped create manuscript figures and participated in the data analysis and interpretation.

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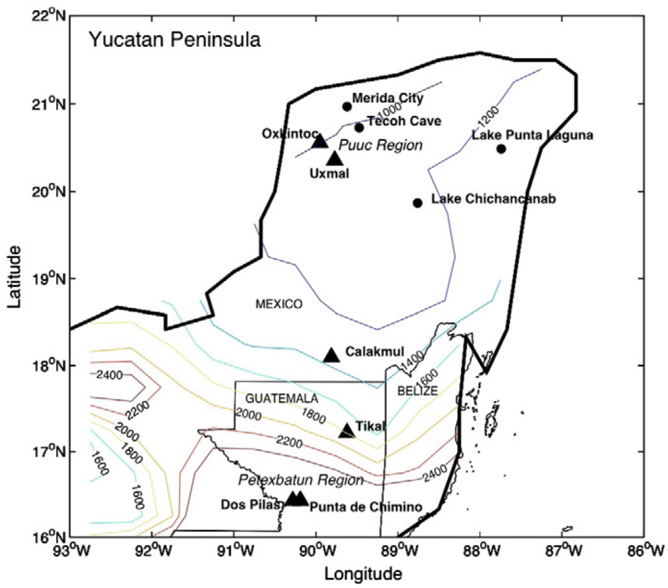

Fig. 1. Map of the Yucatán Peninsula and Maya lowlands including the countries of México, Belize and Guatemala. Color contours represent total annual precipitation isolines (mm/year). Terminal Classic Period Maya sites discussed in the study are indicated (black triangles). The location of Tzabnah cave in Tecoh, Yucatán (20° 45′N, 89° 28′W, 20 m above sea level), Lake Chichancanab (19° 52′N, 88° 46′W) and Lake Punta Laguna (20°38′N, 87°37′ W, 18 m above sea level) are also indicated (black circles).

Recent density records from sediment cores from Lake Chichancanab (Hodell et al., 2005a) suggest a more complex climate pattern than previous studies (Gunn et al., 1995; Hodell et al., 1995; Curtis et al., 1996) and indicate that, as opposed to a century-long drought during the Terminal Classic Period (C.E. 800–950), the north of the Yucatán Peninsula experienced four droughts with durations between 10 and 20 years. As pointed out by Hodell et al., (2005a) however, discrepancies between available lacustrine climate records have been cited as evidence that drought was not widespread during the TCP.

Searching for a unified and robust climate picture based on independent archives is fundamental in order to understand the role of climate in the Terminal Classic Period collapse and transformation of the Maya civilization. Here we present a new, absolute-dated, high-resolution stalagmite δ^{18}O record from the northwest Yucatán Peninsula that provides a much more detailed picture of climate variability during the last 1500 years and, particularly, over the Terminal Classic Period.

2. Methods

2.1. Speleothem collection and location

In the year 2004 we collected a 45 cm stalagmite specimen, named Chaac after the Maya god of rain, from cave "Tzabnah" in the village of Tecoh (20°43.83′N, 89°28.47′W, 20 m above sea level) (Fig 1, Supplementary Fig S1). Tecoh is located in the northwest Yucatán Peninsula only 30 km from the modern city of Mérida, the largest city in the Yucatán Peninsula today (~1 million people) and about 50 km northeast from the Maya Puuc region and the city of Uxmal (Fig. 1). The northwest Yucatán Peninsula region is semi-humid with mean annual precipitation of 1112 mm, 60–70% of which falls during the summer rainy season between June and October. Seasonal precipitation in the Yucatán Peninsula is determined by the movement of the ITCZ, the strength and movement of the Bermuda High and the easterly trade winds (Hastenrath, 1984). These factors give rise to two distinct wet and dry seasons. The northward movement of the ITCZ during boreal summer brings precipitation during the wet season that lasts from May to October. The wet season is punctuated by a relative decrease in precipitation in July and August resulting in bimodal annual cycle of precipitation (Magaña et al., 1999). The northern Yucatán Peninsula, where Tecoh is located, is characterized by a sharp meridional gradient in annual precipitation as a result of subsidence related to the descending branch of the Hadley Cell (Waliser et al., 1999).

2.2. Speleothem chronology

The speleothem time scale is based on 12 absolute U/Th dates (Supplementary Table S1). ^{234}U–^{230}Th dating was conducted at the Radiogenic Isotope Laboratory, the University of New Mexico. Calcite powders weighing from 0.06 to 0.15 mg were used for dating. The samples were spiked with a mixed ^{229}Th–^{233}U–^{236}U spike. U and Th were separated using conventional anion exchange chromatography. U and Th isotopes were measured using a Thermo Neptune multi-collector inductively coupled plasma mass spectrometer (MC-ICPMS) which was optimized for U-series analytical work as described by Asmerom et al. (2006). ^{234}U was measured on a secondary electron multiplier with high abundance filter, while the other isotopes of uranium were measured on Faraday cups with amplifiers that had mixed 10^{10}, 10^{11} and 10^{12} Ω resistors for ^{233}Uand ^{236}U, ^{235}U and ^{238}U respectively. Mass fractionation was monitored using the ^{236}U/^{233}U ratio, while SEM/Faraday gain was set using sample standard bracketing. A similar procedure was used for Th isotope measurements with ^{230}Th measured in the SEM and ^{229}Th and ^{232}Th measured in Faraday cups. The samples had very low uranium concentrations, most in the 200s of ppb (Supplementary Table S1). But many of them had very low ^{232}Th concentrations also (up to three orders of magnitude lower than U concentration), thus a number of the samples were very sensitive to initial ^{230}Th/^{232}Th corrections (e.g. samples YO4-CH17, YO4-CH18, YO4-CH3, YO4-CH19, YO4-CH21, YO4-CH22). We used an initial ^{230}Th/^{232}Th atomic ratio of $4.4\times10^{-6}\pm50\%$ determined from two three-dimensional isochrons that yielded values of $10.26\times10^{6}\pm1.1\times10^{6}$, and $0\pm14\times10^{6}$, and from a near-zero-aged calcite at the stalagmite's top. CRM145 U isotope standard was measured with the samples obtaining the conventionally accepted δ^{234}U value of -36.5 ± 0.5‰ [35]. $\delta^{234}U=[[^{234}U/^{238}U_{sample}/^{234}U/^{238}U_{secular\ equilibrium}]-1]\times10^{3}$, where, $^{234}U/^{238}U_{secular\ equilibrium}=\lambda_{238}/\lambda_{234}$, $\lambda_{230}=9.1577\times10^{-6}\ year^{-1}$, $\lambda_{234}=2.8263\times10^{-6}\ year^{-1}$, $\lambda_{238}=1.55125\times10^{-10}$ year^{-1} (Cheng et al., 2000). U and Th procedural blanks were in the range of 5–10 pg and had little effect on ages.

We applied a polynomial and piecewise linear model and found a maximum age difference between these models of 31 years during the Medieval Climate Anomaly time interval. We developed the chronology based on the piecewise-linear model because it results in excellent agreement with an independent and well-dated stalagmite δ^{18}O record (errors <15 years) from subtropical China (Zhang et al., 2008) over the transition to the Medieval Climate Anomaly, when these two records display similar environmental trends (Supplementary Fig. S2). This model indicates that Chaac grew continuously from C.E. 478 to the year 2004, when Chaac was retrieved from the cave (Fig. 2). Parts of Chaac are distinctly laminated, including the interval covering the Terminal Classic Period. To test the age model in the critical interval defining the TCP we counted laminations and compared the results to the U/Th age model. The average number of laminations in the time interval between CE 918 and 820, which corresponds to 98 Th-years, is 85 ± 10 (Fig. 3). This test provides an independent confirmation of the U/Th age model. The U/Th date of C.E. 942 corresponding to the onset of the Medieval Climate Anomaly in Chaac is comparable to the age indicated by the well-dated (Th-dating errors ≤5 years) subtropical China stalagmite δ^{18}O record for this same event (Zhang et al., 2008) (Supplementary Fig. S2). This observation and the laminae counting suggest that the error in the absolute chronology in Chaac is no larger than ±10 years during the Terminal Classic Period.