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## Beyond the Mayan Lowlands: impacts of the Terminal Classic Drought in the Caribbean Antilles

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### ABSTRACT

High-resolution paleoclimate records from the Mayan Lowlands and the Cariaco Basin have shown that the collapse of the Mayan socio-political structure at the end of the Classic period ~1000 C.E. was linked to a series of severe, multi-decadal drought events, collectively termed the 'Terminal Classic Drought' (TCD), between ~750 and 1100 C.E. Here we present proxy evidence indicating that increased aridity leading up to and during the TCD also strongly affected the Caribbean Antilles. Additionally, the timing of the TCD corresponds with cultural and demographic shifts in the Greater Antilles, including the appearance of Ostionoid cultural traditions, the colonization of new islands, and the intensification of agriculture. We propose that these multi-decadal droughts affected not only the very large and complex socio-political structures governing large populations like that of the Late Classic Maya, but also smaller and less politically complex societies across the Caribbean. However, instead of resulting in societal collapses as suspected in the Mayan Lowlands, these climatic events may have spurred a cultural transition across the Caribbean Antilles that ultimately led to the development of Taíno cultural traditions encountered by Christopher Columbus upon his arrival in 1492 C.E.

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### 1. Introduction

Efforts to assess impacts of climate change on prehistoric human societies contribute to long-standing debates regarding the effects of environmental change on culture and may provide models for potential responses of modern societies to future climate change (deMenocal, 2001; Turner and Sabloff, 2012). Shifts in climate have been put forward as explanations for varied instances of societal change, conflict, and collapse during prehistory (deMenocal, 2001 and references therein; Brooks, 2006; Kumar et al., 2006; Carrión et al., 2007; Polk et al., 2007; Zhang et al., 2008; Buckley et al., 2010; Hsiang et al., 2011, 2013; Kelley et al., 2013; Taylor et al., 2013). Perhaps none of these societal changes has attracted more attention than the disintegration of the Classic Mayan civilization between 800 and 1100 C.E. following a ~700 year period as a dominant socio-political entity in Mesoamerica. While numerous hypotheses have been advanced (Gill, 2000), the political instability that led to the collapse of the Classic Maya has been tied to a series of extended droughts that resulted from a more southerly mean annual position of the intertropical convergence zone (ITCZ), likely

driven by perturbations in Walker Circulation (Haug et al., 2003; Hodell et al., 2005; Peterson and Haug, 2006; Gill et al., 2007; Kennett et al., 2012; Luzzadder-Beach et al., 2012).

Because the ITCZ plays a significant role in global circulation patterns, changes in ITCZ mobility or behavior during the TCD should have impacts that extend far beyond the Mayan lowlands. For example, Yancheva et al. (2007) presented evidence of increased aridity in China coincident with the TCD that they attributed to a more southerly mean annual position of the ITCZ and weakened summer monsoon. Yancheva et al. also pointed out that this drought was coincident with the collapse of the Tang Dynasty in China, highlighting potentially global ramifications of alterations in ITCZ behavior on complex societies. Despite the close proximity of the Caribbean Antilles to the Mayan lowlands, uncertainty exists over the severity of the TCD in this region and its possible impacts on the relatively small populations then inhabiting the islands. Assessment of climate change impacts on these smaller and less politically complex populations could yield new insights into societal responses to climate change and provide a case study contrasting with that of the large and complex socio-political structures of the Classic Maya and Chinese Dynasties.

Here we present evidence of the TCD at a mid-elevation site on the Caribbean island of Hispaniola derived from proxies in sediment cores recovered from two small lakes, Laguna Castilla and

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Laguna de Salvador, on the Caribbean slope of the Cordillera Central of the Dominican Republic. We previously presented reconstructions of paleoclimate spanning the last ~3000 years from these lakes (Lane et al., 2009), but here we specifically focus on the time period of the TCD and include new high-resolution paleohydrological data from Laguna Castilla derived from compound-specific hydrogen isotope analyses of terrestrially derived n-alkanes ( $\delta D_{\text{alkane}}$ ), which have shown exceptional promise as proxies of evapotranspiration (Sachse et al., 2012). We compare the resulting proxy data with a comprehensive archaeological record of the Antilles to assess potential impacts of the TCD on prehistoric Antillean populations.

## 2. Study site

### 2.1. Sediment core locations

Laguna Castilla ( $18^{\circ}47'51''\text{N}$ ,  $70^{\circ}52'33''\text{W}$ , 976 m) and Laguna de Salvador ( $18^{\circ}47'45''\text{N}$ ,  $70^{\circ}53'13''\text{W}$ , 990 m) are small lakes in the Dominican Republic with surface areas of 1.2 and 0.5 ha, respectively (Fig. 1). They are located in the village of Las Lagunas, approximately 40 km northwest of Azua, and occupy basins formed on a massive slump rotation block in the unconsolidated sediments that make up the walls of the Río Cuevas valley (Lane et al., 2009).

While the ITCZ never reaches Hispaniola during its annual migration, precipitation around Las Lagunas is controlled primarily by ITCZ migrational dynamics. Rainfall is highest in the northern hemisphere summer when the ITCZ is located in its most northerly position and proximal doldrum dynamics allow for onshore flow of moisture-laden air in the form of sea breezes that are then orographically modified. Limited meteorological data from Azua indicate a mean annual precipitation value of ~700 mm at sea level, but Las Lagunas at higher elevation likely receives closer to 1000 mm annually (Izzo et al., 2010). Further details regarding the physical setting for this study are in Lane et al. (2009).

### 2.2. Human prehistory in the Caribbean Antilles

Knowledge of human prehistory in the Caribbean Antilles has changed significantly since the seminal work of Rouse (1992). With an increase in the number of archaeological excavations and related studies has come a more complex picture of demographic and cultural dynamics in the region (Keegan et al., 2013). Initial occupation of the Antilles began ~4000 B.C.E. when the

Casimioroid, a lithic culture, began settling the Greater Antilles from southern Mesoamerica. Around 2000 B.C.E. a new migration from the Orinoco River valley, the Ortoiroid, began colonizing the Lesser and Greater Antilles. The Ortoiroid were also a lithic culture, but did apparently cultivate some crops as part of their subsistence base (Keegan et al., 2013). Around 400 B.C.E. the Saladoid began colonizing the Lesser Antilles and Puerto Rico from the Orinoco River region, though not necessarily in that order (Fitzpatrick, 2013), but their expansion apparently stopped at the Mona Passage and the Saladoid did not occupy the remainder of the Greater Antilles at this time. The Saladoid were primarily a horticultural society that relied on crops, particularly manioc, for much of their subsistence.

What happened next in the human history of the Caribbean is currently in debate (Fitzpatrick, 2013), but sometime around 600 C.E. a new cultural tradition, the Ostionoid, appeared throughout the Greater Antilles and then apparently spread into the Lesser Antilles. It remains unclear if the Ostionoid tradition arose from Saladoid roots in Puerto Rico or if it developed in isolation on Hispaniola, where no evidence of Saladoid occupation exists, and then spread through the remaining Greater Antilles, the Lesser Antilles, and The Bahamas (Keegan, 2006; Sinelli, 2013). In either case, the Ostionoid culture is characterized by a change in ceramic tradition and an intensification of agricultural practices (Newsom and Deagan, 1994; Wilson, 1997; Newsom, 2006), particularly in the Cibao valley of the Dominican Republic (Sinelli, 2013). Around 1200 C.E. the Chican Ostionoid tradition became dominant throughout the Greater Antilles; this culture is generally considered the forebearer to the Classic Taíno culture encountered by Europeans upon their arrival in 1492 C.E.

No archaeological studies have been conducted in the Las Lagunas region specifically, but prior lake sediment analyses indicate human occupation of the Laguna Castilla and Laguna de Salvador watersheds between ~1060 and 1250 C.E., placing this occupation within the Ostionoid cultural period (Lane et al., 2009). Declines in arboreal pollen types, increased charcoal fragment abundance, and increased sedimentation rates indicate intensive deforestation and agricultural activity around the lakes during the period (Lane et al., 2009). High abundances of maize pollen and stable carbon isotope signatures indicative of  $C_4$  crops and weeds indicate that maize was a primary cultigen in agricultural fields surrounding the lakes, which is contrary to archaeological interpretations of maize being a very minor component of prehistoric Caribbean diets (Lane et al., 2008a, 2008b).

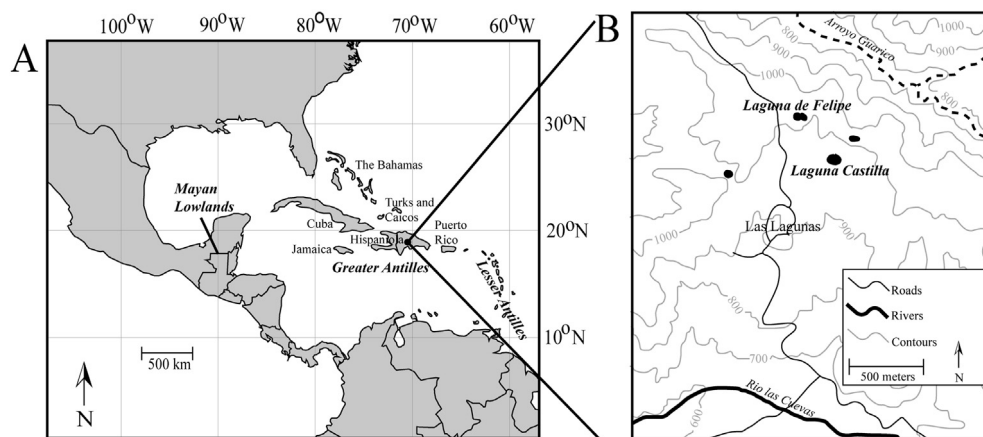


Fig. 1. (A) Locations of Laguna Castilla and Laguna de Salvador along with other islands and geographical regions (Mayan lowlands, Greater Antilles, and Lesser Antilles) discussed in the text. (B) Topographic map of the Las Lagunas area showing positions of Laguna Castilla and Laguna de Salvador. Contours are in meters.

### 3. Materials and methods

We recovered sediment cores from Laguna Castilla (7.8 m) and Laguna de Salvador (5.2 m) using a PVC tube fitted with a rubber piston for the uppermost sediments and a Colinvaux-Vohnout locking piston corer for deeper sediments (Colinvaux et al., 1999). The chronologies of the Laguna Castilla and Laguna de Salvador sediment records are based on AMS radiocarbon dates (7 for Laguna Castilla and 4 for Laguna de Salvador) on bulk sediments and macrofossils converted to calibrated calendar years (B.C.E./C.E.) using the CALIB 6.1.1 computer program (Stuiver and Reimer, 1993) and the dataset of Reimer et al. (2004a). Sedimentation rates were calculated using the weighted means of the probability distributions of the calibrated ages (Telford et al., 2004a,b), and used to linearly interpolate sedimentation rates and ages for lake sediment horizons located between the positions of radiocarbon-dated materials. Information on our methods for pollen, microscopic charcoal, ostracod isotope, and bulk organic carbon and nitrogen isotope analyses are in Lane et al. (2009).

Laguna Castilla sub-samples for n-alkane analysis were lyophilized and ground with a mortar and pestle. Dried sediment sub-samples from 1.5 to 13.0 g dry weight were solvent extracted with a 2:1 mixture of dichloromethane and methanol for 24 h to obtain total lipids. The aliphatic fractions of the total lipid extract were purified using silica column chromatography with hexane as the eluting solvent. Straight-chain monomers were further isolated from branched and cyclic aliphatic compounds using urea adduction.

Compound-specific hydrogen isotope analyses were performed on a continuous flow Finnigan MAT Delta-plus XL mass spectrometer interfaced with a Thermo Finnigan Trace gas chromatograph (GC) Combustion III at the Carnegie Geophysical Institute using a DB-1 silica column (60 m, 0.25 mm i.d., 0.25 µm film thickness). Injection temperatures were 300 °C and samples were injected manually in pulsed splitless mode using high purity helium as the carrier gas. The oven temperature program for the GC was 60 °C isothermal for 2 min, 15 °C/min to 170 °C, 4 °C/min to 320 °C, and 320 °C isothermal for 30 min. High purity hydrogen gas along with alkane mixtures with known hydrogen isotope compositions were used as standards. The Indiana University n-alkane

mixture (provided by A. Schimmelmann) was injected following every fourth sample to monitor precision of the instrument. The standard deviation of the standard analyses over the course of this study was <5‰. <sup>3</sup>H factors were calculated daily using the Isodat software with pulses of increasing reference gas amount. All samples were analyzed in duplicate. Hydrogen isotopic compositions are reported in standard δ-per mil notation relative to VSMOW where:

$$\delta D = 1000 \left[ \left( R_{\text{sample}} / R_{\text{standard}} \right) - 1 \right],$$

where  $R = {}^2\text{H}/{}^1\text{H}$ .

### 4. Results

The uppermost radiocarbon sample in Laguna Castilla postdated 1950 (103.9% of 1950 atmospheric <sup>14</sup>C content) and was calibrated to a calendar age using the CALIBomb program (Reimer et al., 2004b). Except for the lowest date in the Laguna Castilla sediment core, the radiocarbon dates from both lakes are in stratigraphic order. The macrofossil dated near the base of the Laguna Castilla sediment core may have been a root that penetrated older sediments, and it was removed from our age model (Tables 1 and 2; Fig. 2).

The Laguna Castilla δD<sub>alkane</sub> record is similar for all odd-numbered, long-chain (≥25 C) n-alkanes, with relatively low δD<sub>alkane</sub> values (mean δD<sub>alkane</sub> for C<sub>25</sub>, C<sub>27</sub>, C<sub>29</sub>, and C<sub>31</sub> n-alkanes = −183‰) prior to 500 C.E., after which δD<sub>alkane</sub> values increase markedly (mean δD<sub>alkane</sub> for C<sub>25</sub>, C<sub>27</sub>, C<sub>29</sub>, and C<sub>31</sub> n-alkanes = −144‰) until ~1250 C.E. when they again decrease (mean δD<sub>alkane</sub> for C<sub>25</sub>, C<sub>27</sub>, C<sub>29</sub>, and C<sub>31</sub> n-alkanes = −166‰; Fig. 3). Laguna Castilla δD<sub>alkane</sub> values reach their maximum at ~1065 C.E., but are also relatively high around 730 and 1200 C.E. Recovery of shorter-chain n-alkanes was not consistently high enough among all samples to produce a continuous δD<sub>alkane</sub> record for these biomarkers. Laguna Castilla δD<sub>alkane</sub> values correlate strongly with coeval oxygen isotope values (δ<sup>18</sup>O) of ostracod carapaces analyzed in the same sediment core by Lane et al. (2009; Fig. 4).

**Table 1**  
Radiocarbon determinations and calendar age calibrations for Laguna Castilla.

Lab number <sup>a</sup>	Depth (cm)	δ <sup>13</sup> C (‰)	Uncalibrated <sup>14</sup> C age ( <sup>14</sup> C yr BP)	Calibrated age range ± 2 σ <sup>b</sup> (B.C.E./C.E.)	Area under probability curve	Weighted mean <sup>c</sup> (B.C.E./C.E.)
β-196817	66–68	−25.6	103.9% of Modern	1952–1954 C.E. <sup>d</sup>	1.000 <sup>d</sup>	1953 C.E. <sup>d</sup>
β-204702	204–207	−24.5	110 ± 40	1951–1954 C.E. 1800–1940 C.E. 1772–1776 C.E. 1677–1765 C.E.	0.008 0.651 0.007 0.333	1817 C.E.
β-196818	329–331	−25.9	730 ± 40	1383–1365 C.E. 1218–1303 C.E.	0.063 0.937	1276 C.E.
β-171499	536–537	−24.2	1000 ± 40	975–1155 C.E.	1.000	1051 C.E.
β-192641	651–653	−23.8	2190 ± 40	127–120 B.C.E. 382–163 B.C.E.	0.009 0.991	267 B.C.E.
β-171500	724–725	−23.2	2860 ± 40	1130–912 B.C.E. 1159–1113 B.C.E. 1190–1177 B.C.E.	0.970 0.016 0.014	1033 B.C.E.
β-171501	758–761	−25.3	2470 ± 40	469–413 B.C.E. 673–478 B.C.E. 763–678 B.C.E.	0.118 0.600 0.282	602 B.C.E.

<sup>a</sup> Analyses were performed by Beta Analytic Laboratory. Sample β-171500 consisted of charcoal; samples β-204702, β-192641, and β-171501 consisted of non-charred organic macrofossils; and samples β-196817, β-196818, and β-171499 consisted of bulk sediment.

<sup>b</sup> Calibrations were calculated using Calib 6.1.1 (Stuiver and Reimer, 1993) and the dataset of Reimer et al. (2004a,b).

<sup>c</sup> Weighted mean of the probability distribution of the calibrated age.

<sup>d</sup> Date was calibrated using the CALIBomb program (Reimer et al., 2004a,b).

**Table 2**  
Radiocarbon determinations and calendar age calibrations for Laguna de Salvador.

Lab number <sup>a</sup>	Depth (cm)	$\delta^{13}\text{C}$ (‰)	Uncalibrated $^{14}\text{C}$ age ( $^{14}\text{C}$ yr BP)	Calibrated age range $\pm 2 \sigma^b$ (B.C.E./C.E.)	Area under probability curve	Weighted mean <sup>c</sup> (B.C.E./C.E.)
$\beta$ -219035	76.5	-25.7	100 $\pm$ 40	1951–1954 C.E. 1801–1939 C.E.	0.013 0.673	1820 C.E.
$\beta$ -204696	204	-27.5	410 $\pm$ 40	1680–1763 C.E. 1427–1524 C.E.	0.315 0.757	1504 C.E.
$\beta$ -196821	359	-29.8	1280 $\pm$ 40	841–861 C.E. 787–824 C.E.	0.028 0.065	736 C.E.
$\beta$ -192645	504	-25.1	2060 $\pm$ 40	658–783 C.E. 183 B.C.E.–24 C.E.	0.907 1.000	79 B.C.E.

<sup>a</sup> Analyses were performed by Beta Analytic Laboratory. Sample  $\beta$ -192645 consisted of charcoal and samples  $\beta$ -219035,  $\beta$ -204696, and  $\beta$ -196821 consisted of non-charred wood macrofossils.

<sup>b</sup> Calibrations were calculated using Calib 6.1.1 (Stuiver and Reimer, 1993) and the dataset of Reimer et al. (2004a,b).

<sup>c</sup> Weighted mean of the probability distribution of the calibrated age.

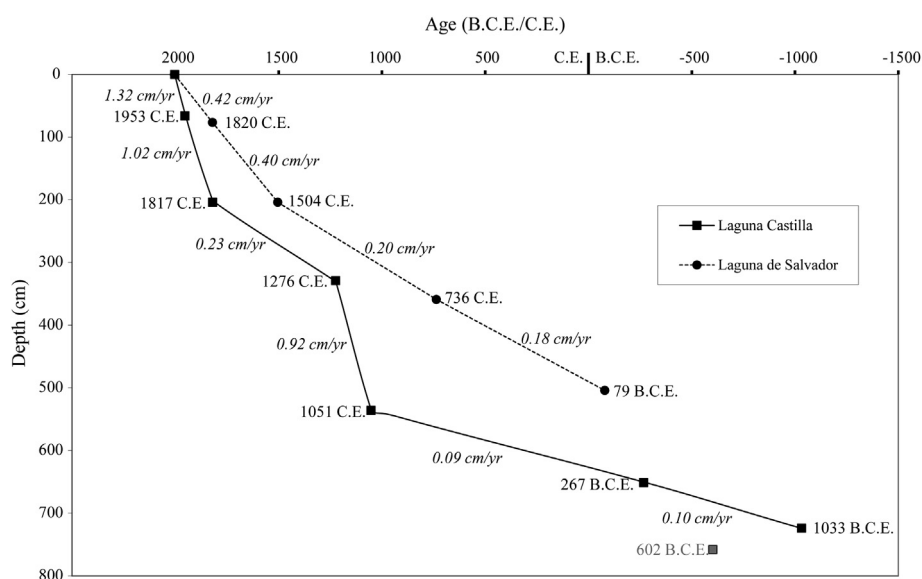
## 5. Discussion

### 5.1. The $\delta D_{\text{alkane}}$ proxy

Long-chain ( $\geq 25$  C atoms), odd-numbered n-alkanes are biomarkers for terrestrially-derived leaf waxes and the  $\delta D_{\text{alkane}}$  of lacustrine sediments has shown promise as a proxy of paleohydrology in the tropics (Schefuss et al., 2011; Douglas et al., 2012; Garcin et al., 2012).  $\delta D_{\text{alkane}}$  values are ultimately controlled by the  $\delta D$  composition of meteoric waters, but subsequent evapotranspiration and species-specific biochemical reactions lead to an apparent fractionation ( $\epsilon$ ) between the  $\delta D$  composition of meteoric waters and  $\delta D_{\text{alkane}}$  (Sachse et al., 2012). In the tropics, the  $\delta D$  composition of meteoric waters is typically controlled by the “amount effect”, whereby decreased (increased) precipitation amounts lead to an increase (decrease) in the  $\delta D$  composition of meteoric waters. However, recent work indicates that evapotranspiration may play a more important role than precipitation in determining  $\delta D_{\text{alkane}}$  values in arid to semi-arid tropical environments where increased evapotranspiration of surface and soil water increases the  $\delta D$  composition of source water, resulting in an increase in  $\delta D_{\text{alkane}}$  values (Douglas et al., 2012). Thus, the amount effect and evapotranspiration processes work in concert to increase

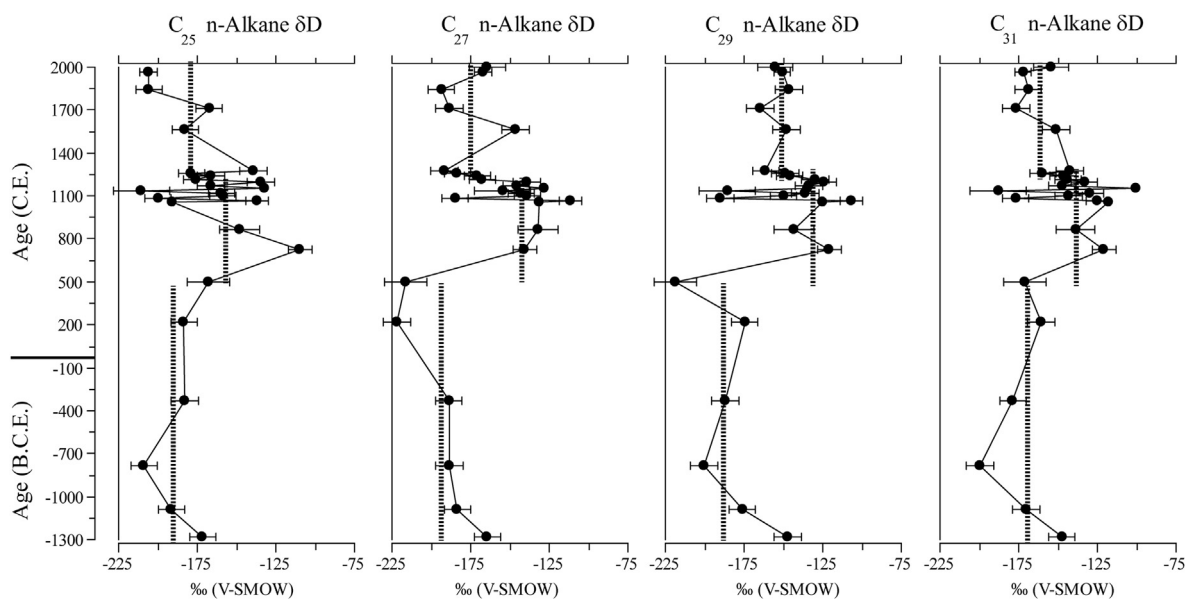
(decrease)  $\delta D_{\text{alkane}}$  values when evaporation to precipitation (E/P) ratios increase (decrease). Subsequent biochemical fractionation processes that occur after incorporation of soil water and during lipid biosynthesis can complicate the interpretation of  $\delta D_{\text{alkane}}$  values in mixed sedimentary pools. In particular, plant life form has been shown to affect  $\delta D_{\text{alkane}}$  composition with graminoids typically displaying more negative  $\delta D_{\text{alkane}}$  values than woody vegetation in the same environments (Douglas et al., 2012; Sachse et al., 2012), requiring researchers to consider paleovegetation changes using pollen or other proxies when interpreting  $\delta D_{\text{alkane}}$  values (Nelson et al., 2013). Despite these complexities, relative variations in  $\delta D_{\text{alkane}}$  values through time hold enormous promise as qualitative, if not strictly quantitative, indicators of paleohydrological variability (Sachse et al., 2012), particularly in arid to seasonally arid tropical locales (Douglas et al., 2012).

The  $\delta D$  composition of short-chain n-alkanes typically attributed to lacustrine algae (e.g.  $\text{C}_{17}$ ) show a strong correlation with lake water  $\delta D$  in most locales (Huang et al., 2004; Sachse et al., 2004). The abundance of short-chain n-alkanes in the Laguna Castilla sediments was too low for dependable isotopic analysis and could not be used as a high-resolution paleohydrological proxy in this study. With recent evidence that the  $\delta D$  composition of terrestrially-sourced n-alkanes (odd-numbered  $\text{C}_{25}$ – $\text{C}_{33}$ ) may be



**Fig. 2.** Age–depth relationships and linearly interpolated sedimentation rates (italics) for the Laguna Castilla and Laguna de Salvador sediment records. The lowermost date for Laguna Castilla (grey) has been omitted as the wood fragment dated was likely from a root that is younger than the surrounding sediment.



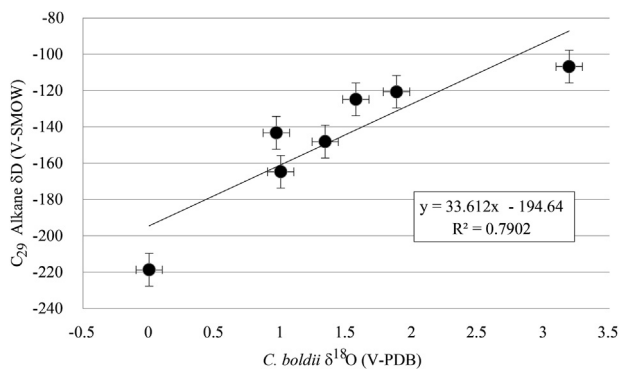


**Fig. 3.** Comparison of long-chain ( $\geq C_{25}$ ) n-alkane  $\delta D$  values in the Laguna Castilla sediment record. Vertical dashed lines represent the mean  $\delta D$  value for defined time periods. Error bars on individual data points represent one standard deviation from the mean.

sensitive to evaporation to precipitation ratios in the arid and semi-arid tropics (Douglas et al., 2012), we used the most abundant of these compounds,  $C_{29}$ , in the Laguna Castilla sediment record as our paleohydrological proxy. Direct comparison of the  $C_{29}$   $\delta D$  data to  $C_{25}$ ,  $C_{27}$ , and  $C_{31}$   $\delta D$  data indicate similar patterns with the large magnitude increase in  $\delta D$  at  $\sim 500$  C.E. apparent in each of the records (Fig. 3). The slightly different patterning in the  $C_{25}$   $\delta D$  data may reflect a potential non-terrestrial source as  $C_{25}$  n-alkanes are often predominant in emergent taxa (Ficken et al., 2000), but the overall pattern of  $\delta D_{\text{alkane}}$  variability is similar to the other long-chain n-alkanes suggesting that the  $C_{29}$  alkane data are representative of hydrologic variability around Laguna Castilla. The  $C_{29}$   $\delta D$  data are also strongly correlated with  $\delta^{18}O$  data (Lane et al., 2009) from coeval samples of the ostracod *Cythridella boldii* ( $R^2 = 0.79$ ;  $p < 0.01$ ), further supporting the use of the  $C_{29}$   $\delta D$  data as a dependable paleohydrological proxy in the Laguna Castilla watershed (Fig. 4).

## 5.2. The Terminal Classic Drought in the Caribbean Antilles

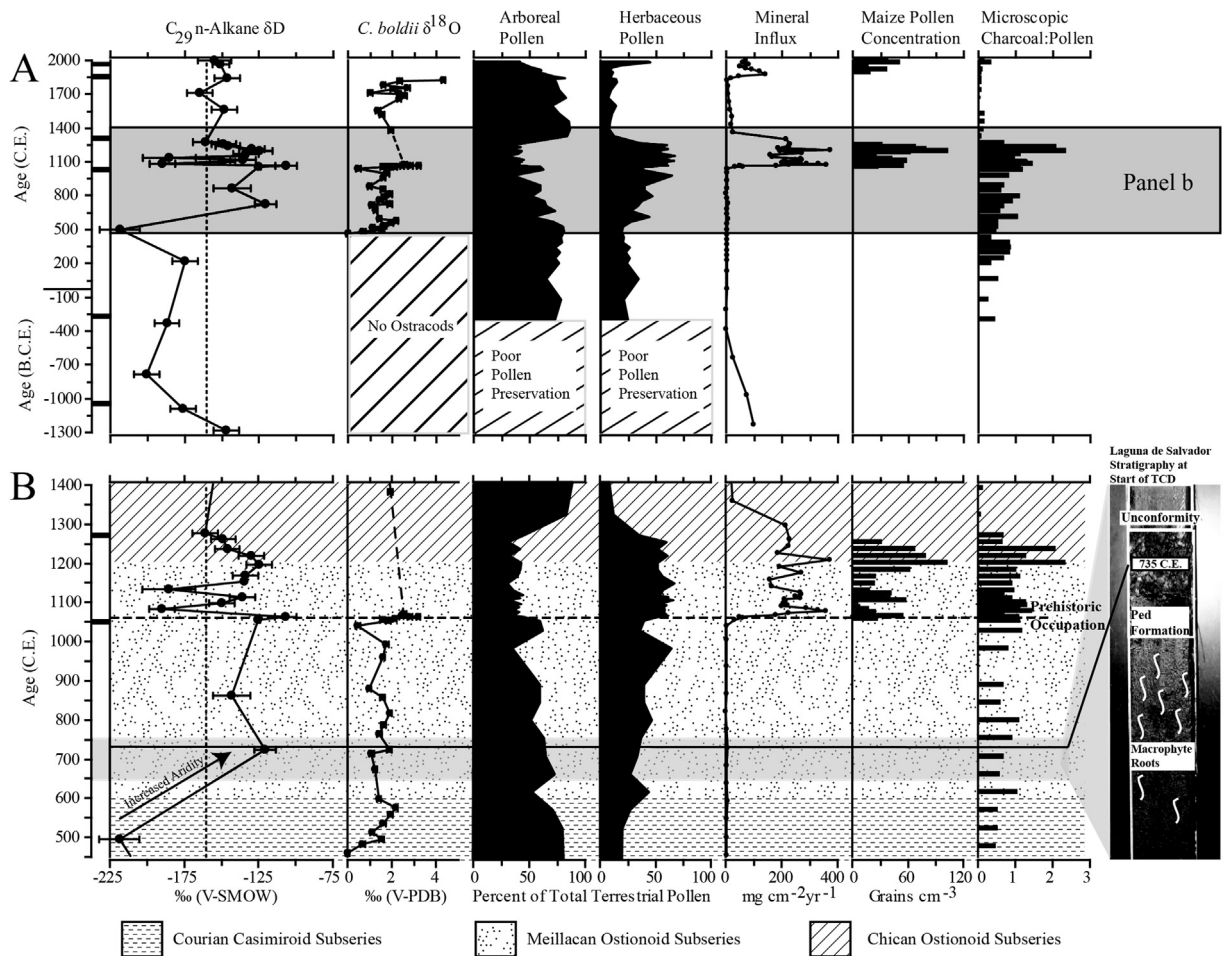
Lane et al. (2009) documented increased aridity coincident with the TCD from oxygen isotope analyses of ostracod shells ( $\delta^{18}O_{\text{ostracod}}$ ) in Laguna Castilla and Laguna de Salvador. However, data



**Fig. 4.** Linear regression analysis of stratigraphically coeval  $C_{29}$  n-alkane  $\delta D$  values and ostracod-based (*C. boldii*)  $\delta^{18}O$  values in the Laguna Castilla sediment record.

were discontinuous because of sporadic ostracod shell presence in the sediment cores, complicating placement of the magnitude or longevity of this drought into a broader context. Our  $\delta D_{\text{alkane}}$  data from Laguna Castilla complement and extend the limited  $\delta^{18}O_{\text{ostracod}}$  data, confirming arid conditions coincident with the TCD and establishing its strong magnitude. The Laguna Castilla  $\delta D_{\text{alkane}}$  values show an extremely large increase (average  $\Delta D_{\text{alkane}} \approx 40\text{‰}$ ) starting at the time of early onset aridity in the Mayan Lowlands associated with the TCD (Curtis et al., 1996; Hodell et al., 2005;  $\sim 500$  C.E.) and culminating with a sharp increase in  $\delta D_{\text{alkane}}$  values coincident with the Late Classic Mayan collapse ( $\sim 1100$  C.E.; Figs. 5 and 6). The increase in  $\delta D_{\text{alkane}}$  values starting  $\sim 500$  C.E. is accompanied by a steady decrease in arboreal pollen and increase in herbaceous pollen, increased carbonate deposition, and stable carbon isotope evidence of increasing  $C_4$  vegetation, all indicating an increase in E/P ratios during this interval (Lane et al., 2008b, 2009). In the sediment record of nearby Laguna de Salvador, evidence of pedogenesis and an unconformity at  $\sim 735$  C.E. indicate exposure and desiccation of the sediments in this now 2.8 m deep lake during this same period (Lane et al., 2009; Fig. 5).

The increase in Laguna Castilla  $\delta D_{\text{alkane}}$  values is most likely the result of increased E/P ratios and not a change in ecosystem structure or meteoric water source. Nelson et al. (2013) showed that a change in mid-latitude ecosystem structure from forest to grassland can result in a negative excursion in sedimentary  $\delta D_{\text{alkane}}$  values without any change in climate due to the relatively low  $\epsilon$  values of trees compared to grasses measured worldwide (Sachse et al., 2012). From our study, the first to directly compare  $\delta D_{\text{alkane}}$  values and paleovegetation proxies spanning a period of drastic ecosystem change in the tropics on decadal time intervals, we suggest that the relationship between ecosystem structure and  $\delta D_{\text{alkane}}$  values may not hold in tropical ecosystems where E/P ratios exert a stronger influence on isotopic fractionations at the watershed scale (Douglas et al., 2012). The strong positive correlation ( $r^2 = 0.79$ ;  $p < 0.01$ ) between our  $\delta D_{\text{alkane}}$  and coeval  $\delta^{18}O_{\text{ostracod}}$  data also indicate that the  $\delta D_{\text{alkane}}$  values are not responding solely to ecosystem structure changes (Fig. 2). As  $\delta^{18}O_{\text{ostracod}}$  data from closed-basin tropical lakes are typically regarded as some of the most dependable proxies of E/P ratios (Lane et al., 2009), this strong correlation provides further evidence



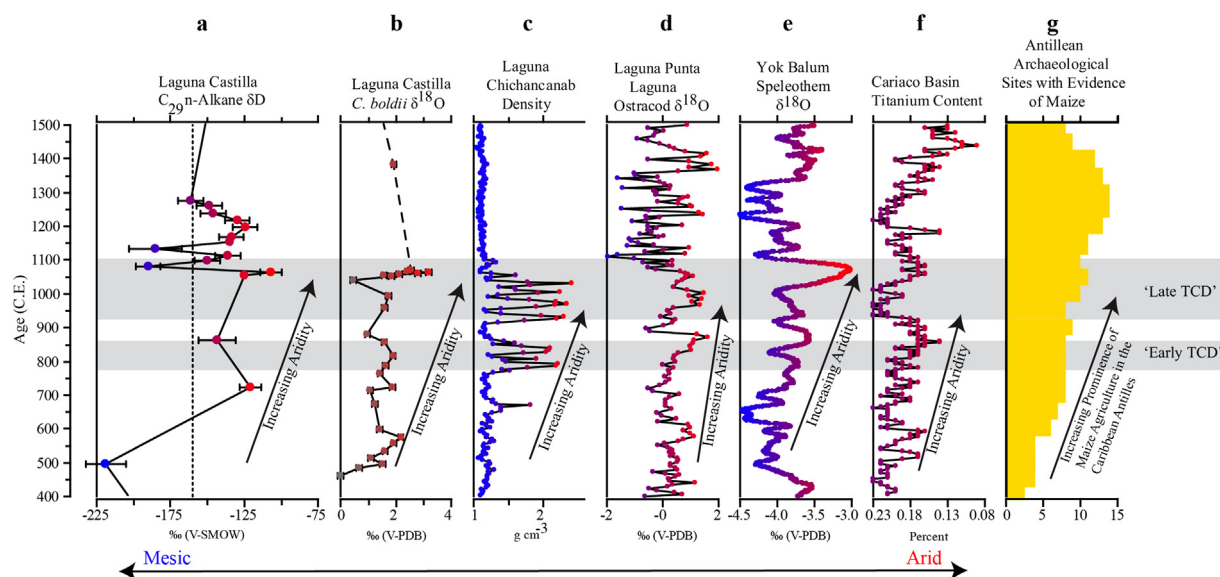
**Fig. 5.** Selected proxy data from the ~3000 cal yr B.P. Laguna Castilla sedimentary record (A) and for the time period encompassing the Terminal Classic Drought (B), including the hydrogen isotope composition of terrestrially-sourced  $C_{29}$  n-alkanes. Archaeological periods (background patterns in B) are based on the chronology of Keegan et al. (2013). Also included in B is a photograph of Laguna de Salvador sediments deposited during the Terminal Classic Drought, showing peds that formed ~735 C.E. followed by an unconformity. The dashed horizontal line labeled 'prehistoric occupation' denotes the first proxy evidence of human settlement in the Laguna Castilla watershed. Error bars represent one standard deviation. Dark bars adjacent to the y-axis indicate the positions of AMS radiocarbon dates. Oxygen isotope data for *C. boldii* ostracod carapaces are discontinuous due to sporadic formation or preservation. The arboreal pollen sum includes pollen from all woody taxa and the herbaceous pollen sum includes pollen from all herbaceous plants except *Typha* sp. (cattail). Microscopic charcoal counts include fragments 50–125  $\mu$ m in length.

that  $\delta D_{alkane}$  values are likely responding to the same variable. We can also be confident that the large amplitude change in  $\delta D_{alkane}$  values are not the result of a change in meteoric water source to Laguna Castilla and Laguna de Salvador, which is currently dominated by the Caribbean Sea just 50 km to the south (Lane et al., 2009). A change to a water source to the north or east would likely decrease meteoric  $\delta D$  values, and in turn  $\delta D_{alkane}$  values, due to enhanced orographic effects on airmasses crossing the Cordillera Central (e.g. Lachniet and Patterson, 2002).

The Laguna Castilla  $\delta D_{alkane}$  record closely matches other proxy data of increased aridity from mainland Middle and South America. Gypsum deposits in Laguna Chichancanab, Mexico (Hodell et al., 2005), increased  $\delta^{18}O_{ostracod}$  values in Laguna Punta Laguna, Mexico (Curtis et al., 1996), increased  $\delta^{18}O$  values in Mexican (Kennett et al., 2012) and Guatemalan (Webster et al., 2007) speleothem records, and low Ti concentrations in sediments of the Cariaco Basin (Haug et al., 2003) all indicate increasingly arid conditions in the circum-Caribbean region between ~500 and 1100 C.E. (Fig. 6). These sites have precipitation regimes dominated by ITCZ migrational dynamics and the mean annual position of the ITCZ may have been suppressed southward at the time resulting in a large reduction in rainfall in the Mayan lowlands during this

interval (Gill et al., 2007; Medina-Elizalde and Rohling, 2012). Simultaneous decreases in precipitation at each of these locations would be expected if the mean annual position of the ITCZ were suppressed southwards due to changes in Walker Circulation or tropical sea surface temperature gradients (Chiang et al., 2002).

Given the prominent role of ITCZ migrational dynamics in Caribbean climate regimes (Hastenrath, 1991), effects of a more southerly mean annual position of the ITCZ during the TCD should be widespread in the eastern Caribbean. Paleohydrological records are rare in the Caribbean Antilles because of a lack of suitable proxy archives, but a number of records do provide additional evidence of a southward displacement of the ITCZ and generally drier climate. Nyberg et al. (2001) reported an increase in the magnetic susceptibility of nearshore marine sediments off the coast of Puerto Rico between ~500 and 1100 C.E. that they associated with increased Saharan dust deposition related to intensified trade winds, which would be expected with a more southerly ITCZ. Beets et al. (2006) presented oxygen isotope and geomorphological evidence of increased aridity and windiness on the island of Guadeloupe in the Lesser Antilles between ~800 and 1000 C.E. that was also associated with archaeological evidence of site abandonment. Donnelly and Woodruff (2007) presented sedimentary evidence of less



**Fig. 6.** Comparisons of Laguna Castilla C<sub>29</sub> n-alkane δD data (a) and ostracod δ<sup>18</sup>O data (Lane et al., 2009) (b) to paleoclimate records from the Mayan lowlands (Curtis et al., 1996; Hodell et al., 2005; Kennett et al., 2012) (c–e) and the Cariaco Basin (Haug et al., 2003) (f), and to the number of archaeological sites in the Caribbean with botanical evidence of maize (g). Gray shading highlights the “Early TCD” and “Late TCD” in the Mayan lowlands as defined by Hodell et al. (2005). Our compilation of archaeological evidence of maize cultivation and consumption in the Antilles is based on published reviews of starch grain, phytolith, pollen, and microfossil analyses in the region by Berman and Pearsall (2008), Lane et al. (2008a), and Mickleburgh and Pagan-Jimenez (2012). The age of first and last appearance of maize evidence at each site was established using varying techniques. In most cases, age assignment was based on the cultural context of the archaeological site as a whole, but in some cases radiocarbon determinations were available for maize microfossils, human skeletons, or encasing sediments (Supplementary Table 1). We have excluded maize pollen at the El Curro archaeological site in the Dominican Republic as the stratigraphy at this site was likely disturbed by subsequent agricultural activity (Lane et al., 2008a).

frequent tropical storms affecting eastern Puerto Rico starting ~700 C.E. that they associated with more frequent El Niño events, which is also consistent with a more southerly mean position of the ITCZ during the TCD.

While we lack the necessary site-specific data to establish quantitative relationships between δD<sub>alkane</sub> values and aridity, and thus cannot quantify the severity of the TCD at our study site, similar increases (~40‰) in terrestrial δD<sub>alkane</sub> values in modern-day neotropical locales significantly correlate to a 75% decrease in the aridity index (mean annual precipitation/potential evapotranspiration; Douglas et al., 2012). We are not strictly proposing a 75% decrease in the aridity index for the Las Lagunas area during the TCD, but these modern relationships do help put the magnitude of this large isotopic excursion in the Laguna Castilla δD<sub>alkane</sub> record into context. Such a large increase in δD<sub>alkane</sub> values is indicative of a very significant decrease in precipitation starting around 500 C.E.

### 5.3. Potential impacts of the Terminal Classic Drought on prehistoric Caribbean populations

While prehistoric population densities and political organization in the Caribbean Antilles were nowhere near those of the Mayan civilization, we propose that Caribbean populations were also affected by the TCD. The time period around 500 C.E. was a particularly notable time of cultural transition throughout the Greater Antilles with the appearance and rapid proliferation of Ostionoid cultural traditions (Keegan et al., 2013). Keegan (2006) suggested that the development of Ostionoid culture may have begun on Hispaniola, which is contrary to prevailing thought that Ostionoid culture had developed from Saladoid roots on Puerto Rico and then spread to Hispaniola from Puerto Rico (Rouse, 1992). This cultural transition is typified by an increase in agricultural activity and population size (Ortiz Aguilu et al., 1991; Rouse, 1992; Curet, 2005), particularly on Hispaniola where Meillacoid Ostionoids had invented canuco (montones) agriculture and were

intensively cultivating crops by around 800 C.E., particularly in the Cibao valley (Sinelli, 2013). The Lesser Antilles were also undergoing significant changes during this period. Hofman (2013) portrayed 400–600 C.E. as a ‘dynamic’ period in the Lesser Antilles, characterized by the development of overarching sociopolitical structures, increased diversity in settlement locations, and colonization of previously uninhabited islands.

Separating correlation vs. causation in paleoclimate and archaeological records is always difficult, if not impossible. However, placing the development and proliferation of Ostionoid cultural traditions into climatic context offers important insight into a potential motivation for these cultural and demographic changes. Perhaps decreased precipitation starting around 500 C.E. spurred increased reliance on dependable, drought-resistant crops such as cassava (manioc) and maize. The intensive settlement and cultivation of the Cibao valley and invention of self-irrigating canuco agriculture by Meillacoid Ostionoids around this time indicate an increased emphasis on dependable freshwater resources (Sinelli, 2013). In contrast to the Mayan lowlands where intensive water resource management was already underway and populations were likely pushing toward maximum carrying capacities (Gill, 2000), this increased reliance on cultivated food resources and invention of new agricultural techniques in the Antilles likely spurred population growth by boosting carrying capacities (Curet, 2005; Sinelli, 2013). This could explain why Antillean populations were growing around 500 C.E. while Mayan populations were on the decline during the contemporaneous Maya Hiatus (535–595 C.E.), at a time when drought is prominent in the Mayan Lowlands (Gill et al., 2007).

The extended period of inferred aridity from 500 to 1050 C.E. in the Laguna Castilla δD<sub>alkane</sub> data is punctuated by a sharp increase in δD<sub>alkane</sub> values at ~1065 C.E. that is unmatched in the entirety of the ~3000 year record (Figs. 5 and 6). This evidence of extreme aridity ~1065 C.E. is also coincident with lacustrine and speleothem evidence of some of the most extreme drought conditions in the last two millennia in the Mayan lowlands (Kennett et al., 2012;



Fig. 6). Maize pollen first appears in the Laguna Castilla and Laguna de Salvador sedimentary records ~1065 C.E. indicating the initial occupation of the watersheds by prehistoric populations at precisely this interval of extreme aridity (Lane et al., 2008a; Fig. 5).

Lane et al. (2009) hypothesized that human settlement at Laguna Castilla and Laguna de Salvador was in response to drought, which increased the attractiveness of areas with freshwater reservoirs—rare on Hispaniola—for human habitation and intensive agriculture. More recently, Sinelli (2013) theorized that a growing Meilacoid population on Hispaniola faced an environmental crisis starting around 1050 C.E. when severe drought conditions contemporaneous with the Classic Maya Collapse forced mass migrations out of northern Hispaniola. Between 1050 C.E. and 1250 C.E. the number of Meilacoid settlements suddenly increased on the previously unsettled islands of the Turks and Caicos and The Bahamas. Sinelli speculated that this migration was out of desperation and required a shift in subsistence strategy that included an increased dependence on marine resources. Considering the geographical proximity and temporal overlap, we find it conceivable that the exodus out of northern Hispaniola identified by Sinelli (2013) was related to the settlement of the Las Lagunas area, but archaeological excavations would be necessary to confirm this hypothesis.

We lack a clear explanation for the abandonment of Las Lagunas ~1250 C.E., but this time period is typified by a transition from Meilacoid to Chican Ostionoid cultural traditions (Keegan et al., 2013). At this same time, populations in Puerto Rico and the northern Lesser Antilles were declining precipitously, while populations in the southern Lesser Antilles were growing (Curet, 2005; Hofman, 2013). Hofman (2013) attributed this demographic shift to an exodus of populations out of the northern Lesser Antilles into the southern Lesser Antilles due to political instability, societal unrest, fissioning, and realignment. Interestingly, the remaining settlements in the northern Lesser Antilles began a sociocultural reorientation toward the Greater Antilles at this time (Hofman, 2013), perhaps related to an influx of Greater Antillean populations and indicating a larger-scale demographic shift to which the abandonment of Las Lagunas can be linked. The increased aridity around 1200 C.E. shown by the Laguna Castilla  $\delta D_{\text{alkane}}$  record could be related to these sociocultural and demographic changes (Figs. 5 and 6), but the causation for this large demographic shift may be sociopolitical, as additional evidence of environmental stress during this period is lacking (Curet, 2005).

#### 5.4. Apparent increases in the prominence of maize agriculture in the Caribbean following the Terminal Classic Drought

Maize is prominent at archaeological sites of Central and South America dating back many millennia (Staller et al., 2006), but evidence of maize cultivation on Caribbean islands is rare (Newsom, 2006). Starch-grain analyses of tools and isotopic analyses of bone indicate that maize was a component of the Caribbean diet by ~3000 B.C.E., but evidence of maize is far more common in Ostionoid contexts than with any previous cultures in the Caribbean (Newsom and Deagan, 1994; Lane et al., 2008a; Mickleburgh and Pagan-Jimenez, 2012; Pagan-Jimenez, 2013; Pestle, 2013). We have compiled all known records of Antillean archaeological sites with evidence of maize cultivation or consumption (macrofossil, starch grain, and fossil pollen analysis) to assess potential linkages with Ostionoid cultural expansion during the TCD. We recognize that simply tallying the number of sites with evidence of maize agriculture or consumption is an imperfect proxy of the prominence of maize in the region because of possible biases in site selection and incomplete surveys for the region as a whole. However, lacking better data we adopt the metric of site number as a working representation of relative changes in the importance of this crop through time.

Our compilation of maize occurrence shows a clear increase in maize distribution starting 500 C.E. and plateauing after ~1000 C.E. coincident with establishment and spread of Ostionoid cultural traditions during the TCD (Figs. 5 and 6). If the hypothesis of Keegan (2006) is correct and Meilacoid Ostionoid cultural development did originate on Hispaniola and spread outwards from there, the sudden rise in the prominence of maize agriculture across the region could have been the result of a transition from horticultural to more intensive agricultural practices, and increased reliance on drought resistant cultigens, such as maize and cassava, during the TCD. Maize was apparently a component of the canuco agricultural practices invented by the Meilacoid Ostionoid (Pagan-Jimenez, 2013).

Subsequent dispersal of this subsistence strategy during emigrations from Hispaniola would explain the increased appearance of maize remains in other Antillean archaeological contexts. The relatively high abundance of maize pollen grains and high  $\delta^{13}\text{C}$  values of the sediments of Laguna Castilla indicate that maize was an important cultigen at this site during Ostionoid occupation (Lane et al., 2008a, 2008b). We propose that significant changes in social and cultural practices, particularly an increased emphasis on water management and increased reliance on relatively drought-resistant crops such as maize — one of the few  $\text{C}_4$  photosynthetic crops in the region — may have been in response to an increasingly arid climate leading up to, and coincident with, the TCD.

## 6. Conclusions

The Laguna Castilla  $\delta D_{\text{alkane}}$  record provides robust evidence that the TCD significantly impacted the island of Hispaniola, and likely the greater Caribbean region. Coincident changes in the Laguna Castilla  $\delta D_{\text{alkane}}$  record and regional archaeological record of cultural transitions and demographic shifts opens the possibility that climate change was a driving mechanism behind these changes in cultural traditions, and more specifically, subsistence strategies. Furthermore, if climate change was responsible for the emergence of Meilacoid Ostionoid cultural traditions on Hispaniola and their spread throughout the region, climate might ultimately be responsible for the development of Taíno societies encountered by Christopher Columbus in 1492, as the Meilacoid Ostionoid transition is recognized as the likely forbearer to Taíno traditions (Sinelli, 2013).

This potential response of Caribbean populations to the TCD provides an interesting contrast to inferred cultural and societal responses of the Classic Maya civilization. Our interpretation is that the impacts of the TCD provided the impetus for more subtle cultural transitions that included intensified agricultural practices and, paradoxically, population increases in the Caribbean. Meanwhile, in the Mayan region of highly complex socio-political structures and high population densities, the TCD resulted in societal collapse and depopulation. These contrasting cultural responses to contemporaneous climatic change in the circum-Caribbean region may hint at the complex interactions between socio-political variables, such as high population densities and hostile neighboring polities, and human response to environmental stressors. The development of a dense network of paleoclimate and paleoecological records (e.g. Mancini et al., 2005; Carrión et al., 2010) from throughout the Caribbean region, combined with the continued refinement of regional archaeology, would undoubtedly help to elucidate these complex relationships.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.quascirev.2013.12.017>.

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