Available online at www.sciencedirect.com
ScienceDirect

Quaternary Research 68 (2007) 53–63

QUATERNARY RESEARCH

www.elsevier.com/locate/yqres

Late Holocene environmental reconstruction using cave sediments from Belize

Jason S. Polk *, Philip E. van Beynen, Philip P. Reeder

Department of Geography, Environmental Science and Policy Program, University of South Florida, 4202 E. Fowler Ave., Tampa, FL 33620, USA

Received 23 February 2006
Available online 10 May 2007

Abstract

Cave sediments collected from Reflection Cave on the Vaca Plateau, Belize show variations in the $\delta^{13}C$ values of their fulvic acids (FAs), which indicate periods of vegetation change caused by climatic and Maya influences during the late Holocene. The $\delta^{13}C$ values range from −27.11‰ to −21.52‰, a shift of ~5.59‰, which suggests fluctuating contributions of C_3 and C_4 plants throughout the last 2.5 ka, with C_4 plant input reflecting periods of Maya agriculture. Maya activity in the study area occurred at different intensities from ~2600 cal yr BP until ~1500 cal yr BP, after which agricultural practices waned as the Maya depopulated the area. These changes in plant assemblages were in response to changes in available water resources, with increased aridity leading to the eventual abandonment of agricultural areas. The Ix Chel archaeological site, located in the study area, is a highland site that would have been among the first agricultural settlements to be affected during periods of aridity. During these periods, minimal water resources would have been available in this highly karstified, well-drained area, and supplemental groundwater extraction would have been difficult due to the extreme depth of the water table.

Keywords: Cave sediments; Central America; Fulvic acids; Maya collapse; Climate change; Karst; Paleoclimate; $\delta^{13}C$ carbon isotope; ITCZ; Belize

Introduction

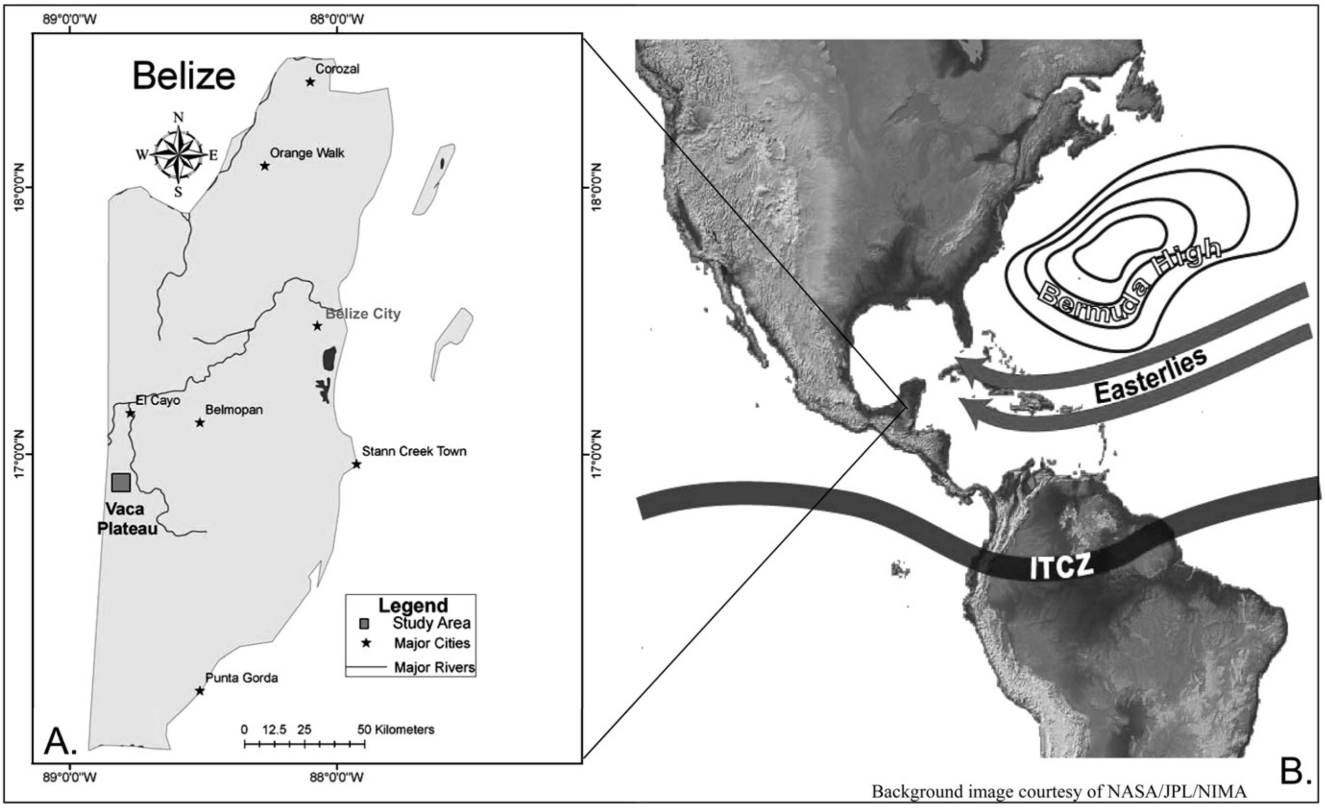
Inferences regarding connections between past climate variability and cultural evolution can be complex, requiring the incorporation of several dynamic and reciprocating factors, including environmental, cultural, and climatic interactions. Paleoclimate data are used to establish periods of climatic variability, which can be compared with the cultural evidence of a civilization's growth or decline in response to those fluctuations. The ancient Maya civilization that inhabited the lowlands of Central America provides an excellent example of complex climatic, cultural, and environmental interactions, but debate continues regarding the cause of the society's collapse ~AD 900 (Curtis et al., 1998; Lucero, 2002; Leyden, 2002; Shaw, 2003; Neff et al., 2006). The factor most often excluded in the interpretation of these complex interactions, possibly due to lack of preservation or the complexity of records, is the environmental response to climatic and anthropogenic influences (Leyden, 2002).

One such area of climate and human interaction is the Northern Vaca Plateau in Belize (Fig. 1), which was populated by the Maya and is a region susceptible to arid periods because it is a highly karstified upland area (Reeder et al., 1996). Topographically diverse and well-drained, the area is quite responsive to climatic variability, which would be compounded by any anthropogenic landscape alteration. In this paper, we present an analysis of environmental change on the Vaca Plateau, Belize through vegetation reconstruction using $\delta^{13}C$ values of fulvic acids extracted from cave sediments, which we propose are a proxy record of Maya alteration of the environment through agricultural practices. Speleothem carbon and oxygen isotope data from another nearby cave in the study area provide information regarding climate variability in the area (Webster, 2000). Previous studies show distinct regional differences in terms of the severity and timing of arid periods that would have affected human occupation and agricultural production throughout Central America (Hodell et al., 1995; Curtis et al., 1996; Haug et al., 2001; Shaw, 2003; Hodell et al., 2005a). These arid

---

* Corresponding author. Fax: +1 813 974 2184.
E-mail address: jspolk@mail.usf.edu (J.S. Polk).

0033-5894/$ - see front matter © 2007 University of Washington. All rights reserved.
doi:10.1016/j.yqres.2007.03.002



Background image courtesy of NASA/JPL/NIMA

Figure 1. (A) Zoomed inset map of the Northern Vaca Plateau study area (gray box) in Belize, Central America. (B) Map of Central America and the surrounding area showing the major climatic influences, including the ITCZ, Bermuda High, and the Easterlies (modified from Soto, 2005).

periods would have impacted the well-drained study area more rapidly and severely than other lowland sites.

Recent evidence has shown that the tropical climate of the late Holocene was more variable than previously thought, especially in the Central American lowlands, lending plausibility to the hypothesis of climate change influencing the collapse of the Maya (Haug et al., 2001, 2003; Hodell et al., 2001; Gunn et al., 2002; Hughen et al., 2004). The Maya were inherently dependent upon agriculture for sustenance, mainly using slash-and-burn techniques combined with terracing and irrigation systems to maintain soil abundance and fertility. In the Central Lowlands of Belize, this agrarian lifestyle was complicated by the well-drained, highly karstified landscape, which is characterized by thin soils, ephemeral water resources, and periodic droughts (Chase and Chase, 1989; Miller, 1996; deMenocal, 2001; Demarest, 2004).

The Maya deforested and terraced the hillslopes of the karst landscape to make them suitable for agriculture (Coultas et al., 1993). Over time, the combination of a growing population and periodic droughts leading up to the Terminal Collapse period (~AD 800 to 1000) would have left the Maya susceptible to climate changes affecting water availability (Cowgill, 1962; Chase and Chase, 1989). However, this susceptibility to climate change was not consistent throughout the entire area of Maya occupation, with certain regions responding more abruptly to environmental and anthropogenic changes (Gill, 2000; Gunn et al., 2002). Events such as the Maya Hiatus (~1470 to 1350 cal yr BP (AD 530 to 650)) (deMenocal, 2001) and the Preclassic Abandonment (~1950 to 1850 cal yr BP (AD 150 to 250)) (Hodell et al., 2001; Haug et al., 2003) had different effects on the Maya, depending on their location. There are no major groundwater or river resources in the study area; hence, the Maya population was reliant on rainfall for irrigation and water storage (Chase and Chase, 1989), thereby making it more susceptible to climate variability than other sites where water resources are more abundant.

Previous studies regarding climate change and the Maya have mainly focused on the analysis of lake sediments from Guatemala (Curtis et al., 1998; Rosenmeier et al., 2002) and the Yucatan Peninsula (Hodell et al., 1995, 2001, 2005a; Curtis et al., 1996). The majority of the lacustrine studies show agreement that periods of aridity occurred during the interval from 1250 to 950 cal yr BP (AD 750 to 1050), which is concurrent with the collapse of the Maya (Hodell et al., 2005a). An analysis of marine sediments from the Cariaco Basin in the Caribbean Sea (Haug et al., 2001, 2003) also found periodic multi-year droughts between 1240 and 1090 cal yr BP (AD 760 and 910) that agree with the lacustrine records of the Yucatan, providing further evidence of climatic change influencing the decline of the Maya.

Webster (2000) performed the only terrestrial paleoclimate study of any significant length in or around Belize, analyzing the δ^{13}C and δ^{18}O values of a speleothem collected from a cave in the study area, which provided a dated record from 2700 cal yr BP (700 BC) to ~200 cal yr BP (AD 1800). The speleothem isotope values indicate periodic aridity recurring approximately every 280 yr. Extended dry periods in the record occurred from ~2350 to 2200 cal yr BP (350 to 200 BC) and from ~1400 to 900 cal yr BP (AD 600 to 1100). However, this study is an indirect measure of climate–human interactions.

Other than the Webster (2000) study, few have analyzed Maya environmental impact on the Central Lowlands of Belize, because the highly karstified landscape preserves little in the way of suitable proxy records. The well-drained nature of the karst landscape in our study area does not allow water to collect and form lakes; hence, no lacustrine sediment is deposited. Additionally, tree ring studies in the tropics are in their infancy, and to provide meaningful data they require more mountainous terrain than what is available in Belize. Consequently, undertaking a study of the paleoclimate–human interactions on the Vaca Plateau required the novel approach of carbon isotope analysis of organic substances extracted from cave sediments. This exploratory approach allows the most direct investigation into these interactions, because we are analyzing cave sediments derived from the same soil that the Maya utilized for agricultural production.

Cave sediments

Cave sediments can result from the allogenic deposition of surface soils into caves (Brinkmann and Reeder, 1995). These sediments record the environmental history of the land above the cave in their stratigraphic layering, providing robust records of terrestrial changes in vegetation and land use, which are not preserved in ever-changing surface soils (Botrell, 1996; Courty and Vallverdu, 2001; Panno et al., 2004). Previous studies regarding cave sediments have mainly focused on stable carbon isotope analysis of bulk organic matter to provide records of depositional disturbance (Turney et al., 2001), agricultural pollution (Botrell, 1996), or the presence of certain vegetation types (Panno et al., 2004). The latter study used the δ^{13}C values from organic matter in cave sediments to determine vegetation and climate change in southern Illinois during the Pleistocene and early Holocene (Panno et al., 2004). They found that cave sediments provide detailed and well-preserved records of environmental change over thousands of years.

To date, no studies have investigated the fulvic acid (FA) fraction of organic matter extracted from cave sediments; however, FAs from soils have been used for paleoenvironmental interpretation (Yamskikh, 1998). FAs are low molecular weight, easily transported, hydrophilic acids, and most closely represent the humic fraction of the decaying organic matter derived from vegetation growing above the cave during sediment deposition (Aiken et al., 1985; van Beynen et al., 2000; Doane et al., 2003). Calcareous clays dominate our study area, preferentially binding FAs to create microaggregates that reduce FA lability (Liao et al., 2006) and movement in the sediment column (Stevenson, 1994; Qualls et al., 2003, Qualls, 2004; Grunewald et al., 2006). Humic substances are not easily degraded by biological processes, such as microbial breakdown (Spaccini et al., 2000, 2006), thus having a high degree of preservation (Biggs et al., 2002; Claret et al., 2005; Grunewald et al., 2006). Calderoni and Schnitzer (1984) found FAs preserved over the last ~29,000 yr in a paleosol on Italy, with no effect of age on their chemical structure or composition. In southwest China, core sediments from Erhai Lake provided fulvic acids ranging in age from ~1900 to 5700 cal yr BP (Xu and Zheng, 2003). These studies attest to the durability and utility of using FAs as a paleoenvironmental proxy.

Carbon isotopes

Paleoecological information is derived from carbon isotopes in soil organic matter because soil isotopic composition reflects the type of local plant matter (Quade et al., 1989). Shifts in vegetation between C_3 and C_4 plants are recorded in the δ^{13}C data from the soil organic acids (Schwartz et al., 1986; Clapp et al., 1997). Plants preferentially favor the lighter ^{12}C isotope, but isotopic preferences between C_3 and C_4 plants differ, causing distinctive δ^{13}C values for each type. Changes from C_3 to C_4 vegetation are indicated by shifts between depleted δ^{13}C values, indicative of dense forested (C_3) conditions, and enriched δ^{13}C values, indicative of the presence of more arid (C_4) vegetation, such as grasses and scrub (Desmarchelier et al., 2000; Dorale et al., 1992). On average, C_3 plant δ^{13}C values range from −33‰ to −27‰, whereas C_4 vegetation ranges from −16‰ to −9‰ (Schwartz et al., 1986; Botrell, 1996; Huang et al., 2001; Tourney et al. 2001). The surface soil, containing organic matter with its associated δ^{13}C values, is then washed into the cave-forming sediments, which provide a long-term record of vegetation change above the cave (Panno et al., 2004).

Study area

The Ix Chel archaeological site study area (Fig. 2), centered at 16°52.84′N and 89°06.68′W, is a 25-km^2 area located on the northern Vaca Plateau, Belize (Fig. 1). The Ix Chel ruins comprise a medium-sized site, containing three groups of buildings, a ballcourt, and a Sak Beh (Fig. 2) (Colas et al., 2006). Despite cultural reference to this area being the Lowlands during Maya occupation, the region's physical landscape is part of the Southern Karst Uplands. The Vaca Plateau, located near the Guatemala border, exhibits high relief, encompassing well-drained, extensively karstified limestone characterized by several moderately-sized residual hills and dry valleys (Reeder, 2003; Webb et al., 2004). The area's limestone consists of the extensively brecciated Cretaceous Campur Formation, which extends over large areas of both Belize and Guatemala (Reeder et al., 1996). The only other exposed unit is the granitic Mountain Pine Ridge area of the Maya Mountains to the east (Reeder et al., 1996). The highest elevation in the study area is ~520 m.a.s.l., with the greatest relief being 120 m from the highest residual hills to the valley floor. Besides the rugged topography, the area has numerous sinkholes and deep vertical caves. Miller (1990) estimated that regional karstification of the area began approximately 700,000 yr ago. Ancient Maya terraces are still present in the landscape, along with abandoned cultural remains.

Vegetation in the area consists of tropical and sub-tropical rainforest-type palms and other plants, including dominant

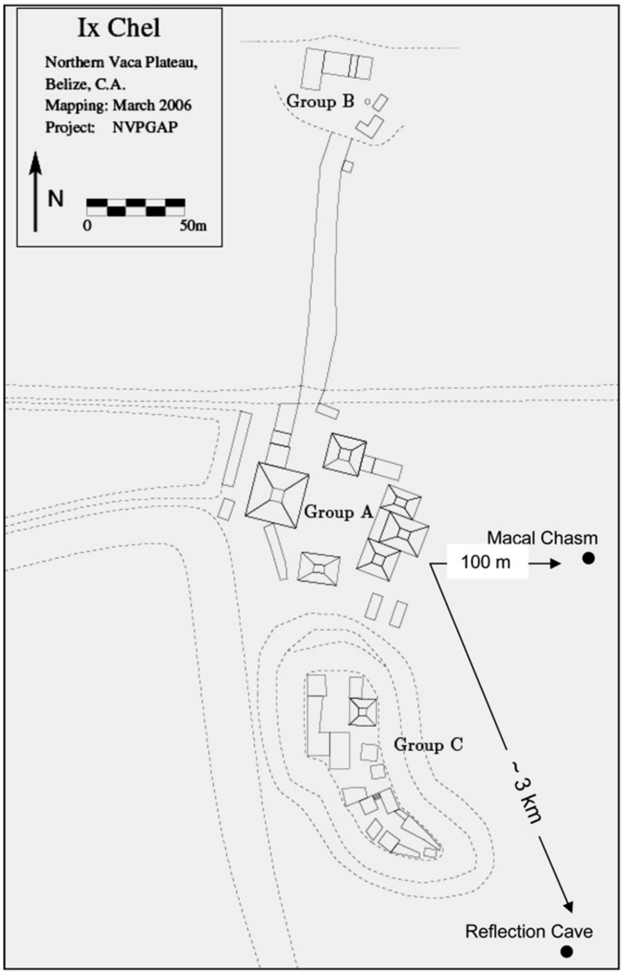


Figure 2. Map of the Ix Chel archaeological site and its relative location to Macal Chasm and Reflection Cave. Dotted lines indicate ancient roads and/or major pathways. Distances to Macal Chasm and Reflection Cave are not to map scale—correct distances noted on map (modified from Colas et al., 2006, unpublished report).

mahogany and ceiba trees. Understory vegetation consists of sapodilla, fig, Spanish cedar, and a diverse variety of palms (Penn et al., 2004). In the well-drained mountainous hilltops, cacti are also present. The soil is predominantly derived from weathered limestone and consists mostly of Cabro stony clays, which are predominantly kaolinite (Furley, 1976). Soils are fairly sparse on the hillslopes, with soil depths of 5 to 10 cm on average (Reeder, 2003). However, the valley bottoms contain several meters of clayey soils due to the accumulation of slope wash from the hillslopes.

The region's climate is tropical rainforest; however, there is a prevailing rainy season from June to November and annual rainfall amounts are between 2000 and 2400 mm. Peak precipitation amounts occur in June and July, reaching maximums of 100 mm per hour (Furley and Newey, 1979). Highest temperatures occur in May, with a mean annual temperature of 25 °C. The main atmospheric influences on precipitation are the Intertropical Convergence Zone (ITCZ) and the North Atlantic High (Bermuda-Azores High). Precipitation increases when the ITCZ is positioned more northerly during the summer and drier conditions prevail when it is displaced further to the south by the North Atlantic High (Fig. 1) (Haug et al., 2003; Hodell et al., 2005b).

Reflection Cave (Fig. 3) lies at the base of a steep hill approximately 3 km southeast of the Ix Chel ruins (Fig. 2), the largest abandoned Maya settlement in the study area. The cave has an 11-m-deep vertical entrance, branching off into two short opposing passages on either side of the entrance. Sediments are abundant in the cave, representing surface soils washed in from an area around the cave entrance, which then accumulate in a small, confined passage in the cave. Maya activity in the cave, usually indicated by artifacts, remains, structures, or broken formations, could have disturbed the sediments during or after deposition; however, there is no evidence of prior human activity in the cave.

Methodology

Field sample collection

In 2004, fifteen cave sediment samples were collected in stratigraphic order at ~5-cm intervals from a ~82-cm-thick sediment bank along a narrow, isolated passageway halfway down the north branch of Reflection Cave (Fig. 3). Samples were taken at this resolution because the scope of the study was exploratory and intended to determine whether these cave

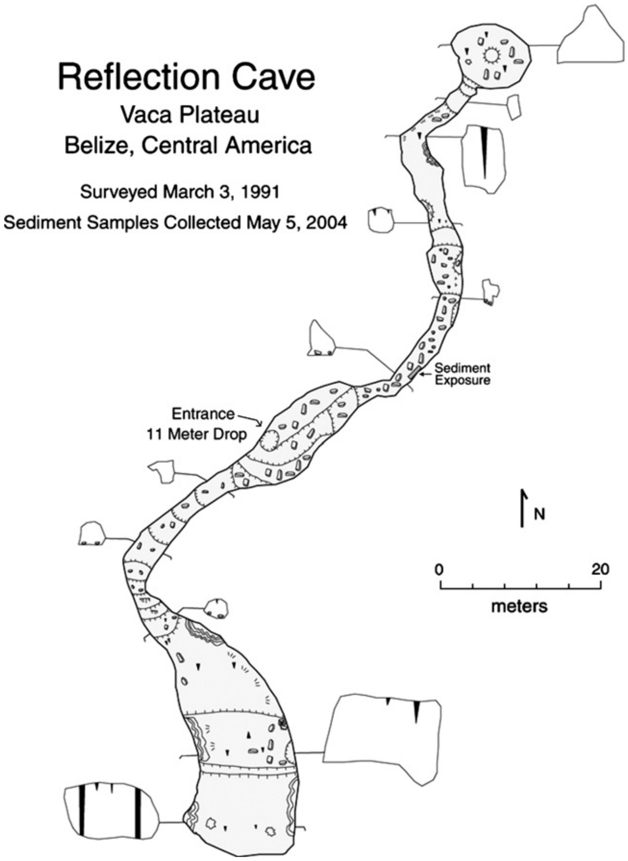


Figure 3. Map of Reflection Cave on the Vaca Plateau, Belize with marked location of sediment bank exposure where samples were collected.

sediments had any value for paleoenvironmental reconstruction. The samples were bagged, sealed, and brought back to the University of South Florida's Soils and Physical Geography Lab, where each sediment sample was air-dried for 24 h prior to analysis.

Radiocarbon dating

Radiocarbon dates were obtained for layers where sufficient organic carbon was present in the form of charcoal, seeds, wood, and organic matter, to establish a chronological record of deposition for the sediment bank. The dating was performed at the University of Arizona AMS Lab using a General Ionex accelerator mass spectrometer. Dates were calibrated to calendar ages using the CalPal computer program and reported to within the 95.4% confidence limits of the calibration (Weninger et al., 2005).

Stable carbon isotopes

FAs were extracted from the sediments for carbon isotope ($\delta^{13}C$) analysis according to the methods described by Hayes and Wilson (1997). Initially, the sediment samples were dried and ground, and then mixed in a 1:10 soil to 0.1 M HCl ratio in centrifuge tubes and shaken overnight. This mixture was then centrifuged for 30 min at 13,000 rpm. After decanting, the residue was washed with distilled water, centrifuged at 13,000 rpm for 30 min, and the supernatant was decanted and added to the HCl extract from the first round of centrifuging.

To precipitate the humic acids and leave the FAs in solution, the sediment residues were mixed in a 1:10 ratio with 0.1 M NaOH and shaken for 3 h under an atmosphere of N_2. Individual slurries were then centrifuged (13,000 rpm for 30 min) and the yellowish-brown supernatant was decanted and acidified with 6 M HCl to a pH of 1.0. This process was repeated on each residue until the supernatants were virtually clear (~8 times). The acidified supernatants were combined for each sample once clarity was obtained, refrigerated, and left overnight to allow flocculation. After flocculation, the FA fractions were then obtained by centrifuging (13,000 rpm for 30 min) and the supernatant from each was added to the previously combined acidified supernatants obtained prior to flocculation, leaving the solid FAs suspended within ~50 ml of brine water.

The isolated FA fractions then had the excess water removed using a Buchi Rotavapor R-114 to ~30 ml. Each sample was then put in a deep-freezer at −75 °C and left overnight. Completion of the drying process was performed by placing the samples in a Labconco Vacuum Freeze-Dry System for 72 h, until they became powdered and crystalline. The powdered FAs were placed in sealed containers and kept cool and dry until they were analyzed.

$\delta^{13}C$ of the FA fractions were measured with a Carlo-Erba NA2500 Series II elemental analyzer coupled to a Thermo-Finnigan Delta+XL isotope ratio mass spectrometer in continuous flow mode located at the University of South Florida's College of Marine Science Paleoclimatology, Paleoceanography and Biogeochemistry Laboratory in St. Petersburg, Florida. Samples of ~30 μg were placed in tin containers and dropped from a Costech Zero-blank Autosampler into an EA combustion furnace thermostatically stabilized at 1000 °C, where they were combusted with an excess of ultra-high purity (UHP) O_2. Combustion products were entrained in a UHP He carrier stream and passed through a reduction furnace (to remove excess O_2 and reduce NO_x to N_2), a water trap and a GC column (3 m, 0.25" dia. 5 A mol sieve) before entering the IRMS via an open-split interface (ThermoFinnigan ConFlo II). Analyzed gases were measured against reference gases (UHP N_2 and UHP CO_2) and are expressed in per mil (‰) relative to their respective reference materials (VPDB for $\delta^{13}C$). Estimates of analytical precision were obtained by replicate measurements of internal lab reference materials and yield a precision of ±0.3‰ for $\delta^{13}C$.

Results

Chronology

Radiocarbon dates from charcoal, wood, seeds, and organic matter from nine layers of sediment in Reflection Cave provide a chronology of deposition (Table 1, Fig. 4). The age of the sediment bank's surface was assumed to be modern based on the post-bomb ^{14}C date of the top layer. Dates at depths of 45 and 58 cm were out of sequence, possibly due to old organic material used for the dates being stored on the surface, and later flushed into the cave by a severe rain event. These dates were still used in constructing the age model (Fig. 4) and all other dates were in chronological order. The depth-to-age model was constructed using a second-order polynomial regression model to provide a chronological record for the $\delta^{13}C$ values of the FAs (Fig. 5). Although the r^2 of the regression is 0.80 ($p < 0.001$), the number of dates used (nine) provides acceptable confidence in the timescale reconstruction.

Interpretation of FA carbon isotopes

The carbon isotope record for Reflection Cave ranges from −27.1‰ to −21.5‰, exhibiting variability of ~5.6‰ (Fig. 5). As seen in Figure 5, the period from 2500 to 2400 cal yr BP

Table 1
AMS radiocarbon dates, calibrated ages, and errors from charcoal, wood, and organic matter in reflection cave sediments

Accession no.	Sample ID	Depth (cm)	Age (^{14}C yr BP)	± (1σ)	Age (cal yr BP)	± (2σ)
AA60342	REF04-01	0	Post-bomb	–	0	–
AA63332	REF04-02	12	817	39	737	68
AA60341	REF04-03	22	1975	39	1935	82
AA63333	REF04-04	38	2072	64	2050	160
AA60340	REF04-05	45	1437	38	1342	54
AA63334	REF04-06	58	2690	120	2792	320
AA60339	REF04-07	63	2071	41	2050	110
AA63335	REF04-08	68	2361	37	2403	98
AA60338	REF04-09	78	2586	39	2688	128

Dates were calibrates using the CalPal radiocarbon calibration program (Beyond the Ghost version 2005).

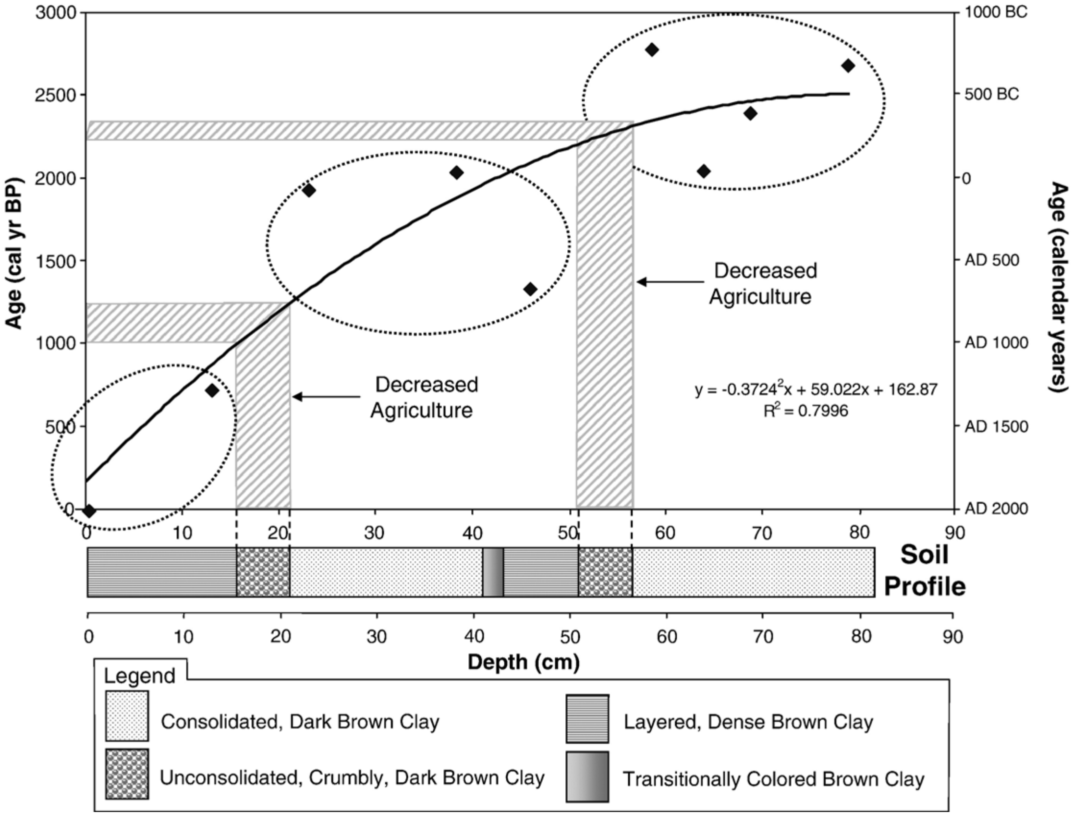


Figure 4. Depth-to-age model for Reflection Cave sediments using radiocarbon dates from Table 1. Circles indicate clusters of dates representing suggested periods of Mayan occupation. Soil profile and legend are included to show relationship between layer characteristics and transitions and periods of Mayan depopulation as shown by diagonal-hatched gray bars.

(500 to 400 BC) shows δ^{13}C values becoming more negative from ∼−22.5‰ at 2500 cal yr BP (500 BC) to −26‰ by 2400 cal yr BP (400 BC). Around 2400 to 2100 cal yr BP (400 to 100 BC), δ^{13}C values shift from −26‰ to −21.5‰ and from 2100 to 1500 cal yr BP (100 BC to AD 500) there is a prolonged period of enriched δ^{13}C values ∼−22‰. This period is punctuated by a short interval of isotopic depletion approximately 1900 cal yr BP (AD 100). After 1550 cal yr BP (AD 450) there is a steady decline toward more depleted values (−27‰). At ∼850 cal yr BP (AD 1150), the sediments record a brief period of relative enrichment (Fig. 5).

Three possible causes for this variability are sediment transport, residence time of the FAs in the soil, and changing vegetation type. Pertaining to sediment transport and residence time, the age model (Fig. 4) shows a fairly linear relationship between sediment depth and age. This suggests a continuous input of sediment into the cave, whereby the δ^{13}C values are representative of decaying surface vegetation. Therefore, the remaining explanation is that the cave sediments record changes in vegetation type.

The two isotopic end members of vegetation in the study area are natural vegetation (C_3) and agricultural vegetation, predominantly maize (C_4), which occurs during Maya occupation. The relative quantities of each determine the isotopic values of the surface soils, which then collect in the cave as sediment. Therefore, the overall isotopic values for a certain period of time represent the relative proportions of natural and agricultural vegetation. It is doubtful, due to the steep topography of the study area and amount of forest cover, that complete shift to agricultural (C_4) vegetation occurred. Consequently, even during periods of Maya occupation both types of vegetation will be present. Reflection Cave's catchment area incorporates both terraced (agricultural) and non-terraced (natural) slopes, thereby creating an ideal depository of relative change in vegetation over time. Taking this explanation and applying it to the cave sediment δ^{13}C values, −27.1‰ is representative of natural vegetation and −21.5‰ is representative of contribution from Maya agriculture. Therefore, the periods of Maya occupation in the study area are before 2400 cal yr BP (400 BC) and between 2300 cal yr BP (300 BC) and 1500 cal yr BP (AD 500) (Fig. 5).

Discussion

Interpretation of cave sediment record

The cave sediments from Reflection Cave provide a robust archive for environmental reconstruction, having been deposited fairly continuously over the past 2500 yr, according to the age model (Fig. 4). Vegetation changes in the surrounding landscape above Reflection Cave are seen in the δ^{13}C data, which displays a maximum shift of 5.6‰ (Fig. 5), suggesting substantial environmental changes during the depositional period. The sedimentary δ^{13}C values do not show major shifts

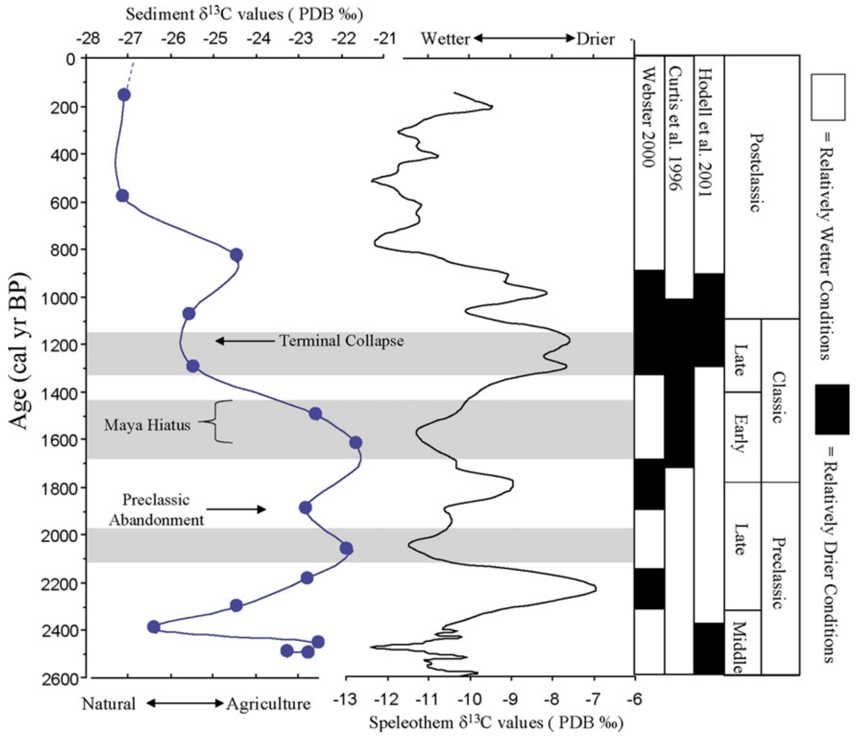


Figure 5. Reflection Cave sediment δ^{13}C record, as derived from depth-to-age model equation $y=-0.3724\times+59.022\times+162.87$, compared with speleothem (Webster, 2000, 3-point running mean) δ^{13}C record and δ^{18}O record. Speleothem δ^{13}C values shifted ~200 yr earlier to account for adjustment of dead carbon input during radiocarbon dating. Comparison also made to δ^{18}O records from Curtis et al. (1996) and Hodell et al. (2001) lake sediment cores. Dark bars indicate periods of aridity, while white bars indicate relatively wetter conditions (modified from Webster, 2000). Gray highlights indicate important periods where the speleothem and cave sediment records illustrate the climate and human impact relationship, where wetter (drier) conditions equate to increased (decreased) agriculture during Maya occupation of the site.

between C_3- and C_4-dominated systems, as discussed previously, but rather indicate variable contributions of agricultural (C_4) plants to the overall carbon isotope signal. More depleted (or, conversely, enriched) cave sediment δ^{13}C values suggest less (or more) maize on the surface. The cause of declining agriculture is suggested to be periods of prolonged aridity (Pessenda et al., 2001, 2005).

Suppression of the natural forest δ^{13}C values in the cave sediments during Maya occupation likely occurred during wet periods suitable for agriculture. Not only would this deforestation have decreased the density of the natural C_3 vegetation, but the addition of isotopically heavy C_4 crops, such as maize (δ^{13}C value ~−14.4‰) (Fronza et al., 2001), would have created more enriched δ^{13}C values in the surface soils (van Noordwijk et al., 1997). Therefore, the δ^{13}C values between −22.5‰ and −21.5‰ during the period of Maya occupation of the site reflect contribution from agricultural C_4 plants, thus causing δ^{13}C values related to a mixed C_3–C_4 environment. The natural C_3 vegetation is likely to have developed resilience towards recurring, periodic droughts over time, and would be able to recover once agriculture wanes because of arid conditions.

The Maya are presumed to have been utilizing the area for agriculture, although less intensively, around 2600 yr ago, when the population was lower. The area around the much larger Caracol archaeological site, located approximately 8 km to the south, has an occupation history that dates back to ~2600 cal yr BP (600 BC) (Chase and Chase, 1998). Activities associated with Caracol likely affected our study area during this time as well, given their close proximity to each other (and the size of Caracol). The sediment δ^{13}C data record suggests some agriculture was occurring within the study area prior to 2500 cal yr BP (500 BC), and decreasing for a short period at ~2400 cal yr BP (400 BC) (Fig. 5). We propose this was a short, pronounced dry period that led to a decline in agricultural production in the area. The carbon isotope values between −22.5‰ and −21.5‰ from 2300 to 1500 cal yr BP (300 BC to AD 500) coincide with the period of Maya occupation at the site (Colas et al., 2006, unpublished report). A brief period of agricultural decline occurred during this period at ~1900 cal yr BP (AD 100), which coincides with the timing of the Preclassic Abandonment (Webster, 2000; Haug et al., 2003).

About 1500 cal yr BP (AD 500), δ^{13}C values in the sediment record indicate the declining practice of agriculture, becoming more negative (−27‰), which is characteristic of a C_3-dominated environment receiving little contribution from the isotopically heavier C_4 agricultural plants. This period of agricultural decline coincides with the Maya Hiatus (~1470 to 1350 cal yr BP (AD 530 to 650) (deMenocal, 2001), and a contributing factor to depopulation would have been the lack of available water resources needed to sustain agriculture and a large population. The study area would likely have been among the first sites to be affected by aridity due to its naturally well-drained upland terrain, causing a shift away from agricultural land use that preceded many other lowland areas. By 1200 cal yr

BP (AD 800), the δ^{13}C values indicate the site was no longer used for agriculture, coinciding with the Terminal Classic collapse (Curtis et al., 1996; Hodell et al., 2001; Haug et al., 2003).

Proxy climate record comparisons

Webster (2000) reconstructed a useful carbon and oxygen isotope record from a speleothem in Macal Chasm, located only a few kilometers from Reflection Cave. The carbon isotopes from the speleothem record are interpreted to show periods of variable precipitation for the study area. Depleted (enriched) carbon isotope values in the speleothem correspond to increased (decreased) soil productivity caused by wetter (drier) conditions (Webster, 2000; Dorale et al., 1992, 1998, 2002) (Fig. 5). Oxygen isotopes from this same speleothem agree with the climate interpretation from the carbon isotopes.

A comparison between the speleothem and cave sediment δ^{13}C values provides support for our interpretation of the contribution of Maya agriculture (Fig. 5). There is a consistent offset of ~200 yr between the two records, and the Macal Chasm record has been shifted ~200 yr earlier to allow better comparison. We feel this is justified due the larger error associated with Webster's (2000) ^{14}C dates, since speleothem radiocarbon dating suffers from variable input of dead carbon, whereas our record does not. Such a shift is not unreasonable based on preliminary U-series dates of the speleothem, which suggests the radiocarbon ages are too young by this increment (Webster, personal communication, 2006).

A comparison of the speleothem carbon isotope data interpretation of changing climate, and the cave sediment carbon isotope data, reveal matching periods of aridity (decline of Maya agriculture), while periods of increased wetness agree with increased agricultural activity (Fig. 5). We propose that the speleothem carbon isotopes show changes in the natural vegetation in response to climate variability, because Macal Chasm (speleothem cave site) is located at a high elevation near the Ix Chel ruins above the terraced landscape, which often remained forested and was not used for agriculture (Coultas et al., 1993; van Noordwijk et al., 1997). Consequently, during arid periods, the speleothem carbon isotopes recording a decrease in soil productivity would be enriched in ^{13}C . This proposal is supported by the speleothem oxygen isotopes (Fig. 5). However, the cave sediment carbon isotopes record the presence of Maya agriculture on the landscape in addition to the natural vegetation. This is because Reflection Cave is located in a shallow, terraced valley that was used for agriculture, approximately 100 m lower in elevation than Macal Chasm, incorporating sediment from a larger catchment area in the landscape. In summary, the isotopic trends from both records, while showing the same climate events, move in opposite directions.

The Webster (2000) record shows a brief period of aridity ~2400 cal yr BP (400 BC), which corresponds to a decrease in agriculture indicated by the more depleted δ^{13}C values in the cave sediment record (Fig. 5). The decrease in agriculture, likely a result of Maya depopulation of the area, allowed the natural vegetation to dominate the landscape and cause depleted δ^{13}C values. After 2400 cal yr BP (400 BC), a shift toward depleted δ^{13}C values in the speleothem δ^{13}C data indicates wetter conditions and higher soil productivity, providing conditions conducive to increased agriculture, as shown by enriched δ^{13}C values recorded by the cave sediments, which reflect the input of C_4 (maize) vegetation (Fig. 5). Moist conditions suitable for agriculture continue in the area until ~1500 cal yr BP (AD 500), when the speleothem δ^{13}C values begin to show enrichment because of drier conditions suppressing the natural C_3 vegetation. The cave sediment δ^{13}C values agree with the speleothem δ^{13}C values during this period, showing an enrichment of δ^{13}C values from ~2300 to 1500 cal yr BP (300 BC to AD 500), then moving toward depleted δ^{13}C values associated with natural forest recovery, no longer being affected by human alteration of the landscape (Fig. 5).

Around 1900 cal yr BP (AD 100) there is a brief period of aridity seen in the speleothem δ^{13}C data, which coincides with a decline in agricultural activity, as indicated by a slight depletion in the cave sediment δ^{13}C data. Our resolution does not enable a closer decadal examination of this period; however, the timing only slightly leads the Preclassic Abandonment (~1950 to 1850 cal yr BP (AD 150 to 250)) seen in many other records from the region (Hodell et al., 2001; Haug et al., 2003). This difference in timing is most likely a result of the high susceptibility of our study area to aridity, stressing the Maya population to the point of a short-term decline in agriculture.

The continuous decline in agriculture occurring from ~1500 to 1200 cal yr BP (AD 500 to 800), as reflected in the more depleted cave sediment δ^{13}C values, suggests the area was heavily impacted by drought during this time (as reflected in more enriched speleothem δ^{13}C values), which began during the Maya Hiatus ~1470 to 1350 cal yr BP (AD 530 to 650) (deMenocal, 2001). It is possible the study area, being naturally more susceptible to drought due to deforestation and abundant agricultural alteration of the landscape, caused the Maya to depopulate the area and prevented population numbers from reaching those prior to the Hiatus. However, the area would not have been entirely deforested due to the steep topography, and consequently major decreases in evapotranspiration due to deforestation are unlikely to have been the main cause of aridity in this region. From ~1200 cal yr BP (AD 800) until the present, the speleothem and cave sediment δ^{13}C values show a general trend toward more negative values, indicating the absence of Maya influence on the landscape, which allowed both records to respond only to natural vegetation change, hence they are in isotopic agreement.

The slight differences in the interpretation of the two records can be attributed to resolution (speleothem record is a 3-point running mean) and the calibration of radiocarbon dates in the speleothem (which must estimate the amount of dead carbon contributing to the ^{14}C dates). This is not a problem, however, for dates obtained from the cave sediments (Gascoyne, 1992; Webster, 2000; Fairbanks et al., 2005).

Comparisons with the well-documented regional lacustrine records, as seen in Figure 5, help corroborate our cave sediment δ^{13}C data regarding environmental reconstruction during the late Holocene. These include lake sediment $\delta^{18}O$ data from Guatemala and Mexico, which show prolonged episodes of drought, although the timing and severity of these events are not always synchronous due to regionality effects (Curtis et al., 1998; deMenocal, 2001; Shaw, 2003; Demarest et al., 2004). The Lake Punta Laguna record from Mexico (Curtis et al., 1996) reported aridity between 1750 and 1100 cal yr BP (AD 250 and 900), with maximum dryness at ~1300 and 1100 cal yr BP (AD 700 and 900), during the Maya Hiatus and Terminal Classic periods, respectively. The former period coincides with the start of the agricultural decline shown in the cave sediment $\delta^{13}C$ data (Fig. 5). Further lacustrine studies in the Yucatan by Hodell et al. (2001) found two periods of aridity that coincide relatively closely to decreasing agriculture indicated in the cave sediment record $\delta^{13}C$ data, including the period ~2400 cal yr BP (400 BC) and from 1300 to 900 cal yr BP (AD 700 to 1100).

Climatic causes of aridity

Increasingly frequent periods of cyclic aridity have occurred in Mesoamerica during the last 2600 yr, and atmospheric influences affecting climate in the region are the probable cause (Haug et al., 2003; Hodell et al., 2005b). The migration of the ITCZ is the main factor influencing precipitation in the Caribbean region, due to its seasonal latitudinal migration (Haug et al., 2001) (Fig. 1). When the ITCZ is located to the north, the Easterly trade winds, positioned by the North Atlantic High, push warm, moist Caribbean air up the Maya Mountains, increasing convective activity and precipitation (Haug 2003; Hodell et al 2005b). The dry season occurs when the ITCZ is in its southernmost position.

Haug et al. (2001, 2003) proposed that when the ITCZ mean annual position is further to the south, northern South America experiences prolonged drought. This would affect precipitation amount in Belize as well, decreasing the strength of the Easterlies, which direct moist air to the Vaca Plateau. In the past, this scenario has occurred for durations of decadal and even centennial lengths, causing reduced precipitation and long-term drought episodes in Mesoamerica. During wetter conditions, expansion of Maya occupation and agriculture would likely have occurred on the Vaca Plateau, due to increased availability of water resources. The concurrence of Haug et al.'s (2003) Maya collapse and the southern position of the ITCZ correspond closely with the major shift in our $\delta^{13}C$ values in the sediment record. Therefore, the likely mechanism for such a shift in our carbon isotopes (decline in agriculture) was the changing mean position of the ITCZ, which would have led to decreased precipitation.

Conclusions

Carbon isotopes extracted from sediments in Reflection Cave record changing environmental conditions over the last 2500 yr on the Northern Vaca Plateau in west central Belize. The location of the cave on the landscape collects sediment from a large catchment area, thereby allowing it to record changes in agriculture during Maya occupation. Cave sediment fulvic acid $\delta^{13}C$ values indicate the presence of Maya agriculture in the study area around 2500 cal yr BP (500 BC), which declines until ~2300 cal yr BP (400 BC). After this, agriculture again increases, as evidenced from more enriched $\delta^{13}C$ values, which last throughout the Maya occupation until ~1500 cal yr BP (AD 500). At ~1900 cal yr BP (AD 100) there is an abrupt decline in agriculture, consistent with the Preclassic Abandonment period. Beginning 1500 cal yr BP (AD 500) and coinciding with the Maya Hiatus, conditions became drier and agricultural activities begin to decline, thereby reducing agricultural (C_4) plant presence on the landscape and causing a shift in the sediment $\delta^{13}C$ values toward depletion. Carbon and oxygen isotopes from a speleothem collected in Macal Chasm (Webster, 2000), a cave within the study area, show changes in aridity and its effect on natural vegetation. The speleothem $\delta^{13}C$ and $\delta^{18}O$ data closely support the cave sediment record interpretation.

Intensive agriculture and landscape manipulation at this site seems to have waned earlier than other records of Maya activity around the region (Curtis et al., 1996, Haug et al., 2003; Hodell et al., 2005a), punctuated by declining agriculture beginning during the Maya Hiatus. This provides evidence for our supposition that a highly karstified, well-drained upland occupation site would have been among the first areas to be affected during periods of prolonged drought. As the area was depopulated, land once used for agriculture began to return to forest.

The consensus of the proxy climate records from Mesoamerica indicate that regional aridity occurred at differing times and severity across the region, providing substantial evidence of abrupt climate change that was detrimental to cultural evolution (Haug et al., 2003; Hodell et al., 2005a; Neff et al., 2006). Prolonged periods of southward ITCZ and NAH migration may be responsible for periodic episodes of extended drought conditions in the area, and the Northern Vaca Plateau would have been highly susceptibility to such events. While the sediments from Reflection Cave provide only one small piece of the much larger puzzle, they provide another means by which past environmental changes in Mesoamerica can be understood. Further use of cave sediments in the area to reconstruct environmental change at a higher resolution will provide continued insight into environmental change and the Maya impact on the area's landscape.

Acknowledgments

The authors would like to thank the members of the 2004 Vaca Plateau Geoarchaeological Project field expedition. We thank Ethan Goddard (*USF*- St. Petersburg) for assistance with processing samples for $\delta^{13}C$ and Grant Harley for help with radiocarbon dating sample extraction. We are grateful to Dr. James Webster for access to his dissertation data and information through personal communication. We thank Dr. Jaime Awe, Director of the Belize Institute of Archaeology, and Dr. John Morris, Director of Research for the Archaeology Institute, for their continued support of this project. We also thank Dr. Pierre Robert Colas, from the Department of Anthropology at Vanderbilt University, for his assistance with the archaeological interpretations of the study area. We also thank Dr. Peter Harries for his insightful review of this article. This research was funded in part by a National Speleological Society International Travel Grant and the University of South Florida.

References

Aiken, G.R., McKnight, D.M., Wershaw, R.L., MacCarthy, P. (Eds.), 1985. Humic Substances in Soil, Sediment, and Water. John Wiley and Sons, New York.

Biggs, T.H., Quade, J., Webb, R.H., 2002. δ^{13}C values of soil organic matter in semiarid grassland with mesquite (*Prosopis*) encroachment in southeastern Arizona. Geoderma 110, 109–130.

Botrell, S., 1996. Organic carbon concentration profiles in recent cave sediments: Records of agricultural pollution or diagensis? Environmental Pollution 91 (3), 325–332.

Brinkmann, R., Reeder, P., 1995. The relationship between surface soils and cave sediments: an example from west central Florida, USA. Cave and Karst Science 22, 95–102.

Chase, A.F., Chase, D.Z., 1989. The investigation of Classic Period Maya warfare at Caracol, Belize. Mayab 5, 5–18.

Chase, A.F., Chase, D.Z., 1998. Scale and intensity in Classic Period Maya Agriculture: Terracing and settlement at the “Garden City” of Caracol, Belize. Culture and Agriculture 20 (2/3), 60–77.

Calderoni, G., Schnitzer, M., 1984. Effects of age on the chemical structure of paleosol humic acids and fulvic acids. Geochimica et Cosmochimica Acta 48, 2045–2051.

Clapp, C.E., Layese, M.F., Hayes, M.H.B., Huggins, D.R., Alimaras, R.R., 1997. Natural Abundances of ^{13}C in Soils and Water. In: Hayes, M.H.B., Wilson, W.S. (Eds.), Humic Substances in Soils, Peats, and Waters: Health and Environmental Aspects. The Royal Society of Chemistry, Cambridge, pp. 159–175.

Claret, F., Schafer, T., Rabung, T., Wolf, M., Bauer, A., Backau, G., 2005. Differences in properties and Cm(III) complexation behavior of isolated humic and fulvic acid derived from Opalinus clay and Callovo-Oxfordian argillite. Applied Geochemistry 20, 1158–1168.

Colas, P.R., Stengert, K.C., Wolfel, U., 2006. The Mapping of Ix Chel: A Terminal Classic secondary Maya site on the Northern Vaca Plateau, Belize, Central America. In: Reeder, Philip P. (Ed.), Technical Report to Government of Belize.

Coultas, C.L., Collins, M.E., Chase, A.F., 1993. The effect of Mayan agriculture on terraced soils of Caracol, Belize. In: Foss, J.E., Timpson, M.E., Morris, M.E. (Eds.), Proceedings of the First International Pedo-Archaeology Conference. Special Publication No. 93–4. Agricultural Experiment Station, University of Tennessee, Knoxville.

Courty, M.A., Vallverdu, J., 2001. The microstratigraphic record of abrupt climate changes in cave sediments of the Western Mediterranean. Geoarchaeology 16 (5), 467–500.

Cowgill, U.M., 1962. An agricultural study of the southern Maya Lowlands. American Anthropologist 64 (2), 273–286.

Curtis, J.H., Hodell, D.A., Brenner, M., 1996. Climate variability on the Yucatan Peninsula (Mexico) during the past 3500 years, and implication for Maya cultural evolution. Quaternary Research 46, 37–47.

Curtis, J.H., Brenner, M., Hodell, D.A., Balser, R.A., Islebe, G.A., Hoogheimstra, H., 1998. a multi-proxy study of Holocene environmental change in the Maya Lowlands of Peten, Guatemala. Journal of Paleolimnology 19, 139–159.

Demarest, A.A., Rice, P.M., Rice, D.S., 2004. The Terminal collapse in the Maya Lowlands: Assessing collapses, terminations, and transformations. In: Demarest, A.A., Rice, P.M., Rice, D.S. (Eds.), The Terminal Classic in the Maya Lowlands: Collapse, Transition, and Transformation. University Press of Colorado, Boulder, pp. 545–572.

deMenocal, P.B., 2001. Cultural responses to climate change during the Late Holocene. Science 292, 667–673.

Desmarchelier, J.M., Goede, A., Ayliffe, L.K., McCulloch, M.T., Moriarty, K., 2000. Stable isotope record and its paleoenviornmental interpretation for a late Middle Pleistocene speleothem from Victoria Fossil Cave, Naracoorte, South Australia. Quaternary Science Reviews 19, 763–774.

Doane, T.A., Devevre, O.C., Horwath, W.R., 2003. Short-term carbon dynamics of humic fractions in low-input and organic cropping systems. Geoderma 114, 319–331.

Dorale, J.A., Gonzalez, L.A., Reagan, M.K., Pickett, D.A., Murrell, M.T., Baker, R.G., 1992. A high-resolution record of Holocene climate change in speleothem calcite from Cold Water Cave, Northeast Iowa. Science 258, 1626–1630.

Dorale, J.A., Edwards, R.L., Ito, E., Gonzalez, L.A., 1998. Climate and Vegetation History of the Midcontinent from 75 to 25 ka: A Speleothem Record from Crevice Cave, Missouri, USA. Science 282, 1871–1874.

Dorale, J.A., Edwards, R.L., Onac, B.P., 2002. Stable isotopes as environmental indicators in speleothems. In: Yuan, D.-X. (Ed.), Karst Processes and the Carbon Cycle. Geological Publishing House, Beijing, China, pp. 107–120.

Fairbanks, R.G., Mortlock, R.A., Chiu, T., Cao, L., Kaplan, A., Guilderson, T., Fairbanks, T.W., Bloom, A.L., Grootes, P.M., Nadeau, M., 2005. Radiocarbon calibration curve spanning 0 to 50,000 years BP based on paried ^{230}Th/^{234}U/^{238}U and ^{14}C dates on pristine corals. Quaternary Science Reviews 24, 1781–1796.

Fronza, G., Fuanti, C., Grasselli, P., Serra, S., Guillou, F.R.C., 2001. δ^{13}C and δ^{18}O-values of glycerol of food fats. Rapid Communication in Mass Spectrometry 15, 763–766.

Furley, P.A., 1976. Soil-slope–plant relationships in the Northern Maya Mountains, Belize, Central America: III. Variations in the properties of soil profiles. Journal of Biogeography 3 (3), 303–319.

Furley, P.A., Newey, W.W., 1979. Variations in plant communities with topography over tropical limestone soils. Journal of Biogeography 6, 1–15.

Gascoyne, M., 1992. Palaeoclimate determination from cave calcite deposits. Quaternary Sciences Reviews 11, 609–663.

Gill, R.B., 2000. The Great Maya Droughts: Water, Life, and Death. University of New Mexico Press, Albuquerque.

Grunewald, G., Kaiser, K., Jahn, R., Guggenberger, G., 2006. Organic matter stabilization in young calcareous soils as revealed by density fractionation and analysis of lignin-derived constituents. Organic Geochemsitry 37, 1573–1589.

Gunn, J.D., Matheny, R.T., Folan, W.J., 2002. Climate-change studies in the Maya area: a diachronic analysis. Ancient Mesoamerica 13, 79–84.

Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C., Rohl, U., 2001. Southward migration of the Intertropical Convergence Zone through the Holocene. Science 293, 1304–1308.

Haug, G.H., Günther, D., Peterson, L.C., Sigman, D.M., Hughen, K.A., Aeschlimann, B., 2003. Climate and the collapse of the Maya Civilization. Science 299, 1731–1735.

Hayes, M.H.B., Wilson, W.S., 1997. Humic Substances, Peats and Sludges: Health and Aspects. Royal Society of Chemistry, Cambridge.

Hodell, D.A., Curtis, J.H., Brenner, M., 1995. Possible role of climate in the collapse of Classic Maya civilization. Nature 375, 391–394.

Hodell, D.A., Brenner, M., Curtis, J.H., Guilderson, T., 2001. Solar forcing of drought frequency in the Maya Lowlands. Science 292, 1367–1370.

Hodell, D.A., Brenner, M., Curtis, J.H., 2005a. Terminal classic drought in the northern Maya lowlands inferred from multiple sediment cores in Lake Chichancanab (Mexico). Quaternary Science Reviews 24, 1413–1427.

Hodell, D.A., Brenner, M., Curtis, J.H., Medina-Gonzalez, R., Ildefonso-Chan Can, E., Albornaz-Pat, A., Guilderson, T.P., 2005b. Climate change on the Yucatan Peninsula during the Little Ice Age. Quaternary Research 63, 109–121.

Huang, Y., Street-Perrott, F.A., Metcalfe, S.E., Brenner, M., Moreland, M., Freeman, K.H., 2001. Climate change as the dominant control on glacial–interglacial variations in C_3 and C_4 plant abundance. Science 293, 1647–1651.

Hughen, K.A., Eglinton, T.I., Xu, L., Makou, M., 2004. Abrupt tropical vegetation response to rapid climate changes. Science 304, 1955–1959.

Leyden, B.W., 2002. Pollen evidence for climatic variability and cultural disturbance in the Maya Lowlands. Ancient Mesoamerica 13, 85–101.

Liao, J.D., Boutton, T.W., Jastrow, J.D., 2006. Organic matter turnover in soil physical fractions following woody plant invasion of grassland: Evidence from natural ^{13}C and ^{15}N. Soil Biology and Biochemistry 38, 3197–3210.

Lucero, L.J., 2002. The collapse of the Classic Maya: A case for the role of water control. American Anthropologist 104 (3), 814–826.

Miller, T., 1990. Caves and Caving in Belize: An Overview. Caves and Caving 46, 2–4.

Neff, H., Pearsall, D.M., Jones, J.G., Arroyo de Pieters, B., Freidel, D.E., 2006. Climate change and population history in the Pacific Lowlands of Southern Mesoamerica. Quaternary Research 65, 390–400.

Panno, S.V., Curry, B.B., Wang, H., Hackley, K.C., Liu, C.L., Lundstrom, C., Zhou, J., 2004. Climate change in southern Illinois, USA, based on the age and δ^{13}C of organic matter in cave sediments. Quaternary Research 61, 301–313.

Penn, M.G., Sutton, D.A., Monro, A., 2004. Vegetation of the Greater Maya Mountains, Belize. Systematics and Biodiversity 2 (1), 21–44.

Quade, J., Cerling, T.E., Bowman, J.R., 1989. Development of Asian monsoon revealed by marked ecological shift during the latest Miocene in northern Pakistan. Letters to Nature 342, 163–166.

Qualls, R.G., 2004. Biodegradability of humic substances and other fractions of decomposing leaf litter. Soil Science Society of America Journal 68, 1705–1712.

Qualls, R.G., Takiyama, A., Wershaw, R.L., 2003. Formation and loss of humic substances during decomposition in a pine forest floor. Soil Science Society of America Journal 67, 899–909.

Pessenda, L.C.R., Boulet, R., Aravena, R., Rosolen, V., Gouveia, S.E.M., Ribeiro, A.S., L amotte, M., 2001. Origin and dynamics of soil organic matter and vegetation changes during the Holocene in a forest-savanna transition zone, Brazilian Amazon region. The Holocene 11 (2), 250–254.

Pessenda, L.C.R., Ledru, M.P., Gouveia, S.E.M., Aravena, R., Ribeiro, J.A., Bendassolli, J.A., Boulet, R., 2005. Holocene paleoenvironmental reconstruction in northeastern Brazil inferred from pollen, charcoal, and carbon isotope records. The Holocene 15 (6), 812–820.

Reeder, P., 2003. Physical and cultural landscapes on the Northern Vaca Plateau, Belize. Journal of Belizean Affairs 5 (1), 5–30.

Reeder, P., Brinkmann, R., Alt, E., 1996. Karstification on the Northern Vaca Plateau, Belize. Journal of Cave and Karst Studies 58 (2), 121–130.

Rosenmeier, M.F., Hodell, D.A., Brenner, M., Curtis, J.A., Martin, J.B., Anselmetti, F.S., Ariztegui, D., Guilderson, T.P., 2002. Influence of vegetation change on watershed hydrology: implications of paleoclimatic interpretation of lacustrine δ^{18}C records. Journal of Paleolimnology 27, 117–131.

Schwartz, D., Mariotti, R., Lanfranchi, R., Guillet, B., 1986. ^{13}C/^{12}C ratios in soil organic matter as indicators of vegetation changes in the Congo. Geoderma 39, 97–103.

Shaw, J.M., 2003. Climate change and deforestation: Implications for the Maya Collapse. Ancient Mesoamerica 14, 157–167.

Spaccini, R., Piccolo, A., Haberhauer, G., Gerzabek, M., 2000. Transformation of organic matter from maize residues into labile and humic fractions of three European soils as revealed by ^{13}C distribution and CPMAS-NMR spectra. European Journal of Soil Science 51, 583–594.

Spaccini, R., Mbagwu, J.S.C., Conte, P., Piccolo, A., 2006. Changes of humic substances characteristics from forested to cultivated soils in Ethiopia. Geoderma 132, 9–19.

Soto, L.R., 2005. Reconstruction of Late Holocene Precipitation for Central Florida as Derived from Isotopes in Speleothems. Unpublished Masters Thesis, Department of Geology, University of South Florida, Tampa, Florida.

Stevenson, F.J., 1994. Humus Chemistry—Genesis, Composition, Reactions, 2nd ed. Wiley, New York.

Turney, C.S.M., Bird, M.I., Roberts, R.G., 2001. Elemental δ^{13}C at Allen's Cave, Nullarbor Plain, Australia: assessing post-depositional disturbance and reconstructing past environments. Quaternary Science 16, 779–784.

van Beynen, P.E., Ford, D., Schwarcz, H., 2000. Seasonal variability in organic substance in surface cave waters at Marengo Cave, Indiana. Hydrological Processes 14, 1177–1197.

van Noordwijk, M., Cerri, C., Woomer, P.L., Nugroho, K., Bernoux, M., 1997. Soil carbon dynamics in the humid tropical forest zone. Geoderma 79, 187–25.

Webb, E.A., Schwarcz, H.P., Healy, P.F., 2004. Detection of ancient maize in lowland Maya soils using stable carbon isotopes: evidence from Caracol, Belize. Journal of Archaeological Science 31, 1039–1052.

Webster, J., 2000. Speleothem Evidence of Late Holocene Climate Variation in the Maya Lowlands of Belize, Central America and Archaeological Implications. Unpublished Doctoral Dissertation. Department of Geography, University of Georgia, Athens, GA, 233 pp.

Weninger, B., Joris, O., Danzeglocke, U., 2005. CalPal Radiocarbon Calibration Package. University of Cologne, Germany.

Xu, S., Zheng, G., 2003. Variations in radiocarbon ages of various organic fractions in core sediments from Erhai Lake, SW China. Geocemical Journal 37, 135–144.

Yamskikh, A., 1998. Late Holocene soil formation in the valley of the River Yenisei, Central Siberia. Catena 34, 47–60.