ECOSUR

El Colegio de la Frontera Sur

Estudio paleoecológico de alta resolución en sedimentos de manglar

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Introducción

El Holoceno es un periodo interglacial que comprende aproximadamente los últimos 10,500 años (Roberts, 1998). Es una época que se caracteriza por poseer condiciones climáticas favorables para el desarrollo de civilizaciones humanas (Hayashida, 2005). Sin embargo, han existido episodios de cambio climático donde las variaciones ambientales han marcado el fin de grandes civilizaciones. Tal es el caso de la cultura Maya en la península de Yucatán, donde estudios paleoecológicos han demostrado procesos de cambio climático como factor determinante en el colapso de esta civilización hace aproximadamente 1,200 años (Haug et al., 2003; Hodell et al., 1995; Hodell et al., 2005; Rosenmeier et al. 2002), demostrando la importancia en la comprensión de la variabilidad climática a través del tiempo, para comprender la variabilidad climática natural y el papel que desempeñan las actividades antropogénicas sobre el clima (Mueller et al., 2010).

Actualmente, integrar una perspectiva a largo plazo sobre los cambios ambientales, ha adquirido gran interés en la arqueología y la paleoecología, debido a que la variabilidad natural del clima ha sido influenciada por la evolución de sociedades humanas en los últimos 5,000 años. De tal forma que la deforestación, cambio de uso de suelo, quema de combustibles fósiles y otras formas de contaminación atmosférica son actualmente factores importantes que determinan procesos de cambio climático (Hardy, 2003). Es así como nace la paleoecología como un área de la ecología encargada de reconstruir climas pasados, la cual tiene como instrumento el uso de “proxies” o indicadores que son la evidencia indirecta del clima y ambientes pasados (Bell y Walker, 1992).

De acuerdo a Houghton et al. (2001), un indicador climático, o “proxy”, es un registro local que se interpreta mediante principios físicos y biofísicos, y representan las variaciones climáticas a lo largo del tiempo. Los proxies incluyen tanto material biótico como abiótico, donde podemos encontrar los granos de polen, fragmentos de insectos, crustáceos, restos de tejidos vegetales, concentraciones de CO_2, entre otros (Bell y Walker, 1992), siendo los proxies biológicos los más utilizados dada la abundancia de sitios de preservación (Williams et al., 1993).

La palinología es una herramienta importante en la paleoecología y consiste en el análisis del polen que se encuentra depositado en cuerpos de agua como humedales y lagos (Islebe y Torrescano, 2005). Ha sido la herramienta más utilizada en la reconstrucción de climas ya que el polen posee un alto rango de dispersión y conservación en sedimentos lacustres, además de que sus características morfológicas permiten su identificación a un nivel taxonómico considerable (Williams et al., 1993). De esta forma se puede obtener una imagen muy cercana a la realidad de la vegetación de un sitio, que a su vez, es evidencia del clima prevaleciente en un tiempo dado (Williams et al., 1993).

La producción de polen varía de acuerdo a cada especie, su presencia y cantidad, es un buen indicador del tipo de clima que prevaleció en la zona. Su dispersión igualmente varía de acuerdo a la biología de la especie, siendo aquellas que tienen una dispersión anemófila las que se encuentran mejor representadas en los sedimentos lacustres (Williams et al., 1993).

En las reconstrucciones paleoecológicas y paleoclimáticas es fundamental establecer una cronología de eventos mediante el fechado de las muestras depositadas estratigráficamente. Es bien sabido que el proceso de sedimentación en los cuerpos de agua es relativamente continuo. Sin embargo, el fechado de los eventos climáticos que pudieran presentarse en las reconstrucciones paleoecológoicas y paleoclimáticas resulta casi imposible a simple vista. Por lo que se ha recurrido al estudio de “relojes geológicos” para la determinación cronológica de las biológicas, destacando el radiocarbono (^{14}C) como el más utilizado.

El ^{14}C es un elemento que surge del bombardeo de átomos de nitrógeno, provenientes de rayos cósmicos, combinado con neutrones y oxígeno atmosférico, que forman moléculas de dióxido de carbono con isótopo inestable de carbono. Estas moléculas son incorporadas a los sistemas biológicos mediante la fotosíntesis. Cuando un organismo muere, el intercambio de CO_2 con radiocarbono cesa, por lo tanto la concentración de las moléculas con el isótopo inestable se vuelve finita y medible. De esta forma surge la datación mediante ^{14}C como una importante herramienta en las reconstrucciones paleoecológicas y paleoclimáticas (Roberts, 1998).

Finalmente, la correcta interpretación de datos paleoecológicos depende del conocimiento ecológico actual (Islebe, 1999) y permite comprender los patrones de distribución de las comunidades vegetales, que son asociaciones definidas y no azarosas de las plantas (Islebe y Sánchez-Sánchez, 2001). Desafortunadamente, la mayoría de los estudios paleoecológicos se han realizado en Europa y existen pocas reconstrucciones paleoecológicas en la región maya (Leyden et al., 1998; Islebe y Sánchez-Sánchez, 2002; Carrillo-Bastos et al., 2010; Torrescano-Valle e Islebe, 2006).

De acuerdo a la evidencia obtenida hasta el momento, se ha identificado una época seca para la región del Caribe hace 7,500 años antes del presente (AP). El agua en los lagos se encontraba en un nivel muy bajo y con alta salinidad (Whitmore et al., 1996). Para los 6,800 AP, comienzan a registrarse condiciones más húmedas. Sin embargo, entre los 6,000 y 5,000 AP regresó a la zona un periodo seco (Metcalfe et al., 2000). El llenado del Lago de Coba comienza en los años 8400 AP y el de San José Chulchaca a partir de 8200 AP (Leyden, 2002). La cobertura máxima de las selvas ocurrió entre los 7,000 y los 4,000 años AP, periodo en el que se registran las condiciones más húmedas del Holoceno (Leyden et al., 1994; Metcalfe et al., 2000). Leyden et al. (1998), Carrillo-Bastos et al. (2010), Islebe y Sánchez (2002), Torrescano-Valle e Islebe (2006) y Mueller et al. (2009) revelaron, con análisis polínicos, importantes cambios ambientales en los últimos 5,000 años, incluyendo un período de sequías que abarcó entre cerca de 550 años (450 – 1000 AP) que se encuentran relacionados con el auge y colapso de la cultura Maya en el Holoceno tardío (Islebe y Leyden, 2006).

Existen otros trabajos realizados en la zona, dentro de los que podemos destacar el de Torrescano e Islebe (2006) en la parte sur de la península donde demostraron el desarrollo del sistema de manglar a principios del Holoceno medio. Igualmente Islebe y Sánchez (2002) evidenciaron los cambios en la composición del sistema de manglar en el caribe mexicano encontrando fuertes cambios ambientales hacia condiciones secas hace 1500 años. Monacci et al. (2011) realizaron un estudio de la variabilidad climática en sedimentos de manglares ribereños de los últimos 6,000 años en el Río Sibun, Belize con interpretaciones ecológicas a través del proxy polen y su relación con isótopos estables como indicadores climáticos geoquímicos. Sin embargo, el análisis de polen aparentemente no corresponde con las señales que presentan los ecosistemas de manglar en zonas cercanas al rio Hondo al sur de la península de Yucatán descritas anteriormente por Torrescano-Valle e Islebe (2006). Además, los datos biogeoquímicos y biológicos son insuficientes para determinar los procesos de sucesión vegetal y cambio climático. Finalmente, Carrillo-Bastos et al. (2010) caracterizaron los cambios en la vegetación atribuidos a condiciones ambientales cambiantes durante el Holoceno, donde se consideró la presencia de especies de ambientes perturbados en el centro de la península. Debido a la poca cantidad de los estudios realizados y la baja resolución temporal con que se elaboraron, la reconstrucción climática, así como el efecto de las actividades antrópicas sobre el clima local derivados del desarrollo de la civilización maya, se vuelve complicada.

La cultura Maya, ha sido de gran interés entre los paleoecólogos y arqueólogos (Torrescano e Islebe, 2006), ya que es justamente en este periodo donde se documentan los primeros impactos del ser humano en el medio ambiente determinados por la reducción del polen selvático y el aumento de taxa de vegetación abierta alrededor de los 5780 AP en la Península de Yucatán (Curtis et al., 1998) evidenciando un fuerte impacto de la civilización sobre el ambiente debido a las actividades agrícolas y forestales de subsistencia (Abrams y Rue, 1988).

Diversas investigaciones paleoclimáticas han sido realizadas para contribuir a los conocimientos relacionados con el auge y colapso de la civilización maya (Curtis et al., 1996; Haug et al., 2003; Hodell et al., 2005; Hodell et al., 2007; Islebe et al., 1996; Mueller et al., 2009). Los datos paleoclimáticos carecen de interpretaciones sobre el impacto de los cambios ambientales sobre los ecosistemas, dejando vacíos de información que podrían ser útiles para esclarecer el impacto del clima sobre la vegetación y de esta forma comprender mejor las implicaciones ecológicas derivadas del cambio climático. Gill (2000) y Diamond (2005) realizaron una amplia revisión paleoclimática y arqueológica en torno a el colapso de esta civilización donde las investigaciones paleoclimáticas proporcionan evidencia de cambios climáticos circum-caribeños que permiten atribuir el colapso de esta civilización a factores ambientales (Haug et al., 2003; Hodell et al. 2007). Por otra parte, las investigaciones arqueológicas atribuyen el colapso a épocas de inestabilidad social (Kepecs y Boucher, 1996) omitiendo la evidencia de cambios climáticos como posible causa del colapso cultural. La información paleoclimática basada en proxies geoquímicos (e.g. Hodell et al., 2007) aporta evidencia sólida de cambios ambientales. Sin embargo, elaborar reconstrucciones paleoecológicas en estos sitios, donde la densidad de población llegó a ser de hasta 300 habitantes por Km2 (Islebe y Leyden, 2006), podría proporcionarnos información poco confiable sobre cambios de la vegetación debido a que la vegetación en zonas de alta densidad poblacional esta sujeta a fuertes presiones por actividades agrícolas y forestales de subsistencia. Es de suma importancia el conocer al respuesta de la vegetación natural ante procesos de cambio climático para comprender mejor el impacto de las actividades antropogénicas sobre el clima y la vegetación. Kepecs y Boucher (1996) afirman que la porción litoral noreste de la Península era una zona con baja densidad poblacional, era un sitio habitado únicamente por miembros privilegiados de la sociedad maya y las actividades productivas realizadas se limitaban al cultivo de árboles frutales y venta de sal marina. Por lo que esta zona se vuelve el sitio ideal para conocer esta variación natural de la vegetación ante procesos de cambio climático. Es así como surge la idea de realizar la presente investigación, donde el objetivo fue elaborar una reconstrucción paleoecológica de alta resolución al norte de la península de Yucatán con el fin de ayudar a esclarecer con mayor detalle los cambios en el clima de los últimos 4,000 años, las manifestaciones de los eventos climáticos sobre la vegetación, el papel que desempeñaron las actividades agrícolas de la civilización maya sobre el clima y su relación con el colapso de esta civilización.

High-resolution paleoecological reconstruction of mangrove sediments from the northern Yucatan Peninsula: 3800 years of climate and vegetation history

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Abstract

A 1.9 m core was taken within the Biosphere Reserve Ría Lagartos in the northern Yucatan peninsula to develop a paleoecological reconstruction for the last 4000 years through fossil pollen and charcoal analysis. Changes in species composition are associated with changes in rainfall recorded at the regional scale. A wet climate was registered until 3500 cal. BP, where species composition showed a decreasing trend in precipitation. However, the conditions were still favourable for the development of tropical forest vegetation until 1600 cal. BP, when species composition indicated a drier climate. By 925 AD (1026 cal. BP) species composition shows the strongest drought event of the last 4000 years that has been associated with the collapse of Maya civilization in the Late Preclassic. Conditions during the Post-Classic show a trend towards wetter conditions with increases of tropical forest coverage near 1181 AD (770 cal. BP), corresponding to the medieval warm period. The paleoecological interpretation from terminal Postclassic to present is overshadowed by intensive land use, resulting of possible settlements from the arrival of the Spanish in the fifteenth century. Our results show correspondence with regional environmental changes of other studies in the Caribbean zone.

1 Keywords

Northern Yucatan, Climate history, Maya collapse, Mangrove sediments, Fossil pollen, Medieval warm period, Little Ice Age

2 Introduction

Holocene climatic conditions allowed the development of human civilizations in many parts of the world (Hayashida, 2005). The mid-Holocene is characterized by the stabilization of the sea level and water bodies that were favourable for the development of ecosystems in many subtropical areas. However, climate variability has not followed a linear trend of increase or decrease in temperature and / or precipitation. It is known that there have been episodes of increased global temperatures and increase or decrease in continental water bodies mainly due to changes in seasonal precipitation (Hodell et al. 2000).

In the Caribbean there have been major climate changes that have marked the change in plant communities through history (Carrillo-Bastos et al., 2010; Islebe and Sánchez, 2002; Torrescano-Valle and Islebe, 2006; Leyden, 2002; Islebe and Leyden, 2006; Islebe et al., 1996; Wooller et al., 2004; Wooller et al., 2007). In recent decades, the changing climate and understanding the patterns of vegetation change has taken great importance among academics, because ecological manifestations of climate change are directly related to human civilizations development due to favourable conditions for food production and use of natural resources. In this context, the Mayan culture has been studied from different disciplinary angles. The evolution of the Maya culture has been subjected to favourable climate conditions that allowed the development of large population centres. However, also abrupt climate changes have been documented, which have marked the end of the construction of ceremonial centres and have even led to the collapse of this civilization (Hodell et al., 2005; Haug et al., 2003). Understanding the relationship of human societies, such as the Mayan culture, with the environment becomes crucial to understand the effects of human activities on regional climate and can be taken as a reference to understand (and prevent) possible future climate change scenarios.

Variations in precipitation have been determined during the past 3500 years in different parts of the Yucatan peninsula through geochemical proxies (Curtis et al., 1996; Haug et al., 2003; Hodell et al., 2007). Nevertheless, these investigations lack the ecological character, complicating the understanding of climate change impacts on the peninsula vegetation types where precipitation values vary considerably.

Torrescano-Valle and Islebe (2006) conducted a paleoecological reconstruction using fossil pollen, which determined vegetation changes associated with variations in sea level in the southern Yucatan peninsula during the last 6000 years. Carrillo-Bastos et al. (2010) determined vegetation changes of the last 7000 years in the centre of the peninsula due to changes in precipitation and intensive land use activities. Leyden et al. (1996) determined changes in vegetation cover in the northwest region of the Yucatan Peninsula by phytoliths and fossil pollen analysis since the mid- Holocene, where vegetation changes were subject to precipitation variability. Islebe and Sanchez (2002) described changes in mangrove composition systems from the northeastern portion of the Yucatan peninsula over the past 2500 years, and found that changes in species composition were due to possible changes in sea level. Unfortunately, the ecological interpretations from these studies are too general given low temporal resolution. Leyden et al. (1998), meanwhile, described changes in vegetation composition around Lake Cobá, which shows the strong impact of agricultural activities on the vegetation since BC 850.

These changes in vegetation suggest the transformation of adjacent ecosystems by large cultivation areas, obscuring the natural response of vegetation to climate change events.

The Mayan culture developed about 4000 years ago in the Yucatan Peninsula and other parts of Mesoamerica (Coe, 2000). Research suggests that climate change events on a pan-regional scale caused demographic catastrophes on the pre-Hispanic Mayan population (Haug et al., 2003; Hodell et al., 2001; Curtis et al., 1996). Other researchers suggest that social unrest was the determining factor in its demise (Aimers, 2007; Kepecs and Boucher, 1996). There is archaeological evidence that great Maya cities were abandoned from south to north (Gill, 2000). The drought events have been attributed mainly to migration of the ITCZ (Haug et al., 2003). Unfortunately, the information available is still insufficient to determine how climate change affected this civilization and, more important, what was the role of environmental changes in their disappearance around AD 900.

The eastern portion of the northern Yucatan peninsula is an area where population density was lower compared to the central and southern Maya region (Kepecks and Boucher, 1996). It was an area where only the privileged class was allowed to live and was the site of salt trade and fruit tree cultivation (Kepecs and Boucher 1996). Therefore, our study aimed at performing a high-resolution paleoecological reconstruction of the last 4000 years through fossil pollen analysis to determine circum-caribbean climate events manifestations on vegetation as pressure from human activities was lower in the area (Kepecs and Boucher, 1996). Analyzing the effects of climatic changes and impact of agricultural activities of Mayan civilization on the natural vegetation will help to contribute to clarify the causes of the collapse of pre-Hispanic Mayan culture and untangle vegetation dynamics. Finally, the results were compared with existing paleoclimate information from various studies in the region, to establish if the climate conditions described above correspond to an effect of climate change on a circum-Caribbean scale.

3 Materials and methods

3.1 Study zone

The sampling site is a pond located 3.6 km away from coast line within Ría Lagartos biosphere reserve in Northern Yucatan peninsula with coordinates 21º34'46" N y 88º04'19.7" W (Fig. 1). According to CONANP (1999), the climate in the zone is dry with 26ºC as mean annual temperature and 500mm of mean annual precipitation. The area of the biosphere has 10 vegetation types: medium statured or semi-evergreen tropical forest, medium statured or subdeciduous tropical forest, low statured or deciduous tropical forest, low statured deciduous or spiny tropical forest, low statured flooded tropical forest, fringe mangrove, dwarf mangrove, coastal dune scrubs, and flooded grassland (CONANP, 1999). Vegetation directly surrounding the sampling site consists of low statured flooded tropical forest with characteristic species like *Haematoxylum campechianum* L., *Plumeria* sp. and *Thrinax radiata* C. Loddiges. Aquatic vegetation consists of *Cladium jamaicense* H. J. N. von Crantz, Poaceae and *Typha* sp.

3.2 Sampling and processing

With the help of a Russian corer, 50cm sections were obtained till 187cm depth of mangrove sediments. Sections were packed and transported to the laboratory of palynology of ECOSUR for processing. We obtained a total of 64 sub-samples of 1cm^3 along the stratigraphic column. Samples were treated with potassium hydroxide (KOH) and hydrochloric acid (HCl) to remove carbonates and humic acids, respectively. *Lycopodium* spores to calculate pollen concentration and pollen influx were added. Acetolysis was applied to the samples as proposed by Faegri and Iversen (1989) to prepare pollen slides. Optical microscopy (400x) was used to identify pollen grains. For pollen identification the pollen reference collection of ECOSUR Herbarium (CIQR) was consulted as well as Palacios-Chávez et al. (1991).

For charcoal analysis, subsamples adjacent to those used for pollen analysis were taken and were treated by isolation procedures for charcoal analysis proposed by Stevenson and Haberle (2005). Subsequently we performed a count of all particles per cubic centimetre (p/cm3) of charcoal between 125 and 200 microns.

We identified a minimum of 300 pollen grains in each subsample excluding Cyperaceae and other (sub) aquatic taxa. We used the Tilia 1.7.16 software package (Grimm, 2011) to elaborate the pollen diagram and CONISS (Constrained Incremental Sum of Squares) was used for the determination of pollen zones.

Four radiocarbon ages of bulk organic matter were obtained by accelerator mass spectrometry (AMS) prepared by Beta Analytic Inc. in Miami, Florida (Table 1). Chronological calibration was established using the software CALIB 6.1 which uses INCAL09 curve based on 2009 international calibration data sets (Stuiver and Reimer, 1993). Additionally, we developed age-depth model using calibrated ages and linear regression.

4 Results

Mangrove sediments from showed to be appropriate for paleoecological reconstructions as previously stated by Islebe and Sánchez (2002). The grouping of taxa identified allowed a vegetation arrangement of mangrove forest, tropical forest and secondary vegetation. Three pollen zones were established through CONISS (Grimm, 1987) and represented in a pollen diagram (Fig. 2). The average sedimentation rate of the core was 0.57mm/year. 8006 grains cm^{-2} $year^{-1}$ influx of pollen was calculated. Total accumulation is of 10,488,290 pollen grains (Fig. 3). An average resolution of 60 years for vegetation changes was calculated according with a generated age-depth model (Fig. 4).

4.1 Pollen

4.1.1 Zone I (3781 – 3446 cal. BP; BC 1831 – 1497)

Rhizophora mangle L. remains the dominant species of mangrove taxa, although the percentage varies strongly in this period (2 to 25%). *Conocarpus erecta* L. was found <10%. *Avicennia germinans* L. and *Laguncularia racemosa* K. F. Gaertner appear around 3558 cal. BP (BC 1608). *Ficus* sp. and Moraceae are the dominant taxa among the elements of tropical forest. *Brosimum* sp. presents 17% of the pollen sum at 3691 cal. BP (BC 1742), although their abundance during the rest period was <10%. Fabaceae concentration fluctuates around 5% with a peak of 45% by 3468 cal. BP (BC 1519). *Bursera* sp., Euphorbiaceae, Sapindaceae and Arecaceae maintain a ratio <5%, but steadily. Apocynaceae, Malpighiaceae, Rubiaceae and other tropical forest taxa appear recurrently in abundance <3%.

Poaceae represent 10 to 25% of the amount of pollen with peaks of 30% by 3513 cal. BP (1564 BC) and 3647 cal. BP (1697 BC). Asteraceae has percentages <3% consistently. *Cecropia* sp., *Zea mays* L., *Acacia* sp., *Celtis* sp. (Ulmaceae) and Cucurbitaceae have values of <2%. Cyperaceae has values of <20% of the total pollen amount. Charcoal particles were generally lower than 250 p/cm^3 during this period with a peak of 1770 to 3602 cal. BP (BC 1653). This zone has a sedimentation rate of 0.71mm/year.

4.1.2 Zone II a (3443 – 1571 cal. BP; BC 1497– AD 380)

Conocarpus erecta is the dominant species of mangrove elements, representing up to 60% of the pollen sum around 1720 cal. BP. *Rhizophora mangle* has percentages of <10% during this period. *Avicennia germinans* and *Laguncularia racemosa* appear regularly from 2325 cal. BP (BC 374) with values of <2%.

Ficus sp. and Moraceae are the best represented taxa of tropical forest in this period with percentages higher than 30%. *Brosimum* sp. maintains values of <4% but is absent from 1931 cal. BP (20 BC) and 2186 cal. BP (AD 235). Fabaceae appears consistently in this zone with percentages of <10%. Combretaceae / Melastomataceae, *Bursera* sp., Euphorbiaceae and Arecaceae appear repeatedly in this period with concentrations <5%. Rubiaceae, *Metopium brownie* I. Urban, Malpighiaceae and other tropical forest taxa appear occasionally with a concentration <3%.

The diversity of disturbance pollen elements in this zone increased. Poaceae remains dominant among disturbance taxa with variable percentages around 15% and maxima of 26 and 29% by 3226 cal. BP (BC 1276) and 2255 cal. BP (BC 304), respectively. Asteraceae has a concentration <10% and *Zea mays* is present in almost all the zone. *Croton* sp. appears repeatedly <5%. *Acacia* sp. appears continuously from 3226 cal. BP (BC 1276) to 2325 cal. BP (BC 374) with values of <5%. Malvaceae is recorded from 3226 cal. BP (BC 1276) with a maximum of 12% by 1931 cal. BP (BC 20). *Cecropia* sp. and other disturbance taxa appear recurrently with values of <1%.

Alnus sp. and *Podocarpus* sp. appear in this pollen zone with abundances <1%

Charcoal particles remain < 300 p/cm^3, except between 3425 and 3359 cal. BP (BC 1475 - 1409) and 1931 - 1791 cal. BP (AD 20 - 160), and reach a maximum of 1327 and 758 p/cm^3, respectively.

Fungal spores are lower than 10% compared to the total sum of elements with a maximum of 30% by 2603 cal. BP (BC 652).

4.1.3 Zone II b (1571 – 765 cal. BP; AD 380 – 1187)

This period is characterized by a drastic decrease in mangrove element which remains *Conocarpus erecta* as the dominant mangrove taxa with values <20%. *Rhizophora mangle* disappears completely between 956 cal. BP (AD 995) and 1304 cal. BP (AD 647). *Laguncularia racemosa* is absent in this period and *Avicennia germinans* maintains low percentage <1% from 1443 cal. BP (AD 508) to 1165 cal. BP (AD 786) where it disappears.

The elements of tropical forest suffer a sharp decline. *Ficus* sp. decreases sharply from 62 to 8% between 1374 cal. BP (AD 577) and 1095 cal. BP (AD 856), reaching a value <3% at 886 cal. BP (AD 1065). Moraceae was also affected during this period with abundance <15%. Fabaceae, *Brosimum* sp., Euphorbiaceae and other tropical forest taxa did not exceed 2% throughout the pollen zone.

The disturbance elements increase considerably. Poaceae reaches the maximum value of 30% by 1026 cal. BP (AD 925). Asteraceae becomes the dominant taxon of disturbance elements after 1234 cal. BP (AD 716) with a maximum of 49% in 956 cal. BP (AD 995). *Croton* sp. was consistently recorded throughout the pollen zone peaking at nearly 5% at 770 cal. BP (AD 1181). *Cecropia* sp. was registered with value <1% by 1443 cal. BP (AD 508) and 886 cal. BP (AD 1065). Cucurbitaceae, *Myrica* sp. and other tropical forest taxa were found intermittently with value less than 1%.

Pinus sp. occurs almost throughout the pollen zone with values <2% and Cyperaceae decreases sharply from 14 to 3% between 1374 cal. BP (AD 577) and 1304 cal. BP (AD 647).

Charcoal particulates remain < 100 p/cm^3 except at 886 cal. BP (AD 1065) and 1026 cal. BP (AD 925) with an input of 132 and 122 p/cm^3, respectively. The average sedimentation rate in this zone was 0.5mm/year.

4.1.4 Zone III (765 cal. BP– Present; AD 1187 - Present)

This period is characterized by increased *Conocarpus erecta* as dominant taxon among mangrove elements with values oscillating between 30 and 60%. However, there is a decrease to 3% at the upper pollen zone. *Rhizophora mangle* is presented in the upper and lower limits of the zone with value <2%. *Avicennia germinans* increases its concentration relative to the pollen amount with values >5% at 732 cal. BP (AD 1220).

Tropical forest elements show a better representation in this area. Moraceae increases to values higher than 10% with peaks over 30% from 334 cal. BP (AD 1618). Fabaceae is constant with value <1%. *Brosimum* sp. Euphorbiaceae, Arecaceae, Sapindaceae and other forest taxa appear often with values <1%.

Disturbance elements decrease compared to the previous zone. Asteraceae maintains a constant ratio <12%. *Croton* sp. is constant almost the entire zone, but with values <1%. *Zea mays* was recorded only about 400 cal. BP (1552 AD) in the upper limit of pollen zone. *Celtis* sp. (Ulmaceae), Cucurbitaceae and other disturbance elements have values <1%.

Pinus sp. remains present with value <1% and *Alnus* sp. was recorded between 202 cal. BP (AD 1751) and 268 cal. BP (AD 1685).

We obtained a total of 500 p/cm3 of charcoal at 732 cal. BP (AD 1220). The accumulation thereafter decreased to less than 230 p/cm^3 at ~ AD 1950 where it rose to over 550 p/cm^3. The average annual sedimentation rate of the pollen zone is 0.51 mm/year.

5 Discussion

5.1 Middle Preclassic (BC 2000 – 1500; 3781 – 3446 cal. BP)

The climatic conditions show a moist environment where precipitation levels allowed well represented mangrove systems in the study area. The dominance of *Rhizophora mangle* and low percentages of *Conocarpus erecta* are strong evidence of increased salinity (Hogarth, 2010) in the flooded areas that allowed the development of larger populations of *R. mangle* in the study area. The high percentages of *Brosimum* sp., Moraceae and *Ficus* sp. provide valuable information for high levels of rainfall that led to the establishment of tropical forests. These wet climate conditions have been previously described for the north of the peninsula by Islebe and Sanchez (2002) where through mangrove species composition, wet conditions prevailed until 1500 cal. BP (Hodell et al., 1995). Moreover, the presence of *Cecropia* sp., *Zea mays* and charcoal particles during this period provide evidence of agricultural activity. The low percentages of Asteraceae and Malvaceae can be explained by wet conditions and low agricultural activity that allowed accelerated processes of ecological succession. These data give new information of human settlements in this area, because although there are no important ceremonial centres nearby, we found high percentages of *Z. mays* from BC 1944 providing new evidence to previous research by Leyden et al. (1998) where beginning of clearing and agricultural activities in the north and central Peninsula from was pointed at BC 1650. It is noteworthy that the carbon particles, despite giving during this period concentrations less than 160p/cm3, have a maximum value around BC 1653 of 1770 p/cm3 which coincides perfectly with the records of Leyden et al. (1998) on agricultural activities early in the region.

5.2 Late Preclassic (BC 1500– AD 250)

By BC 1500, humid conditions prevail, but with a trend towards drier conditions. The percentages of *Conocarpus erecta* gradually increase and *Rhizophora mangle* decreases evidencing decreased precipitation. Islebe and Sanchez (2002) found that mangrove systems composed mainly of *C. erecta* allow better representation of the surrounding vegetation in the sediments. However, taxa of tropical forest like Moraceae and *Ficus* sp. in our study area maintain a downward trend, which can be interpreted that the decrease of tropical forest pollen is a response to a process of gradual decrease of available moisture. These results are shown to be consistent with sediment data from Lake Chichancanab in central Yucatan peninsula (Hodell et al., 1995) and Lake Punta Laguna located north of Coba (Hodell et al., 2007) where the authors determined that this period was highly variable with sea level variations in response to wet and dry episodes. In lake Miragoane, Haiti (Hodell et al., 1991) and the Cariaco Basin, Venezuela (Haug et al., 2001) decreased precipitation was registered between 2400 and 1200 cal. BP. These events of rainfall variation at different points in the Caribbean region can be explained by processes of movement of the ITCZ (Haug et al., 2001), and at the same time an effect of seasonal variations of solar radiation induced by orbital cycles (Milankovitch) (Hodell et al., 1991).

Although this period had a tendency towards drier conditions, Hodell et al. (2007) claim that there were more moisture events around BC 1140, 610 and 220, and our results show to be consistent with these dates. However, in the study site we found wetter conditions around 2325 cal. BP (BC 374) that were not previously described. The presence of microforaminifera, high percentages of *R. mangle* and reduced *C. erecta* let us to affirm saltwater intrusion. *Brosimum* sp. reaches high percentages and Moraceae and *Ficus* sp. provide evidence of increases in precipitation (Islebe and Sánchez, 2001). The absence of *Cecropia* sp., *Zea mays*, Arecaceae and low percentages of Poaceae, Asteraceae and charcoal particles show that human activities were less intensive in this period.

Charcoal particles were less important in this period. However, between AD 20-160, charcoal particles reach their maximum value as evidence of extensive land use activities. Around AD 229 *Zea mays* disappears, *Conocarpus erecta* percentages increase and forest taxa have low percentages, suggesting a dry period. These records match with severe drought events that marked the pre-abandonment of the Mayan cities between AD 150 and 250 (Curtis et al., 1996; Haug et al., 2003) and have been explained by the migration of the ITCZ to the south that caused a dry episode in the Yucatan peninsula during this time (Haug et al., 2003).

5.3 Classic (AD 250 – 1050)

Reduced *Conocarpus erecta* percentages and the presence of *Rhizophora mangle*, as well as increasing trend of Moraceae, *Ficus* sp. and the presence of *Brosimum* sp., *Bursera* sp., Sapotaceae and other tropical forest taxa are evidence of more humid climatic conditions between 229 and 856 AD. These conditions have been extensively described in the Maya region (Gill, 2000; Aimers, 2007) because it is precisely during this period where large population centers reached their highest development with occupations up to 300 inhabitants per km^2 (Islebe and Leyden, 2006). Moreover, although our survey did not find records of *Zea mays*, the increase in Poaceae, Chenopodiaceae / Amaranthaceae and other elements of disturbance show a period of intensive human activity in the area. The constant presence of *Pinus* sp. can be interpreted as environments of open vegetation that allowed the deposition of pollen from pine and oak forests from distant places (Islebe et al., 1996; Domínguez-Vázquez and Islebe, 2008).

Around AD 856 mangrove elements percentages decline and tropical forest increase as a signal of wet conditions. However, at AD 925 an extreme drought event was characterized by low percentages of Moraceae, *Brosimum* sp. and *Ficus* sp. The high percentages of Asteraceae at AD 995 give evidence of the driest event of the last 3800 years (Hodell et al., 2007). During this dry event, we found the presence of low percentages of *Bursera* sp. and Apocynaceae that correspond to open forest vegetation. This can be explained by the multidecadal scale of our survey, because at some time between AD 850 and 950 there was an increase in humidity calculated by oxygen isotopes in sediments from Lake Punta Laguna (Hodell et al., 2007). However, the interpretation of *Bursera* sp. and Apocynaceae as a sign of increased moisture may be wrong, both taxa may occur in disturbed environments and variable rainfall conditions. More information is necessary to integrate these data to set specific claims about events of high humidity in our study area.

Our data, despite being consistent with other studies in central and northern portion of the Peninsula (Hodell et al., 2007; Leyden et al., 1998), present chronological variations that can be explained by the combination of two main factors: 1) the southward migration of the ITCZ that marked a chronological gradient of decreased precipitation from south to north in the peninsula and marked, in general, a pattern of Mayan cities abandonment with similar characteristics and 2) the response time of vegetation in face of climate change processes as well as the resistance of the vegetation to dry conditions. We obviated this last based on actual precipitation data (INEGI, 1981 cited by Hodell et al., 2007) that show significant differences of precipitation between areas near the north coastline and central portion of the Peninsula (600 - 800mm and 1000 - 1200mm year, respectively). Therefore, the vegetation in the vicinity of the coastline, as there are low values of average annual rainfall, may have a greater degree of tolerance to conditions of reduced precipitation.

Islebe (1999) assert that the aquatic vegetation surrounding water bodies can be used to determine trophic levels and ecological processes at local level. In our survey, the percentages of Cyperaceae vary widely during the 3800 years covered by our investigation. Clearly, from AD 229 onwards conditions were favourable for further development of aquatic vegetation. However, between AD 647 and 1220, the percentages are significantly lower, which allows us to state that there was a drastic decline of wetlands in response to decreased precipitation in this area, giving strong evidence of pronounced regional drought.

Gill (2000) presents different studies suggesting that deforestation and the need for large areas of crops for food production and high demand for water made the Mayan population vulnerable to drought. Other studies attribute the disappearance of the Mayan civilization mainly to social instability (Aimers, 2007). The northeastern portion of the Yucatan Peninsula during the Classic was a site with walled areas, where a privileged class lived and was an area for fruit tree cultivation and marketing of sea salt (Kepecs and Boucher, 1996). It is important to conduct a multidisciplinary research to help a better understanding of civilization collapse causes at the end of the Classic since the site was not under pressure of high population density compared to other sites throughout the Maya region.

5.4 Post-Classic to Presente (AD 1050 - Present)

By 1181 AD increased Moraceae and *Ficus* sp. suggest increased tropical forest coverage in response to more humid conditions. Mangrove taxa are well represented by the appearance of *Rhizophora mangle* between AD 1065 and 1220. The elements of disturbance decrease due to the reduction of human activities, although charcoal particles were more abundant compared with the previous period as a signal of anthropogenic activities in the area. These results are shown to be consistent with those reported by Curtis et al. (1996) which determined the increase in precipitation by oxygen isotopes in sediments from Lake Punta Laguna with maximum value at ~ AD 1100. On the other hand, Haug et al. (2001) determined an increase in rainfall that lasted about 300 years between 1000 and 700 cal. BP for the medieval warm period. The time difference we found with our results reflect a time with high humidity conditions (<150 years) that can be explained by the response time of vegetation climate events coupled with the delay caused by the southward migration of the ITCZ.

After AD 1220, vegetation changes considerably. There were episodes where *Conocarpus erecta* becomes the dominant taxon and other episodes where it disappears. Around AD 1685 and 1884 there are two peaks with high percentages of *C. erecta* accompanied by declining tropical forest taxa. This behaviour, where the vegetation composition suggests a dry climate, coincides chronologically with the Little Ice Age described in previous studies on the Peninsula (Haug et al., 2001; Lozano-García et al., 2007). However, the variability of mangrove elements, tropical forest and the high variability and diversity of disturbance elements possibly make the paleoecological interpretation of this period complicated. Therefore it is necessary to integrate information from other proxies in order to better identify climate events and their effects on vegetation of northern Yucatan peninsula.

6 Conclusions

This high resolution study yielded climate and vegetation history of the last 4000 years in the northern portion of the Yucatan peninsula providing new evidence of the first agricultural activities in the zone. We recorded a more humid period between 3781 - 3446 cal. BP characterized by *Rhizophora mangle* as the dominant species of mangrove systems. Later, during the late Preclassic, moisture levels decreased significantly with sporadic wet periods. We also found evidence of severe drought that may be related to the Mayan pre-abandonment during the Late Preclassic. During the classical period, climate conditions were favourable for the development of tropical forests and mangrove systems. However, towards the end of the Classic, the driest time of the last 4000 years was detected, evidencing a period of extreme drought linked to the collapse of Maya civilization. During the Postclassic, wet conditions returned in the area. Favourable conditions for tropical forest development evidences medieval warm period. Finally, we found evidence of the Little Ice Age between the fourteenth and nineteenth century. Unfortunately paleoecological interpretations are obscured by human activities. Our data corresponds to climatic events recorded in different parts of the Caribbean and Mesoamerica showing that climate events operated on a circum-caribbean scale.

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Fig. 1. Location of the study area in the northern Yucatan Peninsula.

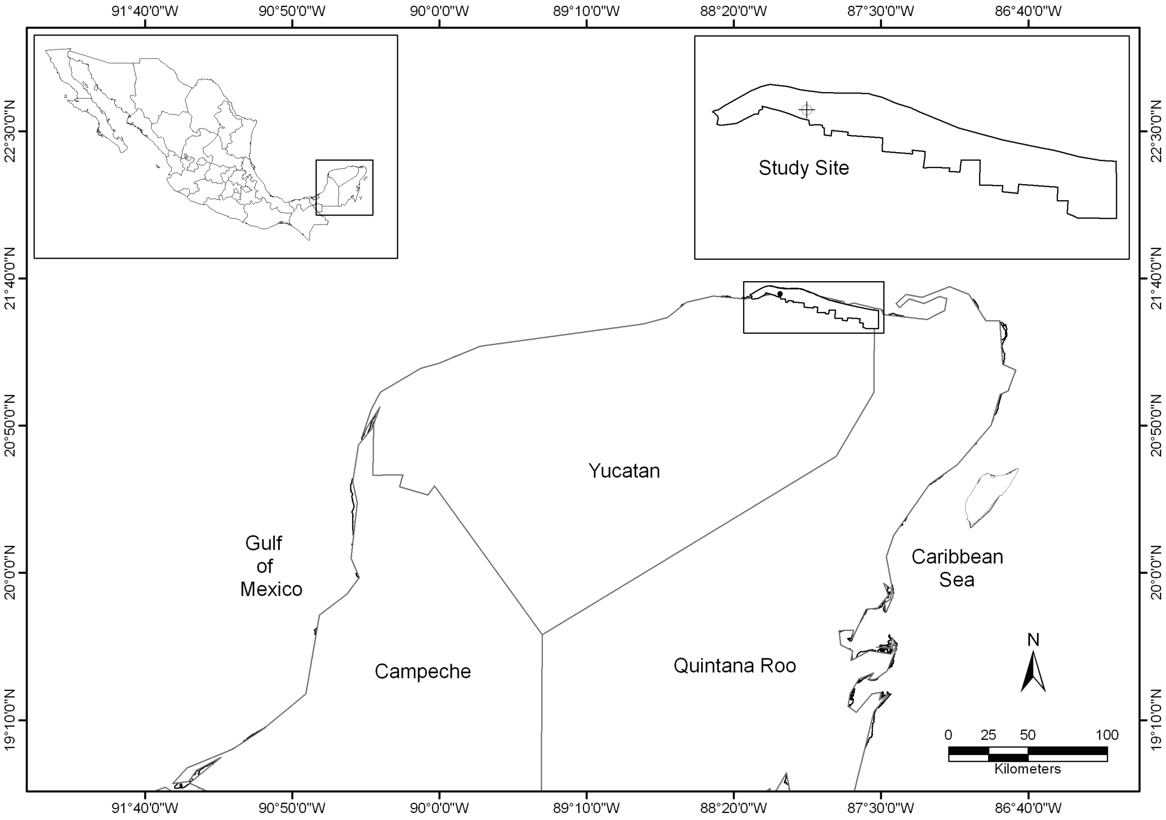

Fig. 2. Percentage pollen diagram. Pollen taxa are ordered according to ecological groups; mangrove, tropical forest, disturbance taxa, aquatics and montane elements.

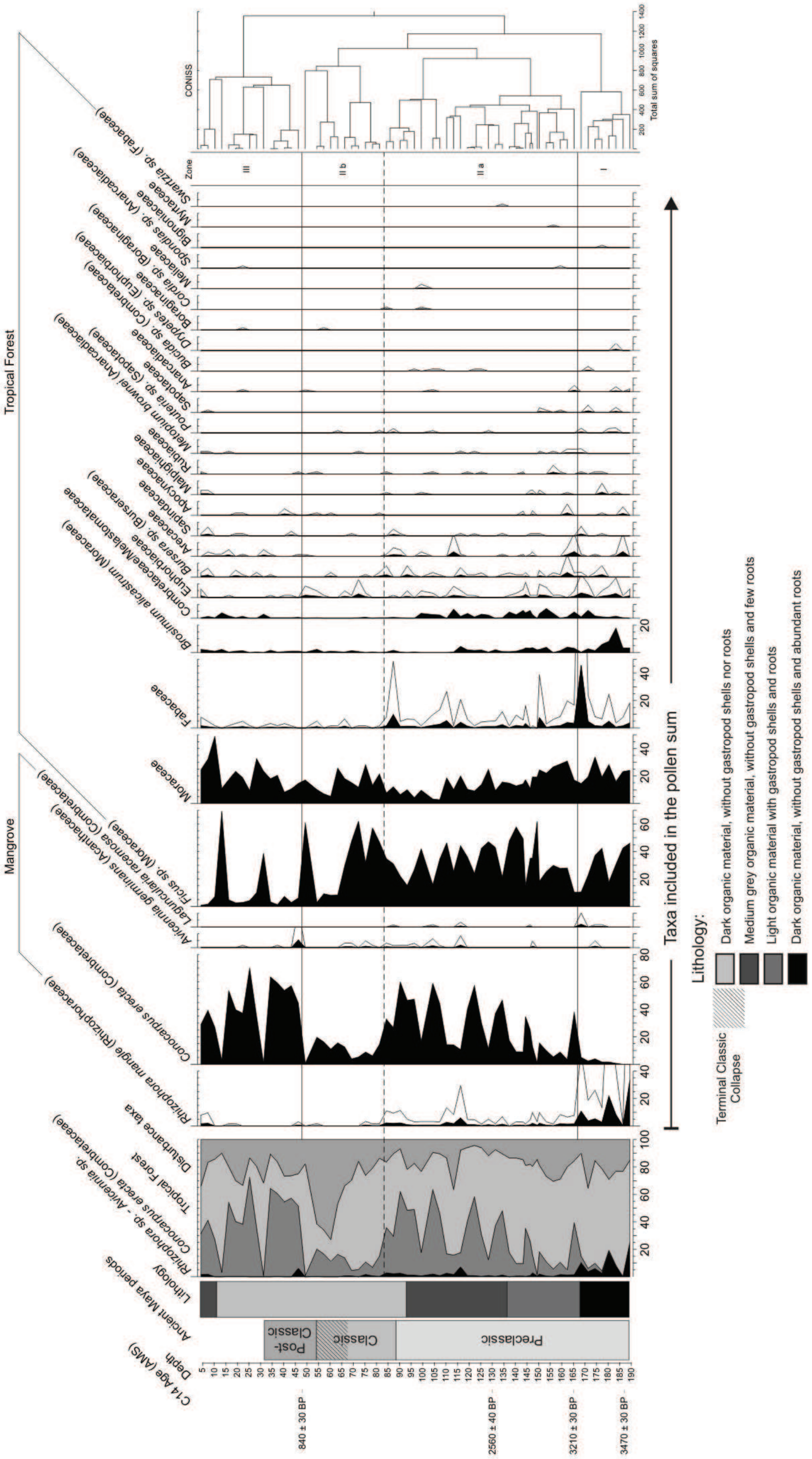

Fig. 2. (Continuation)

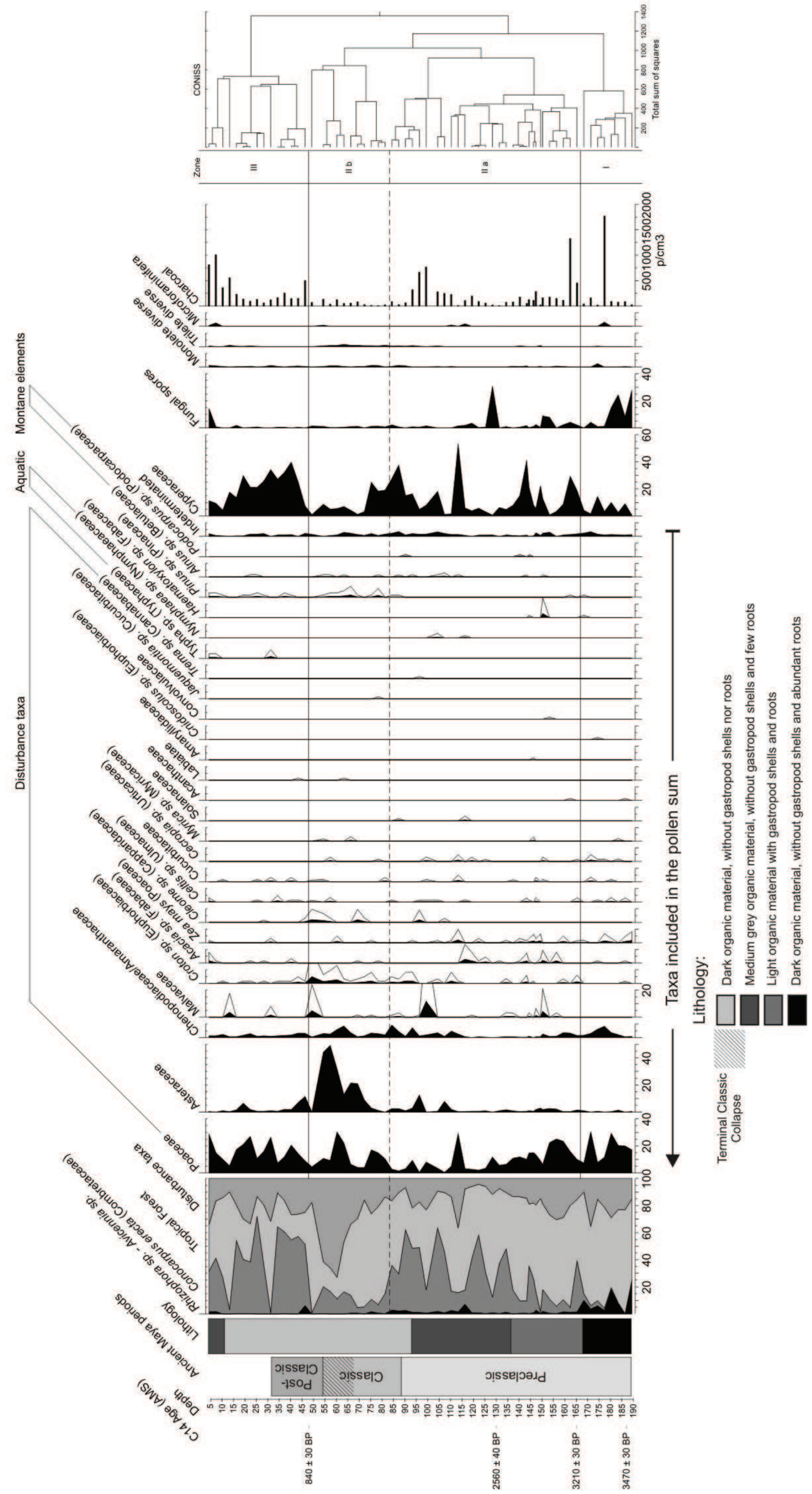

Fig. 3. Pollen accumulation curve of the analyzed core.

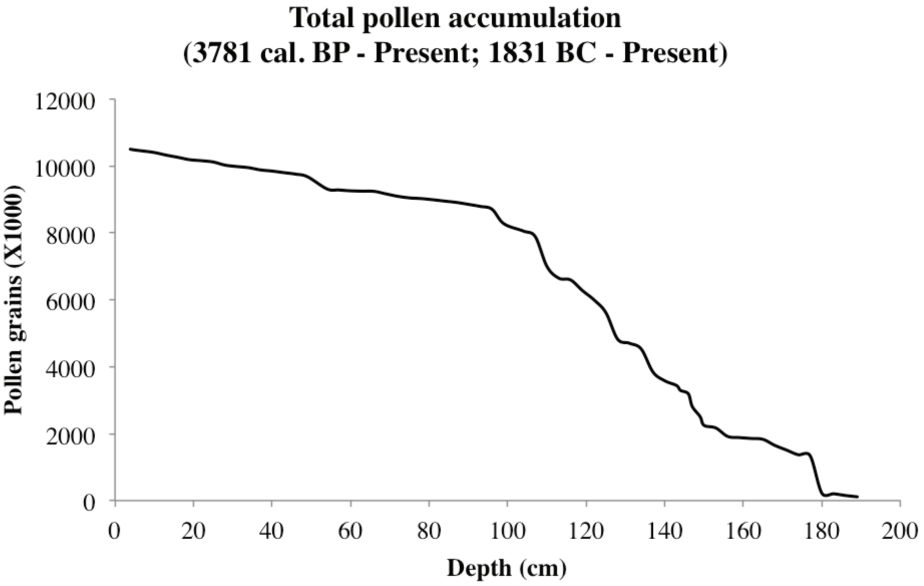

Fig 4. Age-depth relationship. All radiocarbon dates were analyzed at Beta Analytic, USA.

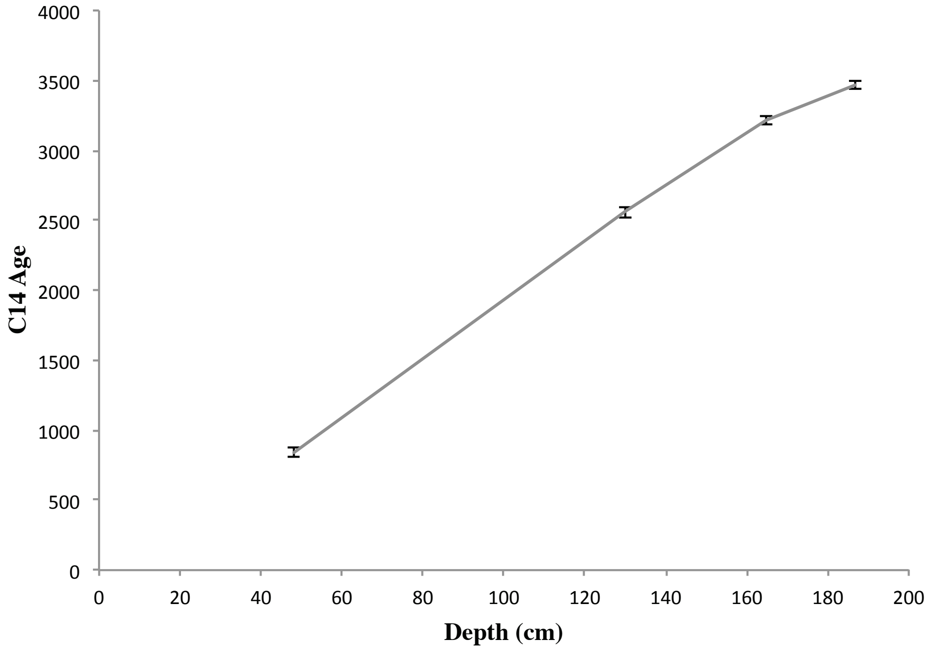

Table 1. Radiocarbon ages

Sample code	Depth (cm)	Measured material	Conventional Radiocarbon age	2 sigma calibrated age (cal. BP)	Two sigma relative area
Col048	48	Bulk organic matter	840 ± 30 BP	685 - 795	0.98
Col130	130	Bulk organic matter	2560 ± 40 BP	2678 - 2758	0.5
Col165	165	Bulk organic matter	3210 ± 30 BP	3369 - 3477	1
Col187	187	Bulk organic matter	3470 ± 30 BP	3683 - 3833	0.93

Discusión y Conclusiones

La variabilidad y abundancia en la composición de especies encontradas en el presente estudio, el cual registra la historia del clima y vegetación de los últimos 4000 años, corresponde cronológicamente con eventos de cambio climático registrados en escala circum-caribeña.

Los sedimentos de manglar mostraron ser apropiados para la elaboración de reconstrucciones paleoecológicas, donde los cambios en la vegetación se determinaron a través de la composición de 56 taxa de polen pertenecientes a 39 familias. La reconstrucción paleoecologica fue posible gracias a que el sitio no presentó importantes asentamientos de comunidades mayas (Kepecs y Boucher, 1996).

Entre 3800 y 3500 AP las especies pertenecientes a los sistemas de manglar se encuentran mejor representadas, dando evidencia de condiciones húmedas. Los primeros impactos de las actividades agrícolas sobre la vegetación se registraron alrededor de 3800 AP (1950 BC), proporcionando nueva evidencia del inicio de las actividades antrópicas en la zona. Entre 3500 y 1500 AP la abundancia de elementos selváticos y los bajos porcentajes de elementos de manglar sugieren que las condiciones fueron más secas, aunque el clima fue aún favorable para el desarrollo de ecosistemas selváticos. Hacia 1722 AP (229 AD), el aumento de *Conocarpus erecta*, así como la disminución de elementos selváticos da evidencia de un periodo de fuerte sequía que ha sido relacionada con el preabandono de las ciudades mayas durante el preclásico terminal. Cabe mencionar que se elaboró un análisis de partículas carbonizadas para la obtención de información complementaria de actividades antrópicas en la zona de estudio, donde es evidente el aumento de las actividades de aclareo en los alrededores de la zona de estudio entre 2186 y 1791 AP (235 BC – 160 AD).

Posteriormente, a partir de 1500 AP, las condiciones climáticas sugieren que los niveles de precipitación fueron favorables para el desarrollo de selvas. Sin embargo, a partir de 1026 AP (925 AD) las condiciones cambiaron hacia climas más secos, donde los altos porcentajes de Asteraceae, así como la disminución de elementos de manglar y selva dan evidencia del evento más seco registrado en los últimos 4000 años, alcanzando su máximo valor hacia 956 AP (995 AD). Estas condiciones de sequía extrema han sido ampliamente descritas en toda la región maya, ya que han sido relacionadas con el colapso de esta civilización, demostrando la escala pan-regional de estos eventos climáticos. Después del evento más seco registrado, encontramos un periodo en donde las condiciones fueron favorables para el desarrollo de vegetación selvática. Hacia 770 AP (1181 AD), encontramos evidencia del aumento de la cobertura de selvas en respuesta al periodo cálido medieval. Sin embargo, las interpretaciones paleoecológicas durante la Pequeña era de Hielo se ven eclipsadas por el aumento de los elementos de disturbio.

Posterior al colapso de la civilización maya durante el periodo Clásico, la reorganización y distribución de la población fue mayor en la zona norte de la Península debido a la mayor disponibilidad de cuerpos de agua (Henderson, 1998), favoreciendo el aumento de las actividades agrícolas y forestales de subsistencia. Estas actividades aumentaron la abundancia de elementos de disturbio y oscurecieron las interpretaciones paleoecológicas. Por lo que es necesario incorporar información proveniente de otros proxies con el fin de esclarecer a mayor detalle los cambios ambientales durante este periodo, dado que la vegetación mantuvo un alto grado de perturbación humana a partir de este periodo.

Aspectos éticos en la investigación

Durante esta investigación, el material biológico utilizado corresponde a material biológico inerte, como es el polen fósil, para su determinación taxonómica, por lo que no se manipuló ningún tipo de material nocivo para la salud ni se hicieron colectas de plantas en el desarrollo de esta investigación.

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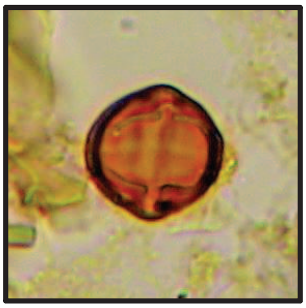
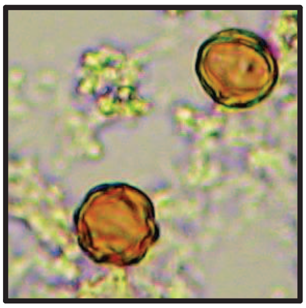
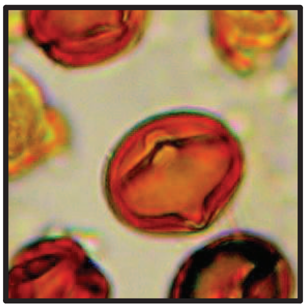
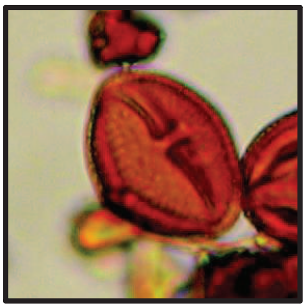
Anexo. Polen determinado en las muestras

Manglar

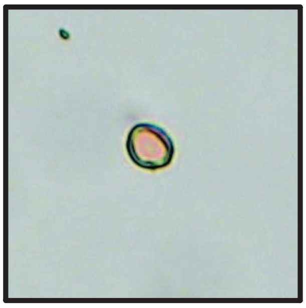

Rhizophora mangle
(Rhizophoraceae)


Conocarpus erecta
(Combretaceae)

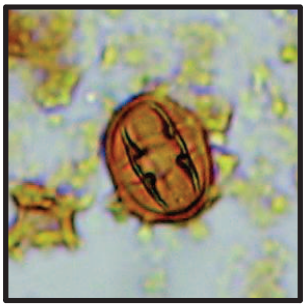

Laguncularia racemosa
(Combretaceae)

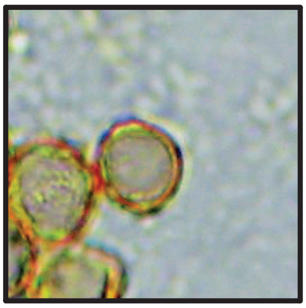

Avicennia germinans
(Acanthaceae)

Selva


Ficus sp.
(Moraceae)


Moraceae


Fabaceae


Brosimum alicastrum
(Moraceae)

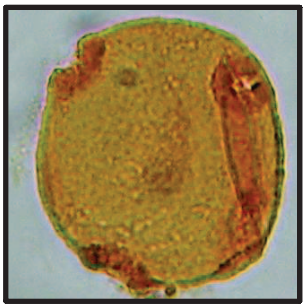

Combretaceae


Bursera sp.
(Burseraceae)

Anexo. Polen determinado en las muestras

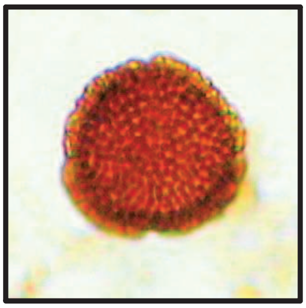
Selva

Arecaceae

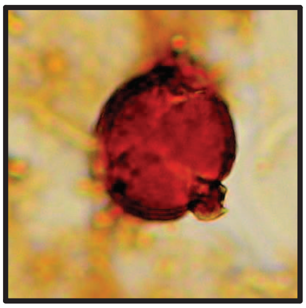


Apocynaceae

Malpighia sp.
(Malpighiaceae)



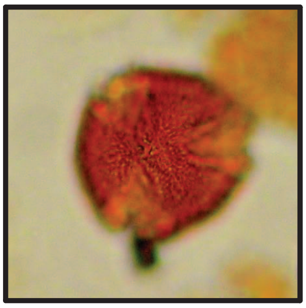
Rubiaceae



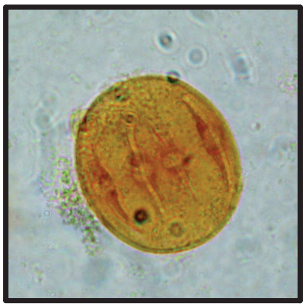
Metopium brownei
(Anarcadiaceae)

Pouteria sp.
(Sapotaceae)

Drypetes sp.
(Euphorbiaceae)



Cordia sp.
(Anarcadiaceae)

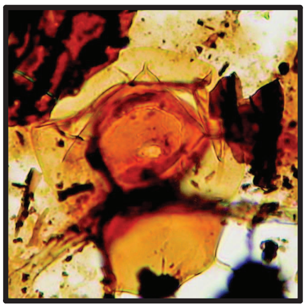


Meliaceae

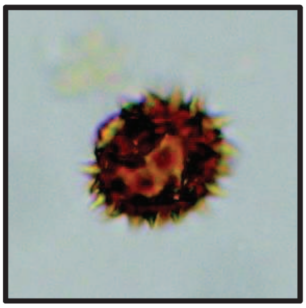
Myrtaceae

Anexo. Polen determinado en las muestras

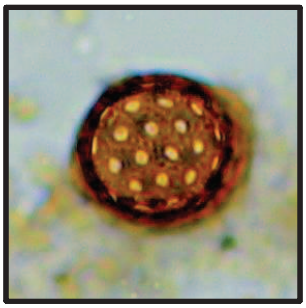
Disturbio



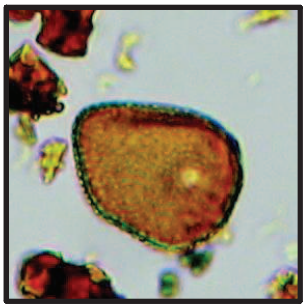
Poaceae



Asteraceae



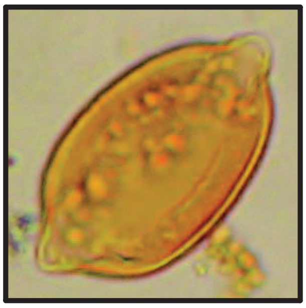
Chenopodiaceae/
Amaranthaceae



Croton sp.
(Euphorbiaceae)

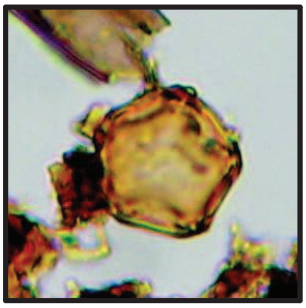
Acacia sp.
(Fabaceae)

Acuáticas

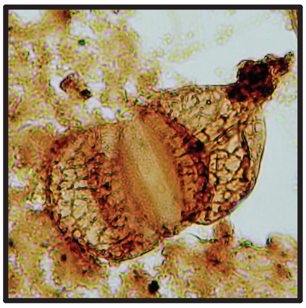


Nymphaea sp.
(Nymphaeaceae)

Elementos montanos



Alnus sp.
(Betulaceae)



Podocarpus sp.
(Podocarpaceae)