UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO

PROGRAMA DE POSGRADO EN CIENCIAS DE LA TIERRA

IMPACTO NATURAL Y CULTURAL DE LAS SECUENCIAS EDAFOSEDIMENTARIAS DEL HOLOCENO EN LA REGIÓN SURORIENTAL DE MÉXICO

Un estudio geoarqueológico en las Tierras Bajas Mayas

T E S I S

QUE PARA OPTAR POR EL GRADO DE:
DOCTOR E N C I E N C I A S DE LA TIERRA

P R E S E N T A

BERENICE SOLÍS CASTILLO

COMITÉ TUTOR
Dra. Elizabeth Solleiro Rebolledo, Instituto Geología
Dra. Beatriz Ortega Guerrero, Instituto de Geofísica
Dr. Mario Arturo Ortíz Pérez, Instituto de Geografía

JURADO EXAMINADOR
Dra. Elizabeth Solleiro Rebolledo, Instituto de Geología
Dr. Mario Arturo Ortíz Pérez, Instituto de Geografía
Dr. Rodrigo Liendo Stuardo, Instituto de Investigaciones Antropológicas
Dra. Esperanza Muñoz Salinas, Instituto de Geología
Dr. Alexander Correa Metrio, Instituto de Geología

MÉXICO D.F. Agosto del 2014

Dedicatoria

A mi tribu, a la que tanto quiero..!!

A tí, que te amo..!!

A todos aquellos que con sus lazos de amistad me han proporcionado alegría y cariño..!!

AGRADECIMIENTOS

Ahora, estas palabras expresan un camino de aprendizaje en compañía de personas que me han mostrado una perspectiva científica de la vida cotidiana, gracias!!

Agradezco a todos los contribuyentes fiscales que con sus aportaciones hicieron posible que el Consejo Nacional de la Ciencia y Tecnología así como el Instituto de Geología de la UNAM me brindarán el apoyo económico para la realización de mis estudios de doctorado.

A los proyectos PAPIIT INI17709, PAPIIT INI10710 (E. Solleiro).

A los proyectos bilaterales CONACYT-DLR J010/0705/09 y CONACYT 166878 (E. Solleiro).

Al proyecto PAPIIT INI08714 (S. Sedov).

A la Coordinación de Estudios de Posgrado por todo el apoyo recibido

A la Coordinación del Posgrado en Ciencias de la Tierra por su apoyo y dedicación.

Agradezco enormemente a mi tutora Elizabeth Solleiro porque me ha guiado en el quehacer científico, por su constante apoyo, paciencia y compromiso durante la realización de esta tesis. Asimismo, ***¡GRACIAS SENSEI!*** *por tu amistad, cariño, franqueza y consuelo durante las largas horas de plática, en las que he aprendido que el éxito está en lo cotidiano, el equilibrio en los principios y la felicidad en las cosas simples de la vida.*

Al Dr. Sergey Sedov por su paciencia y compromiso durante la evaluación de la tesis, por sus inigualables comentarios y, por fomentar mi curiosidad científica.

Gracias a mi comité tutor, Dra. Beatriz Ortega Guerrero y el Dr. Mario Arturo Ortiz por todo el entusiasmo, por sus innumerables sugerencias y comentarios a lo largo de la realización de la tesis.

Gracias a mi jurado de examen de grado Dr. Rodrigo Liendo Stuardo, Dra. Esperanza Muñoz Salinas y Dr. Alexander Correa Metrio por sus valiosos aportes.

A la Prof. Dr. Birgit Terhost de la Universidad de Würzburg en Alemania por haberme recibido durante mi estancia de investigación.

Al M en C. Jaime Díaz Ortega por su valiosa ayuda en la fase de análisis y la elaboración de las láminas delgadas, además de su amistad y constante apoyo.

Al Mtro. Jorge Rene Alcalá por su apoyo y numerosas enseñanzas durante los análisis de laboratorio.

Al Dipl.Geogr. Martin Krech por su ayuda en el laboratorio de extracción de minerales pesados de la Universidad de Würzburg en Alemania.

Al Dipl.Geogr. Tobias Sprafke por las facilidades técnicas en mi estancia en la Universidad de Würzburg en Alemania.

Al Dr. Bodo Damm, Christina Wiesbeck, Daniel Jäger, Bernhard Lucke y Serafían Sánchez por su asistencia en el trabajo de campo.

A la Dra. Christina Thiel por los fechamientos OSL y su ayuda en el trabajo de campo.

Al Dr. Héctor Cabadas Baez por su continua asesoría, también por su amistad y ayuda constante.

A Sara López Rivera por su colaboración y estudios de la paleovegetación de los materiales que conforman la presente tesis. También por sus constante alegría, entusiasmo y su amistad.

Al grupo de paleosuelos, gracias por cada comentario y aportes a mi tesis.

A todos y cada uno de mis amigos mi eterna gratitud, por haberme brindado su amista, confianza y alegría, Gina Ibarra (¡simplemente GRACIAS!), Keiko Teranishi (Te admiro), Yazmín Rivera (gracias por tu apoyo), Claudia Serrano y Esperanza Torres (por cada palabra, gracias!), Maricela Coronado (gracias por cada sonrisa), Oney Salazar (gracias por tu confianza), David Chucho (por las horas de plática), Ana Hernández (sonríe siempre) Paris Ferrand (gracias compañero arqueólogo) y Carlos Hinojosa (gracias amigo norteño).

A tí, Gabriel Vázquez ¡GRACIAS! por cada despertar que me llena de sonrisas..!!

¡GRACIAS! A todos aquellos que por mi distracción no agradecí correctamente, pero saben que los estimo, mil disculpas.

Impacto Natural y Cultural en las Secuencias Edafosedimentarias del Holoceno en la Región Suroriental de México:
Un estudio Geoarqueológico en las Tierras Bajas Mayas

INDICE

Impacto Natural y Cultural en las Secuencias Edafosedimentarias del Holoceno en la Región Suroriental de México:
Un estudio Geoarqueológico en las Tierras Bajas Mayas

RESUMEN

La región de las Tierras Bajas Mayas es controlada por un sistema fluvial dinámico y complejo que responde a los cambios ambientales. Esta respuesta ha quedado registrada en las diferentes fases de sedimentación y pedogenésis dentro de la cuenca del Río Usumacinta, el cual es considerado como uno de las cuencas más importantes de México, con una extensión de 75,000 km^2. En la Sierra Norte de Chiapas se describen cuatro ambientes geomórficos y el resto pertenecen a la planicie aluvial del río Usumacinta. Las unidades de la Sierra de Chiapas son las más antiguas de la zona de estudio y son controladas por procesos tectónicos y de modelado kárstico. Los suelos que caracterizan estas unidades son suelos de poco desarrollo en las partes elevadas (Leptosoles réndzicos) hasta suelos con alto grado de desarrollo, ubicados en las posiciones bajas (Luvisoles). Por su parte, las unidades dentro de la planicie aluvial son más jóvenes (Pleistoceno tardío-Reciente) y exhiben un sistema de terrazas en las cuales se registraron paleosuelos que fueron utilizados como un indicador para la reconstrucción de los cambios en las condiciones ambientales durante el Holoceno. Las secciones fueron correlacionadas por la morfología de los paleosuelos, edades de radiocarbono y materiales arqueológicos tipo de cada uno de los periodos de ocupación humana en el área: Formativo, Clásico y Post-clásico. Los paleosuelos más antiguos se caracterizan por sus fuertes rasgos gleycos y contienen concreciones de carbonatos con edades de 5450-5380 años cal. A.P.; sin embargo los carbonatos fueron depositados posteriormente producto de los paleosuelos desarrollados durante el Holoceno medio. Los paleosuelos en la parte superior de la

secuencia coinciden con cada una de las etapas de ocupación; el paleosuelo más antiguo de estos tiene una edad entre los 2000 y 2700 años cal. A.P. con fuertes rasgos vérticos y contiene abundante cerámica del periodo Formativo. Los paleosuelos superiores tienen un menor desarrollo y son afectados por la actividad antrópica, aquí las edades de radiocarbono y la tipología de la cerámica registrada indican que pertenecen al periodo clásico y post-clásico respectivamente. Estos resultados indican que los paleosuelos del Pleistoceno-Holoceno se desarrollaron en climas húmedos, posteriormeten so observa una transición hacia condiciones más secas en el Holoceno medio alrededor de los 5500 años cal. A.P. En el Holoceno tardío, aproximadamente a los 3,000 años A.P. hay un incremento en la estacionalidad que favorece el desarrollo de suelos tipo vertisol.

Natural and Cultural Impact on Pedosedimentary sequences of the Holocene in the Southern Region of Mexico:

A Geoarchaeology study in the Mayan Lowlands

ABSTRACT

The region of the Maya lowlands is controlled by a dynamic and complex river system that responds to environmental changes. This response has been recorded at different stages of sedimentation and pedogénesis. The Usumacinta River is considered one of the most important basins in Mexico, with an area of 75,000 km^2. Four geomorphic environments are described in the Sierra Norte de Chiapas, and in the alluvial plain of the Usumacinta River other four. The units of the Sierra de Chiapas are the oldest in the study area and are controlled by tectonic processes and karst modeling. The soils that characterize these units are soil less development in the upper parts (Leptosols rendzic) and soils with a high degree of development, located in the lower position (Luvisols). Meanwhile, units within the floodplain are younger (late Pleistocene-Recent) and exhibit a system of terraces where paleosols were recorded. These paleosols were used as an indicator of changes in environmental conditions during the Holocene. The sections were correlated by the morphology of paleosols, radiocarbon and archaeological material of each periods of human occupation: Formative, Classic and Post- Classic. Paleosols older are characterized by their strong features gleyic and carbonates concretions dated in 5450-5380 cal. B.P., however these carbonates were later deposited due to develop of paleosols in the upper part of the sequence during the middle Holocene. The paleosols in the upper part correspond with each period of human occupation, the earliest of these paleosols have an age between 2000 and 2700 years cal. B.P. also is characterized by strong vertic features and contains

abundant Formative period ceramics . The upper paleosols have less development by human activity, radiocarbon ages and artefacts recorded indicate that they belong to the classical and pos -classical period respectively. These results indicate that the Pleistocene - Holocene paleosols developed in humid conditions, after are observed a transition to drier conditions in the middle Holocene around 5500 cal. A. P. In the late Holocene, about 3,000 years BP there is an increase in seasonality which favors the development of vertisol soils.

Impacto Natural y Cultural en las Secuencias Edafosedimentarias del Cuaternarío Tardío en la Región Suroriental de México:
<u>Un estudio Geoarqueológico en las Tierras Bajas del Área Maya</u>

1. INTRODUCCIÓN

El cambio en las condiciones ambientales durante el Holoceno medio-tardío en la zona maya es producto de procesos tanto naturales como culturales. Estos cambios se presentan en periodos cortos de tiempo y se deben, en parte, a la continua interacción entre el hombre y su ambiente durante los intervalos de ocupación humana en la región. De hecho, algunas de las principales transformaciones han sido vinculadas con la caída de la Civilización Maya durante el Clásico (Dunning at al., 2002).

En las Tierras Bajas Mayas, el cambio en las condiciones ambientales se ha establecido con base en los registros lacustres estudiados en Guatemala y Belice que cubren desde el Pleistoceno tardío al Holoceno temprano hasta el Holoceno medio-tardío (Leyden et al., 1984; Rosenmeier et al., 2002; Hodell et al., 2005; Hodell et al., 2008; Correa-Metrio et al., 2012; Correa-Metrio et al., 2012). Particularmente, el Holoceno tardío ha llamado la atención en los registros, por su estrecha relación con la ocupación humana en la región (Gill 2000; Haug et al., 2003; Hodell et al. 1995; 2005; Brenner et al., 2002). Los registros mencionados señalan la existencia de condiciones climáticas variables durante los últimos 36,000 años, las cuales no se presentan de forma homogénea en espacio y tiempo, debido a la heterogeneidad de los ecosistemas en el paisaje.

En general, se ha establecido que las condiciones ambientales en el Pleistoceno tardío-Holoceno temprano son húmedas con una tendencia hacia condiciones secas alrededor de los 4,000 años (Mueller et al., 2009; Solís-Castillo et al., 2013a,b), las cuales tuvieron un impacto en el desarrollo cultural de la región maya (Grill 2000; Haug et al., 2003; Hodell et al., 1995; 2005; Brenner et al., 2002). Los sedimentos lacustres de la zona demuestran condiciones de aridez en el Preclásico tardío y el Clásico (Gunn at al., 1995; Hodell et al., 2001). Dunning y Beach (2010) también señalan periodos de una intensa sequía que afecta la región de las Tierras Bajas durante el Clásico. No obstante, Ortiz-Pérez et al. (2005) mencionan que las diferencias en las geoformas del paisaje de las Tierras Mayas producen una alta variabilidad en los ecosistemas modernos, por ende, se supone que esta diferencia también se presenta en los ambientes del Holoceno y, en consecuencia, las reconstrucciones paleoambientales con base en un sólo registro no reflejen las condiciones climáticas de toda la región. Es así, que son necesarios los estudios locales para comprender la dinámica regional. Particularmente, hemos llevado a cabo estos estudios locales en paleosuelos, debido a su amplia distribución espacial. La fuerte dependencia del suelo con los factores ambientales, hacen que el registro paleopedológico muestre las variaciones locales y permita reconstruir el mosaico de microambientes en la región.

Asimismo, en las investigaciones sobre la reconstrucción paleoambiental se evidencia una importante transformación del medio por el impacto cultural en la región desde el Holoceno medio, misma que ha sido estudiada con diferentes proxies para identificar las modificaciones culturales en el paisaje, particularmente aquellas derivadas de las prácticas agrícolas (Dahlin, Chambers y Foss, 1980; Dunning et al., 2002; Beach et al., 2003; Fernández et al., 2005; Dunning, Beach y Luzzadder-Beach, 2006).

Sin embargo, tales estudios son escasos en el noroeste de las Tierras Bajas Mayas, siendo el estudio paleopedológico en las secuencias aluviales del río Usumacinta una de las primeras reconstrucciones paleoambientales en la región (Solís-Castillo et al., 2013; Liendo et al., 2014).

¿Por qué los paleosuelos son útiles en la investigación de la historia ambiental de una región? Para contestar esta pregunta debemos tomar en cuenta que el desarrollo de los suelos se da en condiciones de estabilidad ambiental, lo que quiere decir, en periodos cuando los procesos de sedimentación y erosión son mínimos, de tal forma que los factores pedogenéticos (clima, material parental, relieve, organismos) pueden actuar simultáneamente en el tiempo. Este desarrollo se interrumpe cuando el ambiente sufre cambios por efectos naturales o inducidos. Los sistemas aluviales destacan por su clara respuesta a los cambios climáticos. El incremento en la precipitación, por ejemplo, repercute en un efecto instantáneo en la descarga de la corriente. Por otro lado, existe una compleja relación entre los ríos y el desarrollo cultural, ya que el hombre usa el agua, el suelo y el entorno, aprovechando los recursos, pero al mismo tiempo modificando el sistema. Es por ello que el estudio de la estratigrafía aluvial (que incluye la pedoestratigrafía) representa una herramienta valiosa para entender el cambio ambiental y el impacto antrópico. Sin embargo, es importante considerar que la dinámica de los procesos involucrados en la formación de la planicie aluvial, y que se expresan en el relieve, hacen de los sistemas fluviales un registro particularmente complejo, que debe ser decodificado, separando los indicadores de cambios naturales de aquellos producto de la acción humana.

En este trabajo se presenta un conjunto de resultados que van de la delimitación de las unidades geomorfológico-ambientales, la caracterización de las unidades pedoestratigráficas, la procedencia de los sedimentos y la relación del ambiente y el desarrollo cultural.

a. Hipótesis

Los sistemas fluviales como el río Usumacinta, asociado a un amplio desarrollo cultural en las Tierras Bajas Noroccidentales, permiten plantear la siguiente hipótesis para el trabajo de tesis:

"*la dinámica espacio-temporal del sistema fluvial Usumacinta incluye las fases de inestabilidad en las que se el río deposita sus sedimentos y las fases de estabilidad durante las cuales se desarrollan suelos, constituyendo así un registro cuasi-continuo que refleja el cambio en las condiciones ambientales y el impacto cultural en el paisaje. Tanto los procesos ambientales como antrópicos modifican la arquitectura aluvial y, por ende, la reconstrucción de la historia fluvial permitirá reconocer los mecanismos tanto culturales como naturales que tienen un impacto en la dinámica aluvial*"

A partir de la anterior hipótesis se desprenden los siguientes objetivos:

b. Objetivo:

La presente tesis tiene como objetivo reconocer los mecanismos tanto naturales como culturales que modifican la dinámica fluvial del Río Usumacinta durante el Holoceno a partir del estudio, análisis e interpretación de las secuencias pedosedimentarias en las Tierras Bajas Mayas.

c. **Objetivos Específicos**:

1. Identificar las unidades geomórfico-ambientales presentes en el sistema aluvial Usumacinta.
2. Diferenciar los periodos de estabilidad e inestabilidad del sistema fluvial durante el Holoceno, con base en el estudio de paleosuelos y sedimentos.
3. Reconstruir las condiciones ambientales durante el Holoceno en las Tierras Bajas Mayas.
4. Proponer la relación entre los cambios ambientales y los asentamientos humanos en las Tierras Bajas Mayas durante el Holoceno medio-tardío.

Estructura de la tesis

La tesis se compone de tres productos académicos que incluyen el conjunto de resultados con el fin de dar respuesta a la hipótesis y desarrollar los objetivos planteados. Además de los productos mencionados, la tesis contiene un capítulo metodológico, uno de discusión conjunta e integrativa de los resultados, y las consideraciones finales.

Los productos que se incluyen en la tesis son los siguientes:

- Solís-Castillo, B., Ortiz-Pérez, M.A., Solleiro-Rebolledo, E. Unidades geomorfológico-ambientales de las Tierras Bajas Mayas de Tabasco-Chiapas en el Río Usumacinta: un registro de los procesos aluviales y pedológicos durante el Cuaternario. Boletín de la Sociedad Geológica Mexicana 66 (2): 279-290.

- Solís-Castillo, B., Solleiro-Rebolledo, E., Sedov, S., Liendo, R., Ortiz-Pérez, M.A., López-Rivera, S., 2013. Paleoenvironment and human occupation in the Maya lowlands of the Usumacinta River, Southern Mexico. Geoarchaeology 28: 268-288.
- Solís-Castillo, B., Thiel, C., Cabadas-Baez, H., Solleiro-Rebolledo, E., Sedov, S., Terhorst, B., Damm, B., Frechen, M., Tsukamoto, S., 2013. Holocene sequences in the Mayan Lowlands – A provenance study using heavy mineral distributions. E&G Quaternary Science Journal 62: 4-17.

2. METODOLOGÍA

La metodología consta de tres apartados que corresponden con los objetivos específicos, que de forma detallada se presenta en los artículos producto de la actual investigación.

2.1 La reconstrucción de la arquitectura aluvial

La metodología de reconstrucción de la arquitectura fluvial inició con la delimitación de las unidades geomofológico-ambientales, en la que se consideraron cuatro criterios principales: la génesis de las geoformas, el emplazamiento del relieve, los aspectos vinculados que ocurren regularmente y la cronología de las estructuras y formas. Las unidades se mapearon sistemáticamente con apoyo de la interpretación de fotografías áreas escala 1:75,000. Asimismo, fue obtenido el modelo digital de elevación a partir de los mapas escala 1:50,000 de INEGI (1986), cuya máxima resolución vertical es de 10 m. Con el fin de afinar la definición de las unidades proporcionadas por las imágenes, se realizó una verificación de puntos de control en campo que permiten contrastar el arreglo geomorfológico de cada una de las unidades. El recorrido se llevó a cabo desde la aparición del río Usumacinta en superficie, en la localidad de Boca del Cerro, siguiendo sus afluentes San Pedro y Chacamax y centrándose en las unidades reconocidas en las fotografías áreas.

Una vez establecida la distribución de las unidades en el espacio, fue necesario determinar su temporalidad. Para esta tarea, se requirieron de fechamiento absolutos y relativos. La cronología absoluta se estableció por fechamientos de radiocarbono en la materia orgánica en los paleosuelos encontrados en las unidades geomorfológico-ambientales, así como por fechamientos de luminiscencia óptica estimulada (OSL) en los sedimentos aluviales. Dado que no en todas las unidades se encuentran materiales asequibles para el fechamiento, su temporalidad se estableció por criterios relativos, tales como disección del relieve, elevación, grado de desarrollo de suelos, morfología y correlación de las unidades pedoestratigráficas.

Asimismo, se estudiaron los minerales pesados para detectar el grado de intemperismo de los paleosuelos y la procedencia de los sedimentos aluviales, y, un proxy para determinar la estabilidad relativa del sistema fluvial tanto durante el Pleistoceno como en el Holoceno.

2.2 El estudio de la memoria del suelo

En el estudio detallado de los paleosuelos en las secuencias pedosedimentarias del Holoceno en el río Usumacinta se consideró el análisis e interpretación de las unidades geomorfológico ambientales para establecer las áreas de muestreo; así siete secciones fueron descritas y muestreadas en las diferentes unidades geomorfológicas definidas en el sistema fluvial Usumacinta.

La descripción de los suelos se hizo de acuerdo a la Base Referencial Mundial del Recurso Suelo (IUSS Working Group, 2006) y Retallack (1990). La descripción morfológica de cada sección fue realizada con base en la identificación de paleosuelos y sus horizontes diagnósticos. En la toma de muestras se consideraron tres criterios principales: muestras para análisis de rutina y análisis selectos; b) muestras para fechamiento y c) muestras para el análisis micromorfológico.

Los análisis físicos y químicos se limitaron a aquellas características que proporcionan información paleoambiental:

a. **Cuantificación de las fracciones arena, limo y arcilla.** La cuantificación fue evaluada para determinar las discontinuidades texturales ocasionadas por diferentes ciclos de pedogenésis o de sedimentación-erosión. La distribución del tamaño de grano se realizó separando la fracción arena por tamizado, y, las fracciones limo y arcilla por sedimentación y muestreo de la pipeta.

b. **La determinación del pH.** El pH fue medido usando una relación 1:2 en H_2O como se señala en Soil Survey Laboratory Methods Manual (2004).

c. **El contenido de carbonatos** se cuantifico por pérdida de peso posterior a la disolución con HCl. Las muestras se secaron a 105°C por 72 horas, se pesaron y se acidificaron con 25 mL de HCl O.5M para destruir los carbonatos. Posteriormente, se lavaron con agua destilada y secaron nuevamente a 105°C por 48 horas y se pesaron nuevamente. La diferencia en peso, se cuantificó como el contenido de carbonatos.

d. **El carbono orgánico total** se realizó en el Laboratorio de Edafología Ambiental del Instituto de Geología, UNAM en un Analizador Elemental CHNS/O Perkin Elmer 2400, Series II.

e. **La composición isotópica del carbono** se determino en el Laboratorio de Espectrometría de Masas de Isótopos Estables del Instituto de Geología, UNAM.

f. **La susceptibilidad magnética** se obtuvo de muestras colectadas a intervalos de 10 cm, posteriormente en el laboratorio se homogenizó el material y se colocó en cajas de 8 cm^3 para medirlas en alta y baja frecuencia con un Bartington MS2B de sensor dual. Los valores obtenidos fueron graficados en SI.

g. **Los fechamientos** en la materia orgánica de los horizontes seleccionados, carbonatos y carbón, presentes en diferentes secciones se realizó en los laboratorios de Beta Analytic (Miami, Florida USA).

h. **Los fechamientos por OSL** fueron obtenidos en los sedimentos aluviales, los análisis fueron realizados en Nordic Laboratory for Luminescence Dating en Dinamarca.

2.4 Paleoambiente y ocupación humana en las Tierras Bajas Mayas

El estudio de la relación entre el sistema fluvial, el cambio en las condiciones ambientales y el amplio desarrollo cultural de la región del Usumacinta medio se basó en el registro paleopedológico como un indicador del paleoambiente, estabilidad del paisaje, actividad humana y uso del suelo. La pedoestatigrafía del Holoceno se estudió de forma detallada, específicamente en cuatro secciones en el área aluvial, dos de ellas en el sitio arqueológico de Tierra Blanca. En la Sierra Norte de Chipas, en el sitio Chinikihá se estudiaron tres perfiles.

La posición de los sitios en diferentes posiciones geomorfológicas: Tierra Blanca en la planicie aluvial donde el sistema es dinámico y Chinikihá dentro de los valles de la Sierra de Chiapas, nos permitieron comparar el uso diferencial del paisaje en las etapas de ocupación humana en las Tierras Bajas Mayas. Además de las propiedades ya mencionadas, se utilizaron algunas otras como índices de comparación entre ambos sitios: color, determinado usando la Carta de Color del Suelo Munsell (1975); contenido de arcillas en el suelo, separadas por gravedad posterior a la destrucción de la materia orgánica con H_2O_2 al 15%. La composición isotópica del carbono ($\delta^{13}C$) se estableció sólo en los horizontes A.

Boletín de la Sociedad Geológica Mexicana
Volumen 66, núm. 2, 2014, p. 279-290

3. Resultados

3.1 Unidades geomorfológico-ambientales de las Tierras Bajas Mayas de Tabasco-Chiapas en el río Usumacinta: Un registro de los procesos aluviales y pedológicos durante el Cuaternario

Berenice Solís-Castillo[1,*], Mario Arturo Ortiz-Pérez[2], Elizabeth Solleiro-Rebolledo[3]

[1] Posgrado en Ciencias de la Tierra, Instituto de Geología, Universidad Nacional Autónoma de México, Circuito de la Investigación Científica s/n, 04510, México, D.F.
[2] Instituto de Geografía, Universidad Nacional Autónoma de México, Circuito de la Investigación Científica s/n, 04510, México, D.F.
[3] Instituto de Geología, Universidad Nacional Autónoma de México, Circuito de la Investigación Científica s/n, 04510, México, D.F.

[*] bsolis.geologia@gmail.com

Resumen

En este trabajo se presenta la reconstrucción de los procesos fluviales que han modificado el paisaje aluvial de las Tierras Bajas Mayas con base en la identificación de las unidades geomorfológico-ambientales y su relación temporal desde el Plioceno hasta el Holoceno Tardío. La identificación de las unidades se ha hecho de acuerdo con los siguientes criterios: a) génesis de las geoformas, b) configuración y arreglo de las geoformas, c) procesos de modelado del relieve y d) temporalidad (edades de las estructuras y formas), usando un análisis pedoestratigráfico. Se proponen ocho unidades enumeradas del 1 al 8, de las cuales cuatro (1, 2, 3, 5) se presentan en la porción sur, en la Sierra de Chiapas. Estas unidades son las más antiguas de la zona de estudio y son controladas por: erosión, siguiendo las estructuras tectónicas originales (unidad 1), por procesos de disolución en las rocas calcáreas (karsticidad – unidad 2), por erosión de las rocas sedimentarias clásticas (unidad 3) y por acumulación coluvial en los piedemontes (unidad 5). Los suelos que caracterizan estas unidades son poco desarrollados en las partes elevadas (Leptosoles réndzicos), pero llegan a ser suelos con alto grado de desarrollo en las posiciones bajas (Luvisoles). Por su parte, las unidades dentro de la planicie aluvial (4, 6, 7, 8) son más jóvenes (Pleistoceno-Holoceno Tardío) y exhiben un sistema de terrazas. Los suelos ubicados en las terrazas pleistocénicas (TP3, TP2, TP1, de la más antigua a la más joven), presentes en la unidad 4, muestran una intemperismo intenso. Particularmente en TP1, se encuentran suelos con propiedades gléycas. Los fechamientos obtenidos en la base de la terraza por luminiscencia óptica (OSL) han proporcionado una edad de 122000 años, la cual permite ubicar su desarrollo temporal. La unidad 6 corresponde a depresiones y áreas de inundación en la planicie aluvial. La unidad 8 está restringida al río Chacamax, cuya fuente de sedimentos es autóctona. Por otro lado, la unidad 7 presenta una serie de terrazas desarrolladas en el Holoceno (TH2, TH1). Un fechamiento de 9000 años obtenido en un sedimento ubicado en la TH2 evidencia cambios ambientales en el sistema Usumacinta. Los suelos de la TH1 muestran una pedogénesis caracterizada por propiedades vérticas y procesos de acumulación de materia orgánica y carbonatos, rasgos que documentan condiciones más secas. Su desarrollo ocurre en el Holoceno Medio, periodo en el que se presentan cambios climáticos regionales. Los suelos del Holoceno Tardío, también presentes en TH1, poseen un menor desarrollo. Estos suelos muestran fuerte impacto por actividades humanas que iniciaron en el área desde el Formativo Temprano.

Palabras clave: Unidades geomorfológico-ambientales, procesos fluviales, Usumacinta, pedoestratigrafía, terrazas.

Abstract

This work presents the reconstruction of the fluvial processes that have modified the alluvial landscape in the Maya Lowlands, based on the identification of geomorphologic-environmental units, and their temporal relation from the Pliocene to the late Holocene. The *unit identification has been made according to the following criteria: a) genesis of the geoforms; b) configuration and arrangement of the geoforms, c) processes of the terrain modelling, and d) the temporality (ages of the structures and forms), using a pedostratigraphic analysis. Eight units are proposed, labeled from 1 to 8, four of them (1, 2, 3, 5) are present in the south area, in the Sierra of Chiapas. These units are the oldest in the study area and are controlled by: erosion, following the original tectonic structures (unit 1); dissolution of calcareous rocks (karstic – unit 2); erosion of the sedimentary clastic rocks (unit 3); and colluvial accumulation in the foothills (unit 5). The soils characterizing these units are variable, from poorly developed at higher elevations (rendzic Leptosols), to highly developed in the valley bottoms (Luvisols). On the other hand, the units in the alluvial plain (4, 6, 7, 8) are younger (Pleistocene-late Holocene) and have developed a terrace system. The soils of the Pleistocenic terraces (TP3, TP2, TP1, from the oldest to the youngest), from unit 4, show strong weathering. Soils with gleyic properties are found especially in TP1. Optical luminescence (OSL) dating of material from the base of the terrace reveals an age of 122000 years, which constrains its temporal development. Unit 6 corresponds to the depressions and wetlands in the alluvial plain. Unit 8 is restricted to the Chacamax River, which has an autochthonous sediment source. Unit 7 presents a series of terraces developed during the Holocene (TH2, TH1). An age date of 9000 years in sediment from terrace TH2 gives evidence of environmental changes in the Usumacinta system. The pedogenesis of soils in terrace TH1 is characterized by vertic features and processes of accumulation of organic matter and carbonates, which are related to drier conditions. The development of these soils occurs during the middle Holocene, a period when regional climatic changes are documented. The soils of the late Holocene, also present in TH1, are less developed, and evidence of impact by human activities in the area is high since the Early Formative.*

Keywords: Geomorphologic-environmental units, fluvial processes, Usumacinta, pedostratigraphy, terraces.

1. Introducción

Los ríos son sistemas dinámicos, complejos y no-lineales, cuyos cambios en la forma y dimensión de sus canales y/o afluentes son direccionados por fuerzas internas y externas (Wohl, 2013), entre las que destacan el clima y las actividades humanas. La respuesta de estos sistemas fluviales a los cambios climáticos ha sido ampliamente estudiada en diferentes partes del mundo (Vandenberghe, 1995; Blum y Törnqvist, 2000; Gregory *et al*., 2006; Bridgland y Westaway, 2008). En particular, las sucesiones de terrazas aluviales representan contextos ricos en información sedimentológica, paleoambiental y geoarqueológica (Goldberg y Macphail, 2006) tanto para entender la dinámica ambiental del Cuaternario (Knox, 1996; Bettis *et al*., 2008; Borejsza y Frederick, 2010), como para determinar su influencia en el desarrollo cultural en diversas regiones del mundo (Brown, 2001).

Si bien en México el registro aluvial como fuente de información paleoambiental y cultural no ha sido ampliamente abordado, destacan los trabajos en el centro del país, como en Texcoco (Córdova y Parsons, 1997), Tlaxcala (Heine, 2003; Borejsza y Frederick, 2010), Teotihuacan (McClung *et al*., 2005; Solleiro-Rebolledo *et al*., 2011) y el Lerma (Ludlow-Wiechers *et al*., 2005). Sin embargo, en la región sur las investigaciones son escasas a pesar de que el sistema aluvial Grijalva-Usumacinta ha sido escenario de un amplio desarrollo cultural desde el Holoceno Medio, en donde se tienen las evidencias más antiguas de la domesticación del maíz y el nacimiento de la agricultura en Mesoamérica (Pope *et al*., 2001).

Los primeros estudios sobre los procesos fluviales en la planicie aluvial de Tabasco han sido realizados por West *et al*. (1976), quienes estudian los aspectos físicos más sobresalientes de las planicies aluviales costeras, comparan su desarrollo con las planicies deltaicas del río Mississippi y establecen la génesis de la planicie aluvial del Pleistoceno en las tierras bajas de Tabasco, que se relacionan con las antiguas corrientes del Grijalva y del Usumacinta. Por su parte, Solís *et al*. (2013a, b) han definido los procesos que modifican el paisaje aluvial de la planicie del río Usumacinta, los cuales se evidencian por un sistema de terrazas, desarrollado como respuesta a los cambios en las condiciones ambientales durante el Pleistoceno Tardío y el Holoceno. Dichos cambios han provocado la migración aparente del canal fluvial y la modificación tanto de la tasa de sedimentación como de la procedencia de los sedimentos. Sin embargo, aún queda por determinar, en una forma regional y temporal, la dinámica de los procesos que han jugado un papel importante en el desarrollo del sistema fluvial.

Es por ello que el presente trabajo tiene como objetivo principal delimitar las unidades geomorfológico-ambientales del Sistema Usumacinta, particularmente en la planicie de inundación de la región denominada como Tierras Bajas Mayas y reconstruir los procesos que han modificado el comportamiento del sistema fluvial en los últimos 125000 años. Para dicha reconstrucción, se ha integrado la información de la pedoestratigrafía y cronología elaborada por Solís-Castillo *et al*. (2013a, b), y los registros paleoambientales regionales.

2. Área de estudio

El área de estudio comprende parcialmente la cuenca del río Usumacinta, desde su aparición en superficie, en Boca del Cerro, hasta el municipio de Emiliano Zapata

(Usumacinta Medio), incluyendo los ríos Chacamax y San Pedro (Figura 1). La cuenca del Usumacinta, que se extiende desde el noroeste de Guatemala hasta los estados de Chiapas y Tabasco, en México, cubre una superficie de 122000 km^2 (INEGI, 1986). Los rasgos geomorfológicos que destacan en ella son la Llanura Costera del Golfo, en el norte, y el Cinturón de pliegues y fallas de Chiapas (Sierra de Chiapas), en el sur.

La porción norte de la Sierra de Chiapas está constituida por rocas carbonatadas que varían en edad desde el Jurásico Tardío hasta el Paleógeno. Por su parte, las tierras altas de la región de Chiapas, en el sur, se componen de rocas metamórficas paleozoicas, rocas ígneas extrusivas (andesitas y dacitas), productos piroclásticos y rocas sedimentarias (lutitas, areniscas y limolitas) cuyo rango de edades varían desde el Cretácico hasta el Cuaternario (Hernández-Santana *et al*., 2012). Todas estas rocas han sufrido deformación durante el Mioceno Tardío dando lugar a un conjunto de pliegues orientados NW-SE (Burkart, 1983). Posterior a este periodo de deformación, durante el Plioceno y el Pleistoceno, se inicia el aporte de sedimentos provenientes del Macizo de Chiapas (Padilla y Sánchez, 2007) que cubren la Llanura Costera. La actividad neotectónica ha conformado un sistema de fallas con un desplazamiento variable. Este comportamiento repercute en la morfología de los valles, los cuales se muestran rectos y alineados. También existen valles que cortan los ejes orográficos montañosos, los escarpes de fallas y los lomos de presión (Ortiz *et al*., 2005). Asimismo, los procesos de karstificación controlan la configuración del río que corre siguiendo fallas y fracturas, formando abundantes ríos subterráneos y afluentes efímeros superficiales.

El clima de la región es cálido y húmedo con una precipitación media anual de 1800 mm en la planicie aluvial y 2000 mm cerca de la cordillera. Alrededor del 67 % de la precipitación ocurre en el verano. La temperatura media anual es de 27 °C; durante los meses más cálidos la temperatura alcanza los 30 °C (García, 1988). La vegetación predominante es un bosque húmedo tropical de hoja perenne. En la planicie aluvial, en donde se localizan zonas inundables por largos periodos, se tienen principalmente, pastos y especies acuáticas como *Bactris* y *Ponderia* (Bueno *et al*., 2005; Rzedowski, 2006).

3. Metodología

Inicialmente se delimitaron las unidades geomorfológico-

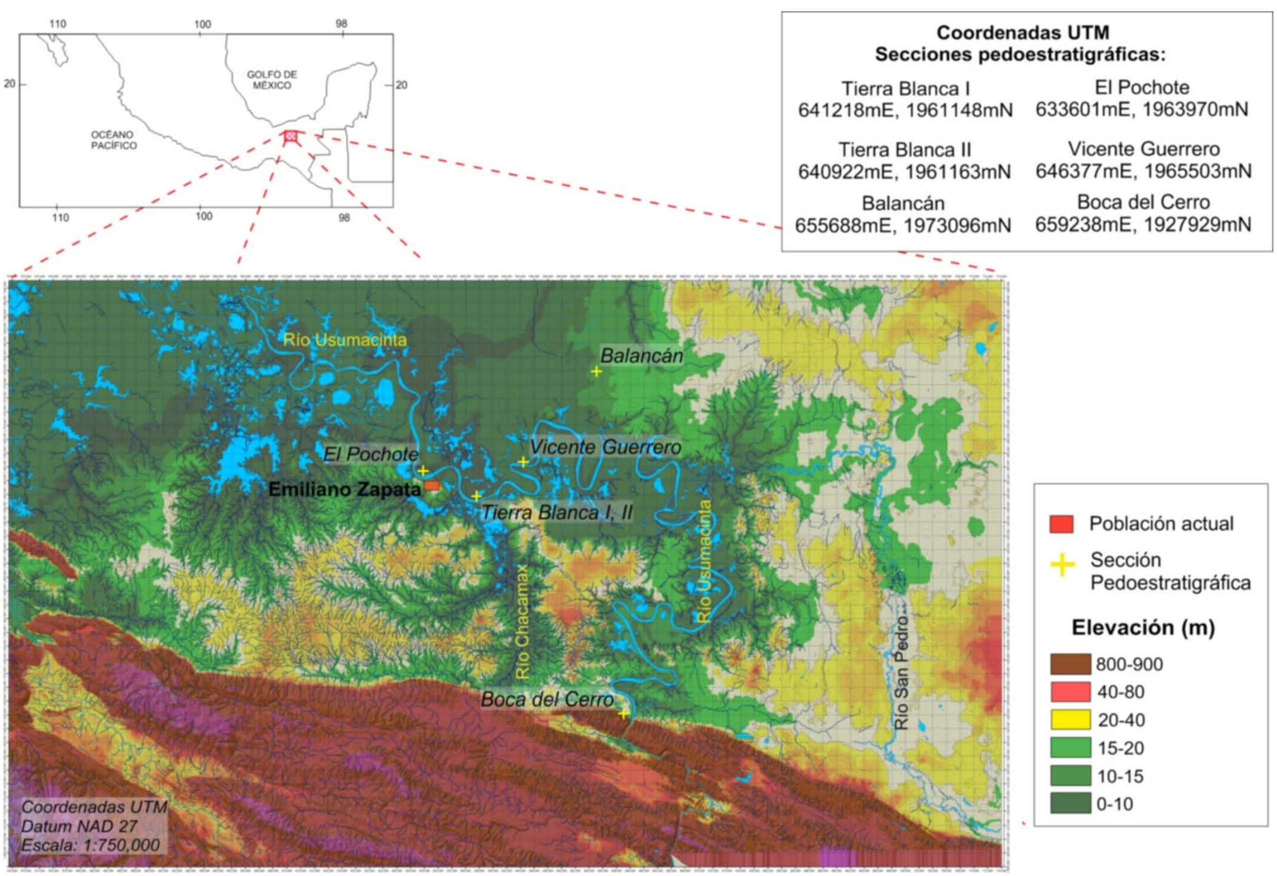


Figura 1. Localización del área de estudio y de las secuencias pedoestratigráficas, en un mapa altimétrico, que muestra la configuración del relieve. En la parte superior izquierda se incluyen las coordenadas UTM de cada sección.

ambientales de acuerdo a las propuestas de Tricart y Cailleux (1972) y la metodología de Kondolf y Piégay (2003). De esta manera, se aplicaron cuatro criterios principales a) génesis de las geoformas, b) configuración y arreglo de las geoformas, c) procesos de modelado del relieve y d) temporalidad (edades de las estructuras y formas).

La cartografía de las unidades se realizó con base en la interpretación de las fotografías aéreas a una escala de 1:75000. El modelo digital de elevación fue derivado de los mapas topográficos a escala 1:50000 (INEGI, 1986), la máxima resolución espacial fue de 10 m. Asimismo, se complementó el análisis con trabajo de campo a lo largo del sistema Usumacinta durante 2011, 2012 y principios del 2013, consistente en un recorrido desde la localidad de Boca del Cerro, siguiendo los afluentes Chacamax y San Pedro y, con 36 sitios de verificación de las diferentes unidades geomorfológico-ambientales, reconocidas en las fotografías aéreas. Es así que fue posible contrastar el arreglo geomorfológico con la información cartografiada.

El control temporal de las formas superficiales se basó en el estudio pedoestratigráfico de Solís-Castillo *et al*. (2013a, b) y un fechamiento por análisis de radiocarbono, realizado por Beta Analytic, Miami, en carbonatos en el paleosuelo de Boca del Cerro (Tabla 1).

4. Resultados

4.1. Análisis geomorfológico

De acuerdo con el análisis geomorfológico, se establecieron ocho unidades geomorfológico-ambientales en las Tierras Bajas Mayas Noroccidentales, enumeradas del 1 al 8 (Figura 2):

Unidad 1. Ambiente de denudación en cimas de pliegues de las calizas del Mioceno. Esta unidad se encuentra en la Sierra Norte de Chiapas y se caracteriza por un fuerte control estructural-tectónico (Ortiz *et al*., 2005), que aunado a los procesos de disección fluvial y remoción de masa, modelan las laderas de los pliegues y los taludes escarpados que se encuentran principalmente en las zonas de mayor elevación de la Sierra (Figura 2). Los suelos que caracterizan esta zona son Leptosoles y Regosoles bajo una selva perennifolia y subperennifolia; con una precipitación media anual de 3000 a 4000 mm (INEGI, 1986).

Unidad 2. Ambiente de disolución kárstica. En este ambiente de disolución, el relieve que se produce es por la circulación fluvial superficial de corrientes efímeras, las cuales disuelven las superficies de escaso declive. Esta unidad se subdivide, de acuerdo a su morfología, en:

Relieve kárstico denudatorio-erosivo de circulación fluvial superficial, en el cual coexiste el proceso erosivo y el de disolución, con formas de escurrimiento corrosivo-erosivo, promoviendo el desarrollo de dolinas y uvalas.

Relieve kárstico denudativo de acumulación residual asociado a las corrientes subterráneas con procesos de infiltración y desplome de galerías subterráneas. En superficie se identifica por la sedimentación en cavidades exokársticas y elevaciones residuales (pequeños promontorios y peñas).

Relieve kárstico acumulativo residual, que se refiere a ciclos de disolución-erosión generando relieves negativos de

Tabla 1. Fechamientos OSL en los sedimentos y de radiocarbono en los suelos registrados en las secuencias.

PERFIL	CLAVE	FECHAS OSL	MATERIAL	EDAD RADIOCARBONO CAL. AP (2δ)
TB-3A[1]	BETA-300446		Materia orgánica	2780-2740
TBII-3A[1]	BETA-300447	-	Carbón	1140-970
TBII-3C[2]	2462	2.1 ± 0.5		
TBII-5Ass[1]	BETA-300448	-	Materia orgánica	2340-2300
TBII-5Bss[1]	BETA-300449	-	$CaCO_3$	720-660
TBIII_07[2]	2463	9.0 ± 2		
TBI-9Bkg[1]	BETA-277572	-	$CaCO_3$	5450-5380
TBI-9BCgk[1]	2464	123 ± 6		
POCH-7Ass[1]	BETA-300444		Materia orgánica	1300-1260
POCH-8Ass[1]	BETA-300445		Materia orgánica	2130-1980
VG-3A[1]	BETA-300450		Materia orgánica	1710-1560
BC-2Btk	BETA-300440		$CaCO_3$	13470-13300

TB- Tierra Blanca; POCH- Pochote; BC-Boca del Cerro
1 Solís-Castillo *et al*., 2013a
2 Solís-Castillo *et al*., 2013b

fondo plano con depósitos eluviales y deluviales. Este relieve representa la etapa más avanzada de la karstificación. En los valles se distinguen Luvisoles (Figura 3a) muy desarrollados que contrastan con suelos incipientes, Leptosoles (Figura 3b), bajo remanentes de la selva baja subperennifolia y vegetación secundaria (pastizales) (INEGI, 1986).

Unidad 3. Ambientes de denudación sobre rocas sedimentarias clásticas. Esta unidad se refiere al relieve bajo, relicto de la erosión; los procesos identificados son de baja energía física debido al control litológico (diferente resistencia de materiales) y al limitado escurrimiento concentrado. Los procesos de acumulación de carácter deluvial y eluvial han retrabajado los materiales que provienen de los márgenes de los flancos anticlinales.

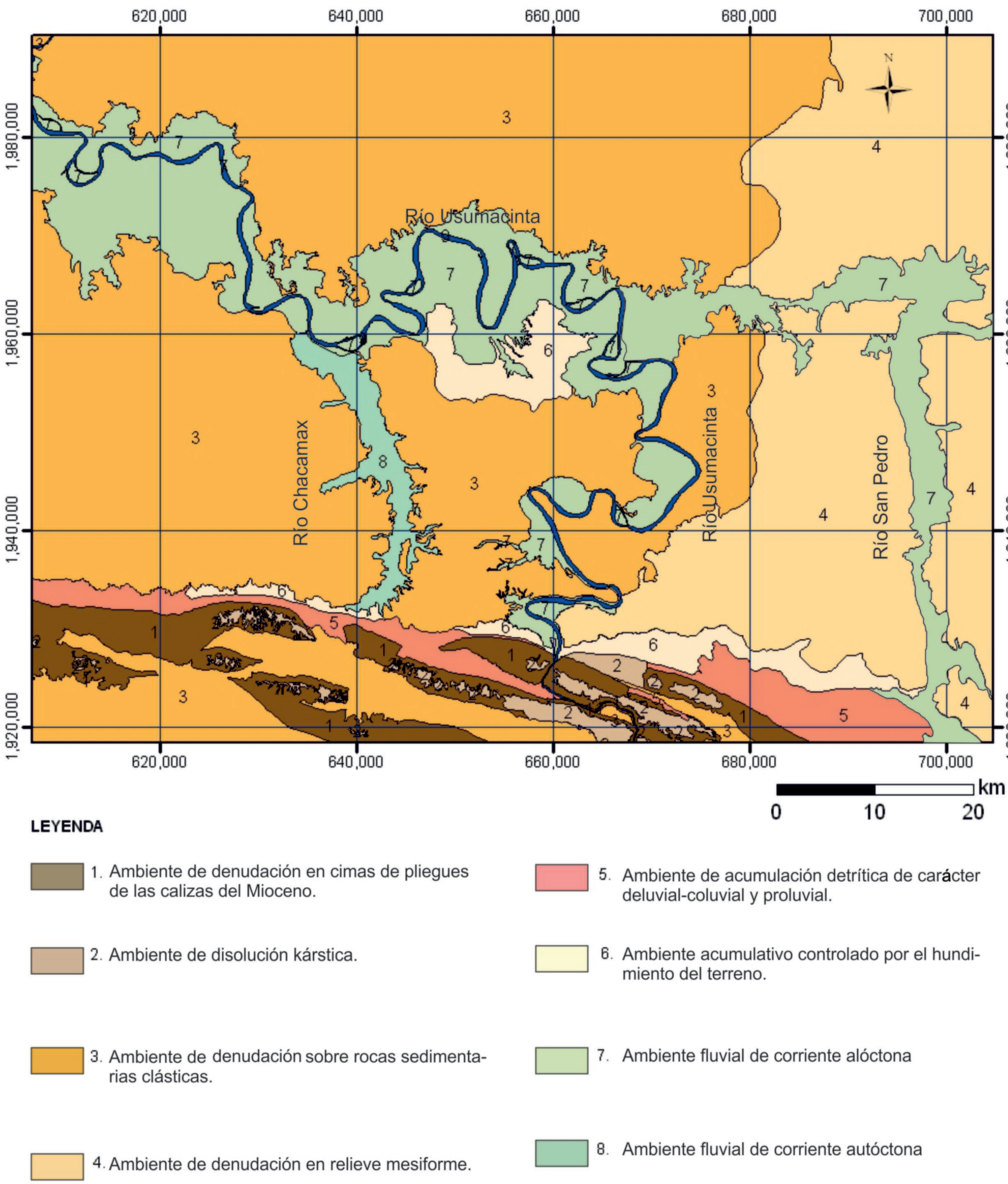


Figura 2. Mapa de distribución de las unidades geomorfológico-ambientales del área de estudio.

Esta unidad define los valles fluviales en la sierra de los ríos Chacamax y Tulijá (Figura 2). En el río Chacamax, se destaca la formación de tres niveles de terrazas pleistocénicas (TP): superior (TP3), medio (TP2), con desarrollo de Cambisoles y Vertisoles (Palma *et al*., 1985), bajo una selva baja perennifolia (INEGI, 1986), e inferior (TP1) en donde se tienen suelos con fuertes propiedades gléycas asociados a inundaciones continuas (Figura 3c).

Unidad 4. Ambiente de denudación en relieve mesiforme. Particularmente, este relieve mesiforme es controlado por elevaciones aisladas formadas por levantamientos del Plioceno-Pleistoceno y por cuerpos intrusivos que se reconocen por la morfología de los escurrimientos. En este ambiente residual actúan procesos de denudación de baja energía. Se distingue por un relieve bajo, colinado, relicto de la erosión de superficies y, al igual que en la unidad 3, se conforma por tres niveles de terraza formados en el Pleistoceno (TP): Superior (TP3), Medio (TP2) e Inferior (TP1); asimismo, se reconocen elementos lineales y locales como lechos fluviales abandonados y brazos remanentes. Estas terrazas del Pleistoceno son las formas más elevadas del paisaje aluvial con una altitud de 100, 88 y 65 m, respectivamente, y determinan el cauce del río Usumacinta, en las que se encuentran los suelos más desarrollados de la planicie (Figura 3d).

Unidad 5. Ambiente de acumulación detrítica de carácter deluvial-coluvial y proluvial. Se considera que esta unidad se inicia en las laderas por la acción conjunta de movimientos gravitacionales y de lavado que se difunden al pie de las laderas, con depósitos heterogéneos, que son modelados por procesos mixtos erosivos-acumulativos y que generan una sedimentación en facies proximales y distales (Figura 2). En los suelos de esta unidad son claros los procesos de coluvionamiento (Figura 3e).

Unidad 6. Ambiente acumulativo controlado por el hundimiento del terreno. Este ambiente está formado sobre cuestas de declive tendido de piedemonte, planicies fluviales inactivas, remanentes, lacustres y palustres. La escorrentía difusa-laminar lleva una escasa sedimentación detrítica de textura fina y arenosa, y su carga es principalmente, de materiales solubles y biogénicos particulados, acarreados por el agua con drenaje deficiente. Su ubicación se restringe a los límites entre la Sierra de Chiapas y el inicio de la planicie aluvial (Figura 2). En esta unidad se desarrollan Leptosoles asociados a vegetación secundaria (pastizales inducidos) y selva baja perennifolia.

Unidad 7. Ambiente fluvial de corriente alóctona. Esta unidad define a los ríos Usumacinta y San Pedro (Figura 1) los cuales incluyen en su cuenca, corrientes y afluentes de orígenes diversos. Es por eso que se ha denominado de corriente alóctona, cuyos sedimentos provienen de otras regiones. Los procesos de erosión y acumulación en este ambiente son controlados por los desbordes de la planicie aluvial del Holoceno. En el Usumacinta se localizan tres niveles de terrazas formadas por la migración lateral del cauce, como consecuencia de los cambios en las condiciones

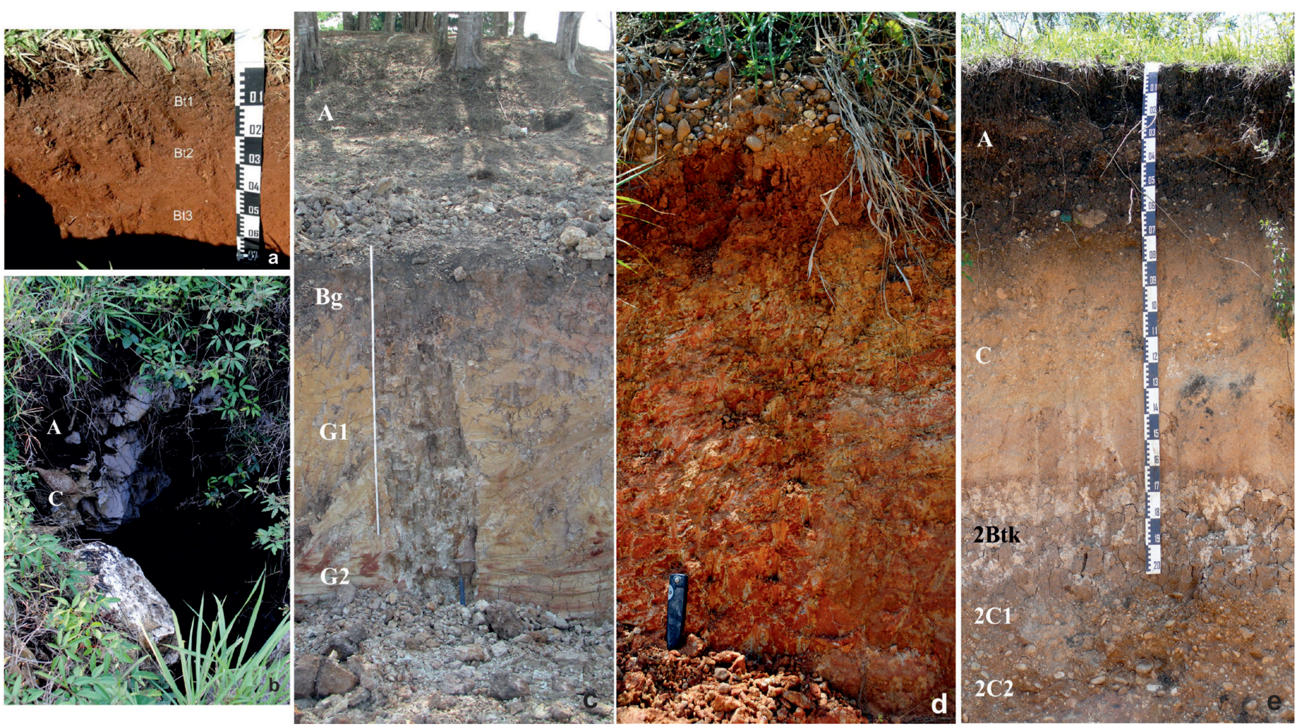


Figura 3. Tipos de suelos que representan a las unidades geomorfológico-ambientales: a) Luvisoles y b) Leptosoles característicos del relieve kárstico acumulativo residual de la unidad 2; c) Gleysoles de la sección Balancán en la Terraza Pleistocénica 1 (TP1) de la unidad 3; d) suelos de la Terraza Pleistocénica 3 (TP3) de la unidad 4; y, e) suelos de la sección Boca del Cerro, en la unidad 5.

ambientales durante el Holoceno. Los tres niveles de terraza se denominan desde las más antigua hasta la más joven, TH2, con una elevación de 15 a 10 m, TH1, entre 10 y 5 m, y TH0 a < 5 m (Figura 4). En estas terrazas es donde se han centrado los análisis pedoestratigráficos (Figura 5). También en el río San Pedro se presentan tres terrazas holocénicas, pero sus características son diferentes, ya que son terrazas erosivas y no acumulativas como en el Usumacinta.

TH0 se delimita por los bordos de ribera baja con declive de desbordes. La terraza TH1 es de inundación ordinaria, asociada a pantanos marginales, de cuenca y cuerpos de agua. La terraza media TH2 (Figura 4) es el nivel de terraza más alta con procesos de lenta disección y denudación planar, cuyos depósitos laterales se localizan en los deltas internos lacustres (TH0 y TH1), barras recientes (TH0) y en las barras de meandro abandonadas (TH2).

Unidad 8. Ambiente fluvial autóctono. Esta unidad se refiere al río Chacamax, cuya cuenca es autóctona y no posee afluentes externos. Se encuentra parcialmente inundada, desarrollando ambientes de ciénega y humedales extensos que funcionan como corredor biológico con vegetación de galería. Está restringido por las terrazas pleistocénicas. Forma un relieve residual con valles intermontanos entre los bloques cuyos patrones son: meandros erosivo-acumulativos, trechos con corte erosivo lineal y tramos mixtos erosivos y acumulativos.

4.2. Análisis estratigráfico

Con el objeto de definir la temporalidad de las unidades geomorfológico-ambientales, se describieron diversas secciones pedológicas. En el relieve kárstico de la unidad 2, se describieron dos perfiles en la Sierra Norte de Chiapas en Chinikihá. En el alto Usumacinta se analizó la sección Boca del Cerro localizada en la unidad 5. Asimismo, se retomó la información relativa a los perfiles Balancán (Solís-Castillo *et al*., 2013b) que caracteriza la estratigrafía de las terrazas pleistocénicas (TP1) de la unidad 3; Tierra Blanca I, II, que se localizan en TH2 de la unidad 7; y El Pochote y Vicente Guerrero ubicada en TH1 de la unidad 7 (Solís-Castillo *et al*., 2013a).

Chinikihá es un sitio arqueológico con una importante presencia durante el Periodo Clásico, con una alta densidad de población y acumulación de poder político (Liendo *et al*., 2014), localizado en unidad 2. Aquí se describieron dos perfiles de suelos. El primero corresponde a un suelo tipo Luvisol, arcilloso de color pardo rojizo, profundo (> 1.50 m), constituido por una secuencia de horizontes A/Bt1/Bt2/Bt3 (Figura 3a), presente en las depresiones kársticas, en las zonas de mayor disolución; en contraste, a partir de las formas calcáreas que conforman las principales elevaciones del paisaje se desarrollan Leptosoles réndzicos (Liendo *et al*., 2014). Este perfil se caracteriza por ser poco profundo (40 cm), de color pardo muy oscuro-negro, rico en materia orgánica, con sólo dos horizontes A/AC (Figura 3b).

La sección Balancán (Figura 3c) de la TP1, de la unidad 3, está caracterizada por un suelo con una configuración de horizontes A/Bg/G1/G2 con fuertes rasgos gléycos, muy arcilloso, con una matriz de color pardo-grisáceo y moteados rojos, ocres y verdes, así como concreciones de hierro y manganeso en formas dendríticas. Este suelo muestra un fuerte intemperismo, tal como lo evidencia la presencia de minerales mega estables como zircón, turmalina y rutilo con algunos componentes metamórficos estables como granate, epidota, monacita y cianita (Solís-Castillo *et al*., 2013b)

El suelo en Boca del Cerro presenta una configuración de horizontes A/C. El horizonte C es un coluvión con abundantes fragmentos de rocas, producto de la denudación de la Sierra de Chiapas. Tal acumulación de materiales sepulta un suelo bien desarrollado constituido por horizontes 2Btk/2Ck (Figura 3e). El horizonte 2Btk posee una estructura en bloques subangulares, una matriz de color pardo-rojiza, cutanes de iluviación delgados y discontinuos, así como abundantes carbonatos que penetran al horizonte inferior (2Ck). La base de este perfil está constituida por sedimentos coluvio-aluviales que indican aportes de diversas fuentes. Los carbonatos presentes en el horizonte 2Btk tienen una edad de 13300 – 13470 años Cal AP (Tabla 1).

Los perfiles Tierra Blanca I, II corresponden con una secuencia compuesta de suelos que han sido caracterizados morfológicamente por Solís-Castillo *et al*. (2013a), que contienen cerámica del Formativo, Clásico y Posclásico Maya, periodos reconocidos por medio de fechamientos de radiocarbono de materia orgánica. De estos tres suelos estudiados, el mejor desarrollado es el que corresponde con el periodo Formativo (paleosuelo 5 de TBII). Su color pardo oscuro y estructura en bloques angulares (con rasgos vérticos) lo caracterizan como marcador pedoestratigráfico. A diferencia, los suelos que corresponden con los periodos Clásico y Posclásico muestran un desarrollo menor, aunque el registro arqueológico es más rico (Liendo *et al*., 2014). Los suelos del periodo Clásico y Posclásico también se han registrado en los perfiles Vicente Guerrero y El Pochote (Figura 5), particularmente, la base de estas secuencias corresponde con el suelo Formativo con rasgos vérticos a una profundidad de 3 y 6 m, respectivamente, sobre los cuales, se depositaron sedimentos aluviales arenosos y fluvisoles con concreciones de carbonatos (Solís-Castillo *et al*., 2013a).

Un rasgo importante de los materiales encontrados en la secuencia de Tierra Blanca se refiere a la sección TBI. Aquí, debajo del paleosuelo Formativo, se encontró un sedimento de carácter aluvial, de 2 m de espesor, de color blanco, textura limosa, estratificación cruzada y laminaciones, con contornos ondulados. Hay una diferenciación en este sedimento que permiten establecer al menos dos fases de sedimentación: una de flujo lento con acumulación de material arcilloso, laminado, con rasgos reductomórficos y huellas de raíces, en la parte inferior; y una fase de flujo más rápido con sedimentos más limosos, con estratificación cruzada. La composición de este material consiste de una mezcla de minerales metamórficos, plutónicos y volcánicos,

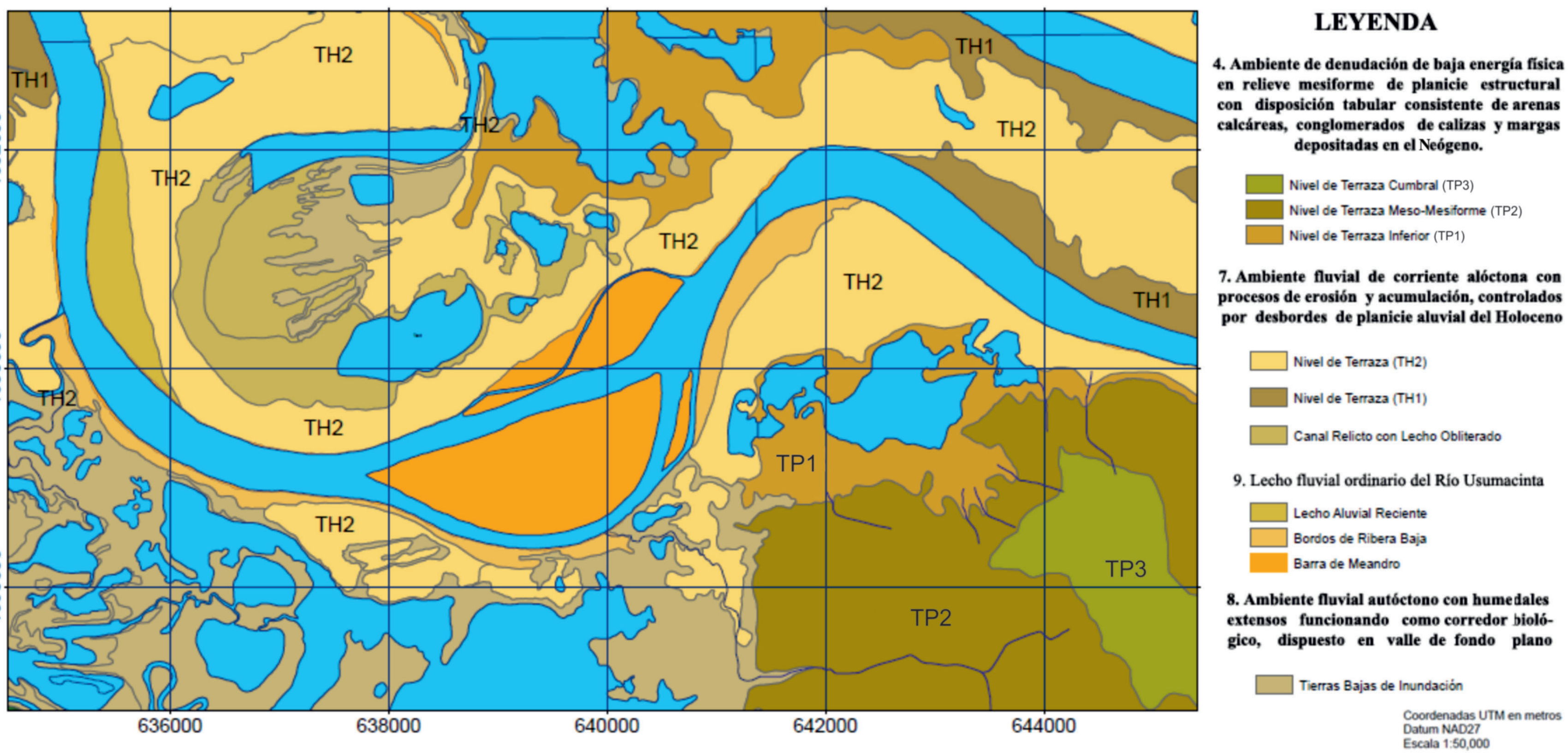


Figura 4. Mapa de las formas aluviales del río Usumacinta que se reconocen en las unidades 4, 7 y 8.

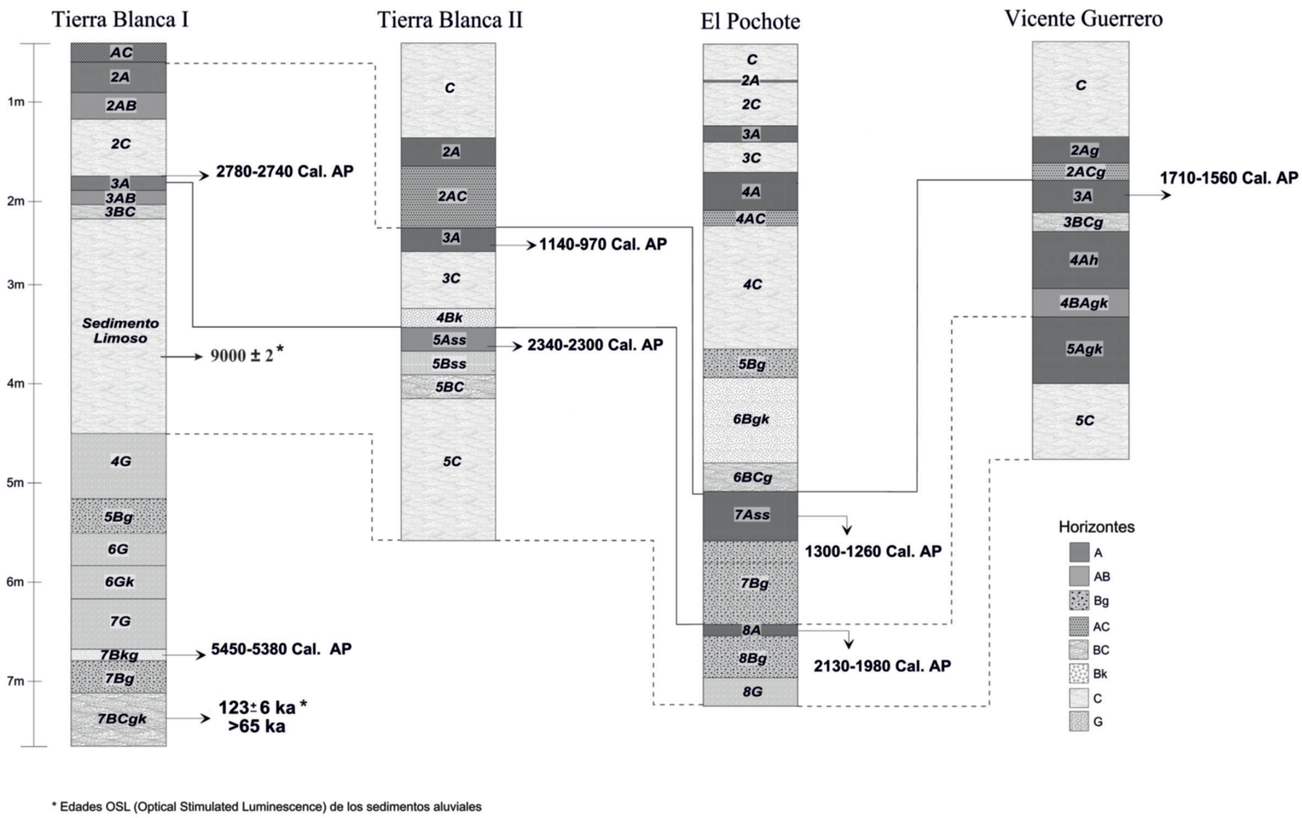


Figura 5. Correlación pedoestratigráfica del área de estudio, basado en los trabajos de Solís-Castillo *et al*., (2013a, 2013b)

principalmente de vidrio volcánico (Solís-Castillo *et al*., 2013b). En este sedimento se realizó un fechamiento con OSL (luminiscencia óptica estimulada), el cual arrojó una edad de aproximadamente 9000 años (Figura 5).

La parte más profunda de la sección TBI presenta una secuencia de suelos con fuertes rasgos gléycos, muy arcillosos, con coloraciones gris-verdosas y presencia de minerales megaestables que denotan un fuerte intemperismo (Solís-Castillo *et al*., 2013b). La edad de esta secuencia es más incierta, ya que se fechó por OSL el sedimento aluvial en su base, resultando en > 65 ky en cuarzo, y 123 ky en feldespatos, lo cual implica que el material parental del paleosuelo se formó durante el Pleistoceno Tardío (Solís-Castillo *et al*., 2013b).

5. Discusión

La diferenciación de los paisajes geomorfológicos-ambientales en la planicie aluvial del río Usumacinta es el resultado de una combinación compleja entre factores estructurales, procesos del modelado del relieve (fases de inestabilidad) y formación de suelos (fases de estabilidad), actuando en el tiempo, presumiblemente desde el Plioceno. Cada sistema ha evolucionado de diferente manera en función de los factores mencionados. A continuación se esboza la influencia de dichos factores en la evolución de las unidades geomorfológicas, desde el Plioceno al Holoceno Tardío.

5.1. Ambientes geomorfológicos ambientales de la Sierra Norte de Chiapas

El ambiente de la Sierra Norte de Chiapas (unidades geomorfológicas-ambientales 1, 2, 3, y 5) se caracteriza por tener un fuerte control tectónico, el cual está determinado por una serie de estructuras plegadas y fallas normales e inversas.

Los procesos particulares de las unidades 1 y 3 se refieren a la erosión de los materiales ubicados en las partes altas de la sierra constituidos por calizas y por rocas sedimentarias clásticas (unidad 3) se produce una fuerte erosión de los materiales y su transporte hacia las partes bajas. En dichas partes bajas del relieve acumulativo, como en Chinikihá, se tienen Luvisoles, los cuales se relacionan con una mayor estabilidad geomórfica pues su desarrollo es mayor. Wiesbeck (2012) menciona que estos Luvisoles poseen un alto contenido de arcilla (entre 70 y 90 %) y un fuerte intemperismo de los minerales primarios. A diferencia, en las partes altas de la sierra, los suelos son más delgados y discontinuos, marcando una mayor dinámica. Es posible que estos suelos delgados y arcillosos se transporten hacia las partes bajas, constituyendo el material parental de los Luvisoles, tal y como se ha documentado en otras regiones kársticas con suelos rojos, como en Yucatán (Cabadas *et al*., 2010).

En los ambientes de disolución kárstica de la unidad 2, la disolución es controlada estructuralmente por fallas longitudinales y paralelas al plano axial de los pliegues. En consecuencia, se desarrolla una secuencia de dolinas, uvalas y poljes de forma alargada y cerrada, arreglados en dirección del lineamiento tectónico. Asimismo, se reconoce una segunda fase de actividad kárstica, debida a la acción conjunta de la corrosión con la fusión de uvalas y dolinas, el desplome de los techos y el hundimiento por la disolución vertical y horizontal.

En las laderas bajas de los pliegues de la sierra (unidad 5), los procesos están controlados por las diferencias litológicas que limitan y concentran los escurrimientos en los flancos anticlinales, los cuales acumulan materiales de carácter deluvial y proluvial. Ejemplo de este tipo de procesos se documenta en la sección de Boca del Cerro, en donde se observa la presencia de material coluvial como material parental de los suelos modernos, de tal manera que el paleosuelo descrito en este lugar también se encuentra sepultado por este tipo de depósitos. Este paleosuelo presenta un horizonte Btk, que muestra un desarrollo moderado. Este tipo de horizontes se forman en lapsos de n x 10^3 años (Targulian y Krasilnikov, 2007) lo que marca un periodo de estabilidad en el paisaje (necesario para la pedogénesis), durante el cual, la sedimentación y erosión fueron mínimas. La edad de los carbonatos en este suelo de 13470 años (Tabla 1) permite establecer el marco cronológico en el que posiblemente concluye la pedogénesis, terminando la fase de estabilidad e iniciando los procesos de coluvionamiento. De esta manera, se puede concluir que la activación de esos procesos ocurre a finales del Pleistoceno. Por su parte, el suelo moderno, cuenta con un desarrollo menor, evidenciado por la presencia de un perfil tipo A/AC (con ausencia de horizonte B), lo que muestra una menor estabilidad durante el Holoceno.

5.2. Ambientes aluviales

5.2.1. Pleistoceno

En las unidades 3 y 4 se identifican tres niveles de superficies de erosión, por denudación planar, que corresponden a las terrazas aluviales del Plio-Pleistoceno determinadas por West *et al*. (1976). Dichas terrazas se formaron durante fases de estabilidad e inestabilidad del río Usumacinta, desde el Plioceno hasta el Pleistoceno y, posteriormente, fueron deformadas por la tectónica regional del Cuaternario (Benavides, 1956). Se han reconocido tres niveles (nivel de cimas) con una altura de 100 m y 88 m de altura y de 65 m, como nivel mínimo. A partir de esta cota se inicia una escasa erosión lineal indicativa de un levantamiento lento activo (Ortiz *et al*., 2005). El segundo nivel es difícil de delimitar debido a la inestabilidad tectónica de la superficie residual que ha sido deformada irregularmente, creando un relieve ondulado de lomas de pendiente tendidas. La ligera deformación se debe, probablemente, a la presencia de domos de carácter diapírico, reconocidos a nivel regional (Martínez-Kemp *et al*., 2006; Cruz *et al*., 2010), que forman una topografía suave, producto del desplazamiento de fallas con componentes verticales inversos y gravitacionales, en el contacto con la sierra (Martínez-Kemp *et al*., 2006; Cruz *et al*., 2010). El nivel inferior corresponde al lecho menor ordinario del río Chacamax.

En estas terrazas aluviales del Plio-Pleistoceno del Usumacinta, se encuentra el suelo de Balancán, el cual muestra un alto grado desarrollo con minerales ultraestables, producidos por el intemperismo intenso de los minerales primarios (Solís-Castillo *et al*., 2013b). Por otro lado, en la unidad 7, sobre TH2, suelos similares a Balancán se encuentran expuestos por la incisión actual del río, registrados en la parte baja de la secuencia de Tierra Blanca. Las edades de los sedimentos en su base, entre 65 y 126 ky obtenidos por luminiscencia óptica (Solís-Castillo *et al*., 2013b), apoyan la idea de la fase de estabilidad prolongada del sistema fluvial durante el Pleistoceno. West *et al.* (1976) y Psuty (1966) consideran que las terrazas aluviales del Pleistoceno se han formado como consecuencia de la sedimentación del río Usumacinta en el último interglacial de 100 – 115 ka, que concuerda con la edad máxima encontrada en la base de la secuencia de Tierra Blanca I (126 ky).

5.2.2. Holoceno

En el Holoceno Temprano se desarrolla el ambiente fluvial de corriente alóctona con procesos de erosión y acumulación (unidad 7). En la sección de Tierra Blanca se tiene evidencia de estos procesos, marcada por la presencia del sedimento de color blanco, laminado y con estratificación cruzada, fechado en 9000 años, por luminiscencia óptica (Solís-Castillo *et al*., 2013b). Es posible, que la tasa de acumulación fuera mayor que la descarga en el cauce, asociada a una mayor precipitación en la cuenca de drenaje. La procedencia de este material, constituido por ceniza volcánica (Solís-Castillo *et al*., 2013) revela claramente el aporte alóctono de sedimentos. Dichos sedimentos se depositan sobre la planicie de inundación pleistocénica (TP1).

Hacia el Holoceno Medio (5450 – 5380 años cal. A.P.), los patrones de sedimentación del río cambian abruptamente debido a condiciones ambientales más secas en las Tierras Bajas Mayas (Solís-Castillo *et al*., 2013a), lo cual provoca una menor descarga del cauce y el abandono de la planicie de inundación, conformando la terraza holocénica TH2. Esta tendencia hacia condiciones más secas también ha sido documentados en otras investigaciones de la región, como en la secuencia del Petén, en Guatemala (Rosenmeier *et al*., 2002).

En este primer periodo de estabilidad en la planicie aluvial, se desarrolla un suelo con edades entre los 5450 cal. A.P. y 2780 cal. A.P. descrito para la sección TBI y también hallado en la base de la sección El Pochote, con una edad de 2130 – 1980 cal. A.P (Tabla 1; Figura 5). Este suelo se caracteriza por tener propiedades vérticas, que indican una fuerte estacionalidad climática. Es sobre esta terraza y suelo, en donde se encuentran los asentamientos más antiguos de la planicie aluvial de Tabasco, correspondientes al Formativo Medio (Solís-Castillo *et al*., 2013a; Liendo *et al*., 2014).

Una nueva fase de actividad se presenta en la planicie aluvial, hace 1900 años, durante la cual se depositan sedimentos aluviales arenosos en TH2. Este evento aluvial forma la TH1, marcando un periodo de inestabilidad. Aún no se sabe con certeza si esta fase de inestabilidad se asocia con cambios climáticos o es el resultado de las actividades humanas que provocan erosión en el área. Sobre estos sedimentos aluviales, se desarrollan Fluvisoles con acumulaciones de carbonatos pedogenéticos, que registran fases secas durante el Clásico Tardío-Posclásico (Tabla 1). Los periodos de inestabilidad se presentan con mayor frecuencia a partir del Periodo Clásico. Es notorio que la terraza más joven, del sistema Usumacinta, TH0, muestra suelos con escaso desarrollo, que indica una mayor dinámica geomorfológica, la cual se ha relacionado con la perturbación antrópica actual.

6. Conclusiones

La reconstrucción del complejo sistema geomorfológico-ambiental de las Tierras Bajas Mayas de Chiapas-Tabasco y su articulación con la Sierra Norte de Chiapas está determinada por: a) el emplazamiento de antiguas estructuras de plegamiento; b) las diferencias litológicas (presencia de calizas y rocas sedimentarias clásticas en la Sierra de Chiapas y sedimentos aluviales heterogéneos en la planicie); c) por la actividad de los movimientos neotectónicos (Mioceno-Cuaternario) y su diferenciación principalmente en la planicie, en forma de bloques deformados; y d) por la intensidad de los procesos del modelado exógeno. En la Tierras Bajas Mayas este modelado exógeno se asocia tanto a cambios climáticos regionales como a la actividad humana desde el Formativo Temprano.

El uso de herramientas pedoestratigráficas en el establecimiento de las unidades geomorfológico-ambientales ha permitido obtener un registro de la dinámica de los procesos aluviales durante los últimos 125000 años. El primer periodo de estabilidad ambiental se registra en el desarrollo de Gleysoles cuya composición mineralógica revela la presencia de minerales ultraestables, producidos por un intemperismo intenso. Este periodo se puede acotar entre 65000 y 9000 años, dados los fechamientos disponibles para los sedimentos del Usumacinta. En el Holoceno Temprano, la dinámica ambiental cambia el cauce y el tipo de sedimentos que se aportan, produciendo, al mismo tiempo, el desarrollo de un nuevo sistema de terrazas.

Los suelos que se encuentran en las diferentes unidades geomorfológicas responden también a la dinámica del paisaje. En consecuencia, las unidades pedológicas en la Sierra de Chiapas muestran un desarrollo relacionado con los procesos de karstificación; en los límites entre la sierra y la planicie, por ejemplo en Boca del Cerro, la pedogénesis actual compite fuertemente con los procesos erosivos, impidiendo la formación de suelos desarrollados. Hacia la planicie, la pedogénesis en las terrazas está asociada no sólo a los cambios en el sistema aluvial, sino a las fases de ocupación humana, la cual ha sido permanente desde el Formativo hasta el Posclásico (Liendo *et al*., 2014).

Agradecimientos

Este trabajo se hizo gracias al apoyo de los proyectos PAPIIT 117709 "Secuencias pedosedimentarias en registros aluviales del Cuaternario: proxies de estabilidad ambiental", y CONACYT P166878 "Carbonatos pedogenéticos en suelos del Cuaternario como indicadores de cambio ambiental e impacto humano". Agradecemos el apoyo de Sergey Sedov, Jaime Díaz, Serafín Sánchez, Birgit Terhorst, Christine Thiel, Bodo Damm, Christina Wiesbeck y Daniel Jaeger, quienes colaboraron en el trabajo de campo. Asimismo, apreciamos el trabajo hecho en la elaboración de los modelos digitales de José Manuel Figueroa y Evelyn Cuevas, y al Dr. Gilberto Silva Romo y a un revisor anónimo por sus valiosas contribuciones que permitieron mejorar el documento.

Referencias

Benavides, L., 1956, Notas sobre la geología petrolera de México, *en* Guzmán, E. (Ed), Symposium sobre yacimientos de petróleo y gas, Tomo III, América del Norte: XX Geológico Internacional, Editorial Stylo, 351-352.

Bettis, A.E., Benn, D.W., Hajic, E.R., 2008, Landscape evolution, alluvial architecture, environmental history, and the archaeological record of the Upper Mississippi River Valley: Geomorphology, 101, 362-377.

Blum, M.D., Törnqvist, T., 2000, Fluvial responses to climate and sea-level change: a review and look forward: Sedimentology, 47(1), 2-48.

Borejsza, A., Frederick, C., 2010, Fluvial response to Holocene climate change in low-order streams of central Mexico: Journal of Quaternary Science, 25(5), 762-781.

Bridgland, D.R., Westaway, R., 2008, Climatically controlled river terrace staircases: A worldwide Quaternary phenomenon: Geomorphology, 98: 285-315.

Brown, A.G., 2001, Alluvial Geoarchaeology: Floodplain archaeology and environmental change: Cambridge University Press, UK, 2nd edition, 377 p.

Bueno, J., Alvarez, F., Santiago, S., 2005, Biodiversidad del Estado de Tabasco. México: Instituto de Biología, UNAM, 333 p.

Burkart, B., 1983, Neogene North American-Caribbean plate boundary across northern Central America: Offset along the Polochic Fault: Tectonophysics, 99, 251-270.

Cabadas, H., Solleiro-Rebolledo, E., Sedov, S., Pi, T., Gama-Castro J., 2010, Pedosediments of karstic sinkholes in the eolianites of NE Yucatán: a record of Late Quaternary soil development, geomorphic processes and landscape stability: Geomorphology, 122, 323-337.

Córdova, C.E., Parsons, J.R., 1997, Geoarchaeology of an Aztec Dispersed Village on the Texcoco Piedmont of Central Mexico: Geoarchaeology, 12, 177-210.

Cruz, M.M.A., Reyes, T.E., López, C.H., Sánchez, R.R., León, R.R., Peterson, R.R., Flores Z.J., Barrera, G.D., Vázquez, C.A., Peña, G.A., Fonseca, S.I., Hernández, A.L., 2010, Estudio Interregional Tectónica Salina y sus Implicaciones en la Exploración Petrolera: Petróleos Mexicanos, 197 p.

García, E., 1988, Modificaciones al Sistema de Clasificación Climática de Köppen: México, Offset Larios, 219 p.

Goldberg, P., Macphail, R.I., 2006, Practical and Theoretical Geoarchaeology: Blackwell Science Ltd, Oxford, USA, 441 p.

Gregory, K.J., Benito, G., Dikau, R., Golosov, V., A.J.J. Jones, A.J.J., Macklin, M.G., Parsons, A.J., Passmore, D.G., Poesen, J., Starkel, L., D.E. Walling, D.E., 2006, Past hydrological events related to understanding global change, *en* Gregory, K.J., Macklin, M.G., Walling, D.E. (Eds.), ICSU Research Project: Past hydrological events related to understanding global change: Catena, 66, 2-13.

Heine, K., 2003, Paleopedological evidence of human-induced environmental change in the Puebla-Tlaxcala area (Mexico) during the last 3500 years: Revista Mexicana de Ciencias Geológicas, 20, 235-244.

Hernández-Santana, J.R., Méndez-Linares, A.P., Bollo-Manent, M., 2012, Análisis morfoestructural del relieve noroccidental del Estado de Chiapas, México: Revista Geográfica Venezolana, 53, 57–75.

INEGI, 1986, Síntesis geográfica y anexo cartográfico del Estado de Tabasco: México D.F., 118 p.

Knox J.C., 1996, Late Quaternary Upper Mississippi River alluvial episodes and their significance to the Lower Mississippi River system: Engineering Geology, 45, 263-285.

Kondolf, G.M., Piégay., H., 2003, Tools in fluvial geomorphology: Chichester, John Wiley & Sons,. 312 p.

Liendo, S.R., Solleiro-Rebolledo, E., Solís-Castillo, B., Sedov, S., Ortiz, M.A., 2014, Prehispanic Population Dynamics in the western Maya Lowlands: Evaluating resilence and vulnerability in ancient landscape, *en* Chase, A., Carborough, V. (eds), Resilence and vulnerability ancient landscape, Transforming Maya Archeology: IHOPE, Antropological papers of the American Antropological Asociation, Willey Backwell, Hoboken, N.J. (en prensa).

Ludlow-Wiechers, B., Almeida-Lenero, L., Islebe, G., 2005, Paleoecological and climatic changes of the Upper Lerma Basin, Central Mexico during the Holocene: Quaternary Research, 64(3), 318-332.

Martínez-Kemp, H., González-Posadas, J.F., Bartok, P., 2005, Salt Involvement in the Jujo-Tecominoacán Thrust Belt, Chiapas-Tabasco Región, South East Basin, Mexico: GCAGS Transactions, 55, 520-530.

McClung, E., Domínguez, I., Gama, J., Solleiro-Rebolledo, E., Sedov, S., 2005, Radiocarbon dates from soil profiles in the Teotihuacan valley, Mexico: geomorphological processes and vegetation change: Radiocarbon, 47, 159-175.

Ortiz, M.A., Siebe, C., Cram, S., 2005, Diferenciación ecogeográfica de Tabasco, *en* Bueno, J., Álvarez, F., Santiago, S. (eds), Biodiversidad del Estado de Tabasco: Instituto de Biología, UNAM-CONABIO, México, 305-322.

Padilla y Sánchez, R.J., 2007, Evolución geológica del sureste mexicano desde el Mesozoico al presente en el contexto regional del Golfo de México: Boletín de la Sociedad Geológica Mexicana, 59, 19-42.

Palma, D.J., Cisneros, J., Trujillo, A., Granados, N., Serrano, J., Argueta, J., 1985, Caracterización de los suelos de Tabasco, uso actual y potencial y taxonomía: SECUR, Gobierno del Estado de Tabasco, 42 p.

Pope, K.O., Pohl, M.E.D., Jones, J.G., Lentz, D.L., von Nagy, C., Vega, F., Quitmyer, I., 2001, Origin and Environmental Setting of Ancient Agriculture in the Lowlands of Mesoamerica: Science, 292, 1370-1373.

Psuty, N.P., 1966, Regiones geomórficas Tabasqueñas: Unión Geográfica Internacional, Conferencia Regional Latinoamericana: Sociedad Mexicana de Geografía y Estadística, tomo III, 38-45.

Rosenmeier, M.F., Hodell, D.A., Brenner, M., Curtis, H., Guilderson, T.P., 2002, A 4000-year lacustrine record of environmental change in the southern Maya Lowlands, Peten: Quaternary Research, 57, 183-190.

Rzedowski, J., 2006, Vegetación de México: México, Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, 504 p.

Solís-Castillo, B., Solleiro-Rebolledo, E., Sedov, S., Liendo, R., López-Rivera, S., Ortiz-Pérez, M.A., 2013a, Paleoenvironment and human occupation in the Maya lowlands of the Usumacinta River, Mexico: Geoarchaeology, 28, 268-288.

Solís-Castillo, B., Thiel, Cabadas, H., Solleiro-Rebolledo, E., Sedov, S. Terhorst, B., Damm, B., Frechen, M., Tsukamoto, S., 2013b, Holocene sequences in the Mayan Lowlands: a provenance study using heavy mineral distributions: E & G Quaternary Science Journal, 62, 4-17.

Solleiro-Rebolledo, E., Sycheva, S., Sedov, S., McClung de Tapia, E., Rivera-Uria, Y., Salcido-Berkovich, C., Kuznetsova, A., 2011, Fluvial processes and paleopedogenesis in the Teotihuacan Valley, México: Responses to late Quaternary environmental changes: Quaternary International, 233, 40-52.

Targulian, V.O., Krasilnikov, P.V., 2007, Soil system and pedogenic processes: Self-organization, time scales, and environmental significance: Catena, 71, 373-381.

Tricart, J., Cailleux, A., 1972, Introduction to climatic geomorphology: Longman, London, 235 pp.

Vandenberghe J., 1995, Timescales, climate and river development: Quaternary Science Review, 14, 631-638.

West, R.C., Psuty, P., Thom, B., 1976, Las Tierras Bajas de Tabasco en el Sureste de México: Gobierno del Estado de Tabasco, México, 409 p.

Wiesbeck, C., 2012, The influence of Mayan land use on soils and pedosediments in karstic depressions in Yucatán, Mexico: Julius-Maximilians-Universität Würzburg, Institut für Geographie, Diplomarbeit zur Erlangung des akademischen Grades einer Diplom-Geographin 143 p.

Wohl, E., 2013. The complexity of the real world in the context of the field tradition in geomorphology: Geomorphology, 200, 50-58.

Manuscrito recibido: Enero 20, 2014.
Manuscrito corregido recibido: Abril 26, 2014.
Manuscrito aceptado: Abril 27, 2014.

E&G
Quaternary Science Journal
Volume 62 / Number 2 / 2013 / 4–17 / DOI 10.3285/eg.62.2.01
www.quaternary-science.net
GEOZON SCIENCE MEDIA
ISSN 0424-7116

3.2 Holocene sequences in the Mayan Lowlands – A provenance study using heavy mineral distributions

Berenice Solís-Castillo, Christine Thiel, Héctor Cabadas Baez, Elizabeth Solleiro Rebolledo, Sergey Sedov, Birgit Terhorst, Bodo Damm, Manfred Frechen and Sumiko Tsukamoto

How to cite: Solís-Castillo, B., Thiel C., Cabadas Baez, H., Solleiro Rebolledo, E., Sedov, S., Terhorst, B., Damm, B., Frechen, M., Tsukamoto, S. (2013): Holocene sequences in the Mayan Lowlands – A provenance study using heavy mineral distributions – E&G Quaternary Science Journal, 62 (2): 4–17. DOI: 10.3285/eg.62.2.01

Abstract: Heavy mineral analysis of alluvial sediments and paleosols on Holocene terraces of the Usumacinta River provided an effective tool to reconstruct sediment provenance in the Mayan Lowlands. Furthermore, the mineralogical data are useful for pedostratigraphic correlations in the region. Based on our observations from the Tierra Blanca profile, the ultrastable detrital heavy minerals assemblage (mostly zircon, tourmaline, and rutile) are the most promising mineral proxies to recognize the provenance of the sediments. Those minerals are accompanied by an intriguing variety of high density authigenic minerals (including titanite). Using the specific characteristics and the ages obtained for some layers, it may now be possible to develop a regional chronostratigraphy for the paleosols and alluvial sequences. Our data suggest that sediments were transported westward in river channels originating from the highlands of Guatemala. The studied materials also contain high amounts of volcanic minerals, most of them fresh and with angular shapes, thus indicating a proximal source, mostly likely from Tacana Volcano, Mexico/Guatemala.

Holozäne Sequenzen in den Tieflandgebieten der Mayas – Eine Untersuchung der Liefergebiete auf Basis von Schwermineralgesellschaften

Kurzfassung: Schwermineralanalysen an alluvialen Sedimenten und Paläoböden des Usumacinta-Flusses sind ein sehr effektives Werkzeug für die Rekonstruktion der relevanten Liefergebiete in den Tieflandgebieten der Mayas. Die mineralogischen Daten können für die pedostratigraphische Korrelation in der Region nützlich sein. Auf der Basis unserer Beobachtungen für Tierra Blanca ist die ultrastabile Schwermineralkomponente (zumeist Zirkon, Turmalin und Rutil) besonders erfolgversprechend für den Nachweis der Liefergebiete der Sedimente. Diese Minerale treten gemeinsam mit einer großen Vielfalt von sehr dichten authigenen Mineralen auf (u.a. Titanit). Unter Berücksichtigung der spezifischen Eigenschaften und der Alter von ausgewählten Horizonten, kann nun versucht werden, eine regionale Chronostratigraphie für Paläoböden und alluviale Sequenzen zu entwickeln. Unsere Daten deuten auf Sedimenttransport in Flussrinnen von den Hochländern Guatemalas gen Westen hin. Die untersuchten Schichten enthalten auch große Anteile an vulkanischen Mineralen mit frischen und eckigen Formen, was auf ein proximales Liefergebiet (wahrscheinlich Tacana Volcano, Mexico/Guatemala) hinweist.

Keywords: *heavy mineral assemblages, pedostratigraphy, micromorphology, alluvial sediments, Mayan Lowlands, Mexico*

Addresses of authors: **B. Solís-Castillo**, Posgrado en Ciencias de la Tierra. Instituto de Geología, UNAM. 04510, México, D.F., E-Mail: bsolisc.geologia@gmail.com; **C. Thiel**, Nordic Laboratory for Luminescence Dating, Department of Geoscience, Aarhus University, Risø Campus, Frederiksborgvej 399, 4000 Roskilde, Denmark; Center for Nuclear Technologies, Technical University of Denmark, Risø Campus, Frederiksborgvej 399, 4000 Roskilde, Denmark. E-Mail: chrth@dtu.dk; **H. Cabadas Baez**, Laboratorio de Geología, Facultad de Geografía, UAEM. 50110, Toluca Edo. México. hvcabadasb@uaemex.mx; **E. Solleiro Rebolledo, S. Sedov**, Instituto de Geología, UNAM. 04510, México, DF. E-Mail: solleiro@geologia.unam.mx; serg_sedov@yahoo.com; **B. Terhorst**, Institute of Geography and Geology, University of Würzburg, Am Hubland, 97047 Würzburg, Germany. birgit.terhorst@uni-wuerzburg.de; **B. Damm**, Institut für Strukturforschung und Planung in agrarischen Intensivgebieten (ISPA), Vechta University, 49364 Vechta. E-Mail: bdamm@ispa.uni-vechta.de; **M. Frechen**, **S. Tsukamoto**, Leibniz Institute for Applied Geophysics Section, S3: Geochronology and Isotope Hydrology, Stilleweg 2, 30655 Hannover, Germany. E-Mail: manfred.frechen@liag-hannover.de; E-Mail: sumiko.tsukamoto@liag-hannover.de

1 Introduction

The reconstruction of the environmental and landscape changes in Mexico for the Late Quaternary is based on numerous data. The majority of data is derived from lacustrine sediments, glacial and paleopedological records; however, due to the fragmentary character of glacial records, hiatuses in lake cores, and low temporal resolution of tephra-paleosols sequences these records are still contradictory (Sedov et al. 2009). With respect to this problem, new insights might be obtained by studying alluvial sequences. Until now the alluvial and fluvial archives in Mexico have not received sufficient attention as a source to understand short-term changes in the landscape; only very few detailed studies deal specifically with flu-

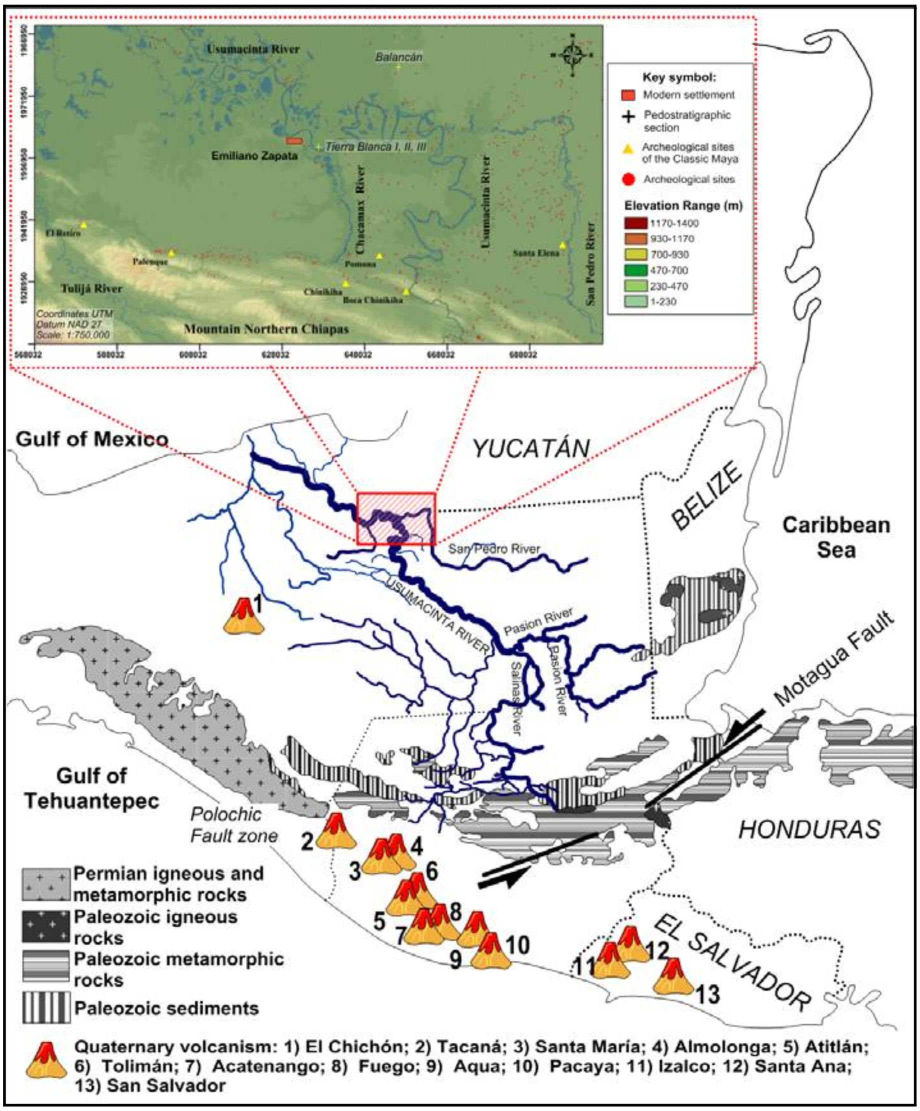


Fig. 1: Location of the study area and simplified geologic map showing the boundary between the Maya and the Chortis blocks. Modified after Ortega-Gutiérrez *et al. (1992), and* French & Schenk *(1997).*

Abb. 1: Lage des Untersuchungsgebiets und vereinfachte Darstellung der regionalen Geologie mit der Grenze zwischen der Maya- und der Cortis-Platte. Verändert nach Ortega-Gutiérrez *et al. (1992)und* French & Schenk *(1997).*

vial Late Pleistocene-Holocene sequences (cf. Solleiro-Rebolledo et al. 2011).

Particularly, the alluvial-paleosol sedimentary sequences in the Southeast of Mexico are highly sensitive to the environmental changes and are rich and detailed Holcene archives (Solís-Castillo et al. 2013). However, river systems are very complex due to the dynamics involved in their formation, thus controlling the different phases of aggradation, degradation, and pedogenesis. Aggradation phases can be recognized by selective sorting of particles due to differential entrainment and transport. This is especially seen in the characteristics of heavy minerals, such as densitiy, grain size and shape. In general, the sorting may be a result of ancient depositional environments and provenance of sediments (Komar 2007). In rivers with high sedimentation rates, heavy minerals are affected by considerable sorting before they reach the alluvial plain (Pirkle et al. 2007).

Alluvial landscapes are very complex due to the presence of discontinuities in vertical successions, being controlled by several forces (climatic, geologic, geomorphic, anthropogenic), and interpretation of the successions can be problematic. Similar sediments can be produced in different and distant areas or periods; this makes paleoenvironmental reconstruction difficult. In consequence, paleosols are important records for the environmental history and can help to unravel the alluvial stratigraphy (Hughes 2010). Alluvial soils exhibit characteristics of both sedimentary and soil formation processes. Such soils are characterized by the textural and mineralogical composition of the material transported across the drainage basins (Kraus 2002). Traditionally, analyses of mineral composition have been applied to paleosols on surfaces of different ages to establish morphostratigraphical units (Schatzl & Anderson 2005). In particular, heavy minerals in soils are used as indicators for sediment provenance. Furthermore, heavy minerals have been used to determine weathering degrees, thus being useful as relative dating tools (Mikesell et al. 2004). In sequences where paleosols show contrasting differences, weathering indices are commonly used to evaluate the intensity of the process and their relation to environmental conditions.

The Usumacinta River in Tabasco, Mexico (Fig. 1) has carried vast quantities of sediments from Chiapas and Guatemala since the Plio-Pleistocene and therefore exhibits a great potential for the application of heavy mineral analyses. At present, detailed information on the heavy mineral assemblages in soils are very scarce for the Mayan Lowlands. This area is known for its high cultural diversity since the Mid- Holocene, which is probably related to the river-channel stability and soil formation on the Holocene terraces, thus providing space for settlements in the alluvial plain (Solís-Castillo et al. 2013).

Altogether, the analysis of mineral provenance is of great importance to better understand the river dynamics and climatic changes in this region, which is reflected in different weathering intensities. Unraveling the changes in the landscape and in the soils will contribute to a better understanding of human migration along the Mayan Lowlands.

It is surprising that most of the information about the climate history of the Maya region comes from studies in Yucatan (Rosenmeier et al. 2002; Hodell et al. 2005; Sedov et al. 2007; Fredick et al. 2008; Cabadas et al. 2010), as well as from Guatemala and Belize (Dahlin et al. 1980; Beach et al. 2003; Fernandez et al. 2005; Dunning et al. 2002, 2006). Until now, for the Maya Lowlands, only Solís-Castillo et al. (2013) provided data on the reconstruction of Holocene climatic changes in the Usumacinta River region on the base of paleopedology.

The authors found that the Late Pleistocene-Early Holocene paleosols show strong weathering and gleyzation related to more humid climatic conditions. These conditions were only observed in the paleosols with gleyic features, while in the alluvial sediments only few oxide-reduction characteristic were found. Mid-Holocene paleosols are characterized by the presence of carbonate concretions combined with vertic features, which indicate a major drying trend as well as fluctuations between wet and dry conditions. Late Holocene paleosols show vertic properties and lack gleyic features; this corresponds to dryer conditions. Further, Middle and Late Holocene paleosols are observed at the base of other sequences located on the younger terraces; these paleosols do not show any signs of oxide-reduction conditions.

In this study we use heavy minerals to detect the weathering degree of alluvial sediments and paleosols ; these data serve as proxy for the relative stability during the Late Pleistocene and the Holocene. Some samples were selected for micromorphology in order to investigate the bulk mineral composition.

Furthermore, the composition of the heavy minerals from the alluvial sediments of the Usumacinta River helped to reconstruct the provenance. In addition, radiocarbon and luminescence ages provide a numerical chronology for the sediments under study.

2 Regional setting and the Usumacinta River

The Mayan Lowlands are characterized by active volcanoes, rugged terrain of the Sierra de Chiapas and the Central Cordillera, and faulting as well as extensive karst systems in the northern lowlands (Figure 1). Volcanism and tectonics are a result of the highly variable spatial and temporal evolution of plate boundaries between Cocos, North American, and Caribbean Plates (Donnelly et al. 1990).

The Sierra de Chiapas is mainly formed by Tertiary folded, northwest-southeast oriented limestones. The limestones show extensive karstic features with abundant subterranean drainage and ephemeral surface streams. The highlands of the Chiapas region are composed of extrusive igneous rocks (andesites, dacites, and pyroclastic products) and sedimentary rocks (shales, sandstones, and limestones). Their ages range from Late Cretaceous to Tertiary, and Quaternary (Hernandez et al. 2012). The Paleozoic geology in Chiapas is characterized by metamorphic rocks, which consist of granitic gneiss and gneiss of biotite and orthoclase, sedimentary rocks, and biotite schists. In the western part of Guatemala, gneiss and schists of quartz are present. The Paleozoic Granitic Massif of Chiapas is composed of pink granite of biotite with graduation to granodiorite (Monografia Geologica-Minera del Estado de Tabasco 1999).

The Usumacinta River is one of the larger fluvial systems in Mexico with a drainage area of 63,804 km^2 (West et al. 1969), which flows through both the highlands of Chiapas and Guatemala and the coastal plains of the southern Gulf of Mexico.

The latter are formed by Late Tertiary (Pliocene) and Quaternary deposits, which are mainly composed of alluvium, lacustrine and marsh sediments, as well as coastal bars and residual soils. During the Holocene, three tributary channels (San Pedro in the east, Chakamax in the center, and Tulijá in the west) flew across the terraces of the Central Usumacinta and discharged into the Lower Usumacinta (Solís-Castillo et al. 2013).

Starting in Guatemala, the Usumacinta River runs northeast to the Bay of Campeche in the Gulf of Mexico (Figure 1). This vast region has been subdivided into two main areas: the Upper Usumacinta (from the rivers Salinas and Passion in Guatemala to Boca del Cerro, Chiapas), and the Lower Usumacinta (from Boca del Cerro to the Gulf of Mexico). In pre-Hispanic times, several population centers were located in these areas. Until now, there is evidence of 2,300 archaeological sites with different characteristics; they are preferably located in the plains of Tabasco. The number of occupation sites in the numerous side valleys along the Usumacinta River in the mountainous region is still unknown (Liendo et al. 2012). The archeological research has revealed a long sequence of occupation for the region ranging from the Middle Preclassic period (800–300 B.C.) to the Terminal Classic period (850 A.D.) (Liendo et al. 2012, and references therein).

In the north, the Usumacinta River flows through the State of Tabasco in an alluvial valley composed of Plio-Pleistocene to Holocene terraces (Ortiz-Perez et al. 2005); these are affected by Neogene tectonic activity with a set of normal faults causing a horst-graben system (Padilla & Sanchez, 2007). The main tributaries follow normal fault planes. The oldest terraces are located in the areas more distant from the sea. In contrast, Holocene terraces are formed by incisions and floodplain deposits along the main channel. Three levels of Holocene terraces have been recognized by Solís-Castillo et al. (2013), referred to as HT2 (at 15–10 m asl), HT1 (at 10–5 m asl) and HT0 (at <5 m asl), from the oldest to the youngest.

3 Materials

In Tierra Blanca (Figure 1), the studied sequence is composed of alluvial sediments intercalated with paleosols. Three profiles were studied (Figure 2): Tierra Blanca (TB) I, TB II and TB III. Solís-Castillo et al. (2013) have presented soil morphologic data, archeological and cultural evidence, as well as radiocarbon ages for TB I and TB II (amongst other sections from the same region). Here, we present new data for TB III and compare them to TB I and II in order to get a more complete understanding of the landscape formation and paleoenvironmental changes. A composite profile is shown in Figure 3. The pedological and sedimentological survey is complemented by micromorphology. Furthermore, three alluvial layers were dated using optically stimulated luminescence (OSL); these ages can be compared with the radiocarbon ages presented in Solís-Castillo et al. (2013). Heavy mineral analysis is used to trace the provenance. In addition to the Tierra Blanca site, data from a sequence in Balancán (Figure 1) are presented; the section in Balancán is also located on a Pleistocene terrace of the Usumacinta River.

The TB I, II and III sequences are located on the oldest Holocene terrace (HT2), and represent the most complete stratigraphic section of the area. In TB I and TB II two types of paleosols are present, gleyic at the base and vertic at the top. They are clearly separated by alluvial sediments (TB III) (Figure 3).

On top of a sandy Pleistocene alluvium the lower part of the composite profile (TB I) contains four paleosols (numbered 6, 7, 8, 9). This section with a total thickness of 267 cm, is characterized by the following horizons: 6G, 7Bg, 8G, 8Gk, 9G, 9Bkg, 9BCgk (Figure 3). A horizons are not preserved due to erosional processes; there is no separation of the individual paleosols by C horizons. All horizons show strong gleyic features expressed as grayish brown colors with reddish-yellowish-greenish mottles, coarse subangular blocky structure, Fe concretions and/or spots, and dendritic Mn. In the paleosols of unit 9 the gleyic features decrease with depth, and at the base of horizon 9BCgk the oxide-reduction characteristics are less. The strongest gleyic features are observed in paleosol 6, where also slickensides are present. One of the most remarkable features in the gleyic unit in horizon 9Bkg is the presence of hard carbonate concretions, around 5 to 10 cm in diameter. These concretions were radiocarbon dated to 5450–5380 cal. B.P. (3240–3110 B.C.) (Solís-Castillo et al. 2013).

The upper paleosols (section TB II; Figure 3) formed on top of silty sediment (i.e. on top of section TB III; Figure 3). The paleosols in section TB II (labeled as paleosols 2, 3, 4, 5) show evidence of human occupation in three different periods (according to the Mesoamerican chronology): Formative (800 B.C. – A.D. 150), Classic (A.D. 150–1000) and Post-classic (A.D. 1000–1500). Paleosols 2 and 3 are weakly developed. Horizon 4Bk is a pedosediment, composed of soil fragments and broken carbonate concretions. Paleosol 5 bears the strongest pedogenic features of all paleosols, and can be subdivided in 5Ass, 5Bss and 5BC, with a total thickness >1 m. This paleosol shows strong vertic features: slickensides, hard angular blocky structure, and vertical cracks. Carbonates in the form of white spots and filling fractures and pores are found throughout the entire profile. The modern surface is made up of ~100 cm of alluvial sediment little affected by pedogenesis (C horizon).

The chronology of these paleosols has been previously established by radiocarbon dating (Table 1) and archeological evidence (Solís-Castillo et al. 2013). The soil organic matter (SOM) in 5Ass was dated to 2340–2300 cal. B.P. (390–350 B.C.) The carbonates disseminated in 5Bss horizon gave a much younger age, 720–660 cal B.P. (1230–1290 A.D.). However, artifacts found in this paleosol belongs to the Formative Period (1800 B.C.–150 A.D.), which confirms its stratigraphic position. Clearly, the carbonates must have formed later. Charcoal from the 3A horizon yielded an age of 1140–970 cal. B.P. (810–980 A.D.). Classic ceramic fragments (A.D. 150–1000) recovered from this paleosol support this date. The upper paleosol 2 has not been dated with any numerical technique; however it contains Post-classic artifacts (A.D. 1000–1500) and thus allows for assigning an age to it.

The alluvial sediments were best expressed in profile TB III located only 10 m to the east of TB I. At the contact to

Tab. 1: Summary of the dating results. Blue OSL data are from quartz, pIRIR$_{290}$ are from K-feldspar. For sample 2464, the quartz is in saturation, i.e. a minimum dose and correspondingly age are given. The radiocarbon ages are taken from Solís-Castillo et al. (2013).

Tab. 1: Zusammenfassung der Datierungsergebnisse. Blaue OSL-Daten stammen von Quarz, pIRIR$_{290}$ von K-Feldspat. Der Quarz für Probe 2464 ist in Sättigung, d.h. es kann nur eine Mindestdosis und ein -alter angegeben werden. Die Radiokarbonalter stammen aus Solís-Castillo et al. (2013).

Lab code	Horizon	Dose rate [Gy/ka]		Equivalent dose [Gy]		Age [ka]		Radiocarbon age
		quartz	feldspar	blue OSL	pIRIR$_{290}$	blue OSL	pIRIR$_{290}$	cal. BP [2σ]
BETA-300447	3A	-	-	-	-	-	-	1140-970 [3]
2462	3C	2.90 ± 0.11	-	6.1 ± 1.4 [1]	-	2.1 ± 0.5	-	
BETA-300448	5Ass	-	-	-	-	-	-	2340-2300 [4]
BETA-300449	5Bss	-	-	-	-	-	-	720-660 [5]
2463	TB3_07	3.27 ± 0.11	-	29 ± 6 [1]	-	9 ± 2	-	-
BETA-277572	9Bkg	-	-	-	-	-	-	5450-5380 [5]
2464	9BCgk	1.98 ± 0.10	2.61 ± 0.11	> 130 [2]	322 ± 10 [2]	> 65	123 ± 6	-

[1] >24 aliquots measured.
[2] 9 aliquots measured.
[3] Charcoal dated.
[4] Soil organic matter dated.
[5] $CaCO_3$ nodules dated.

E&G / Vol. 62 / No. 2 / 2013 / 4–17 / DOI 10.3285/eg.62.2.01 / © Authors / Creative Commons Attribution License

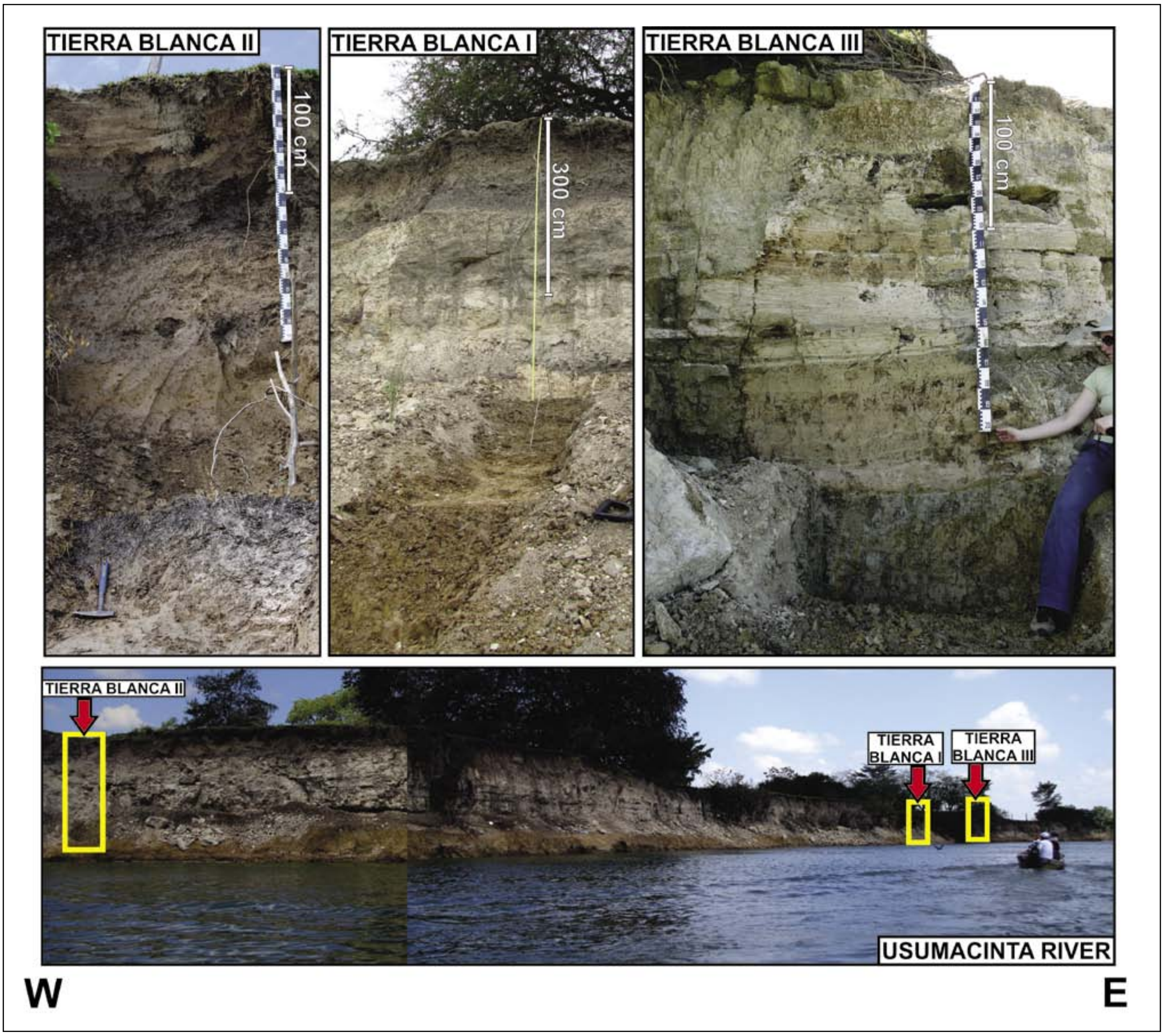


Fig. 2: Photograph showing the positions of the individual profiles in Tierra Blanca.
Abb. 2: Übersichtsaufnahme von Tierra Blanca und einzelne Profile.

paleosols with evidence of human occupation, the overlying sediment is laminated and shows a wavy boundary and has a total thickness of 10 cm. The middle part alternates from lamination to crossed stratification and is characterized by a sand texture, reductomorphic features and carbonate concretions. In this section, two phases representing slow water flow or even standing water can be found (as shown by clayey material with some reductomorphic features and root traces).

The upper part is also laminated, with vertical cracks up to 40 cm in length cutting through the sediment layer (cf. Figure 3). The material of all laminated strata reacts intensively with HCl. We refer to this material as silt sediment due to the dominance of this fraction (62%); however, it also has a high proportion of clay (32%) (Solís-Castillo et al. 2013).

Another profile situated on top of a Pleistocene terrace is found in the Balancán section (Figure 4). It is characterized by a monogenetic soil ($A/Bg/G_1/G_2$) with strong gleyic features (grayish brown colors with reddish-yellowish-greenish mottles, Fe concretions and dendritic Mn). The soils at Balancán are morphologically similar to the ones at the base of the Tierra Blanca sequence. However, the Balancán soils are more intensely weathered as shown by the larger amount of clay, and the more compact and pronounced oxide-reduction features (Figure 4).

4 Methods

4.1 Mineralogy and micromorphology

Thirty-two samples were taken for heavy mineral analyses (cf. Figure 5). The fine sand (63–125 µm) was separated by sieving and pretreated with 10% hydrocholoric acid (HCl) to dissolve carbonates, and subsequently with 30% hydrogen peroxide (H_2O_2) to remove organic matter. The sands were dried and then floated in sodium polytungstate liquid with a density of 2.82 ± 0.02 g/cm³. Heavy minerals were collected in filters and after drying dispersed in Mountex resin with a refraction index of N=1.67. The identification of the minerals was conducted under a polarization microscope after Mange & Maurer (1992). Two hundred mineral grains were counted for each sample.

We furthermore took three samples representative for the three types of materials found: the gleyic paleosols at the base (9Bgk horizon, TB I); the paleosols with signs of human occupation (3A horizon, TB II), and the top of the silty sediment (TB3_00, TB III; cf. Figure 3). Using micromorphology the bulk mineral composition was applied, focusing on the light minerals. The thin-sections (30µm thick) were prepared from undisturbed soil samples, impregnated at room temperature with resin Cristal MC-40. They were studied under a petrographic microscope, and described following the terminology of Bullock et al. (1985). Additionally, the thin section of the silty sediment was scanned with high resolution, 4800 and 9600 dots per inch (DPI) in order to investigate its overall structure.

4.2 Luminescence dating

Luminescence samples were taken by hammering metal tubes into the freshly cleaned profile (cf. Figures 2 and 3); the tubes were sealed to prevent any light intrusion. Additional samples for dose rate determination (dosimetry) were taken from immediately around the tube samples. The luminescence samples were treated under subdued orange light. The material from the outer ends of the tubes was discarded, and the samples were then dried prior to sieving. The fraction 100–150 µm was treated with 30% HCl, 10% H_2O_2, and sodium oxalate prior to density separation using sodium polytungstate (quartz: $\rho < 2.7$ g/cm³ but > 2.62 g/cm³; potassium (K)-rich feldspar $\rho < 2.58$ g/cm³). The quartz grains were subsequently etched at least once in 30% hydrofluoric acid (HF) for 1 hour, while the feldspar grains only got a short (20 minutes) HF etch (10%) to remove the outer layer of the grains. Finally all fractions were treated with 30% HCl to destroy any fluorides that might have build up during HF etching.

The equivalent doses (D_e) were measured with automated Risø TL/OSL readers as small (samples 2463 and 2464) or medium (sample 2462) aliquots mounted on stainless steel cups. Both infrared (IR) light emitting diodes (LED) and blue LEDs were used. For the quartz extracts the luminescence was detected through a Hoya U340 filter, whilst feldspar detection was through a Schott BG39/Corning 7–59 filter (IR stimulation). All measurements procedures are single aliquot regenerative (SAR) protocols (Murray & Wintle, 2000).

Quartz purity checks showed that some aliquots of samples 2462 and 2463 exhibited contamination from IR sensitive material (most likely feldspar), even though the average IR depletion ratio (Duller, 2003) was within 10% of unity. To ensure a quartz signal as pure as instrumentally possible from all aliquots, a double SAR (Banerjee et al. 2001) was applied using a preheat of 200°C (10 s) and a cutheat of 180°C. IR and blue stimulation were for 100 s at 125°C. At the end of each cycle, a high temperature blue clean-out (280°C for 40 s) was inserted. The quartz of 2464 was measured without the IR step as it was found to be clean (IR depletion within 2% of unity); the preheat temperature was 260°C and the cutheat temperature 220°C, respectively. Early background subtraction (Cunningham & Wallinga, 2010) was used to calculate the equivalent doses.

Because the quartz for sample 2464 was found to be in saturation (cf. results section and Table 1), equivalent

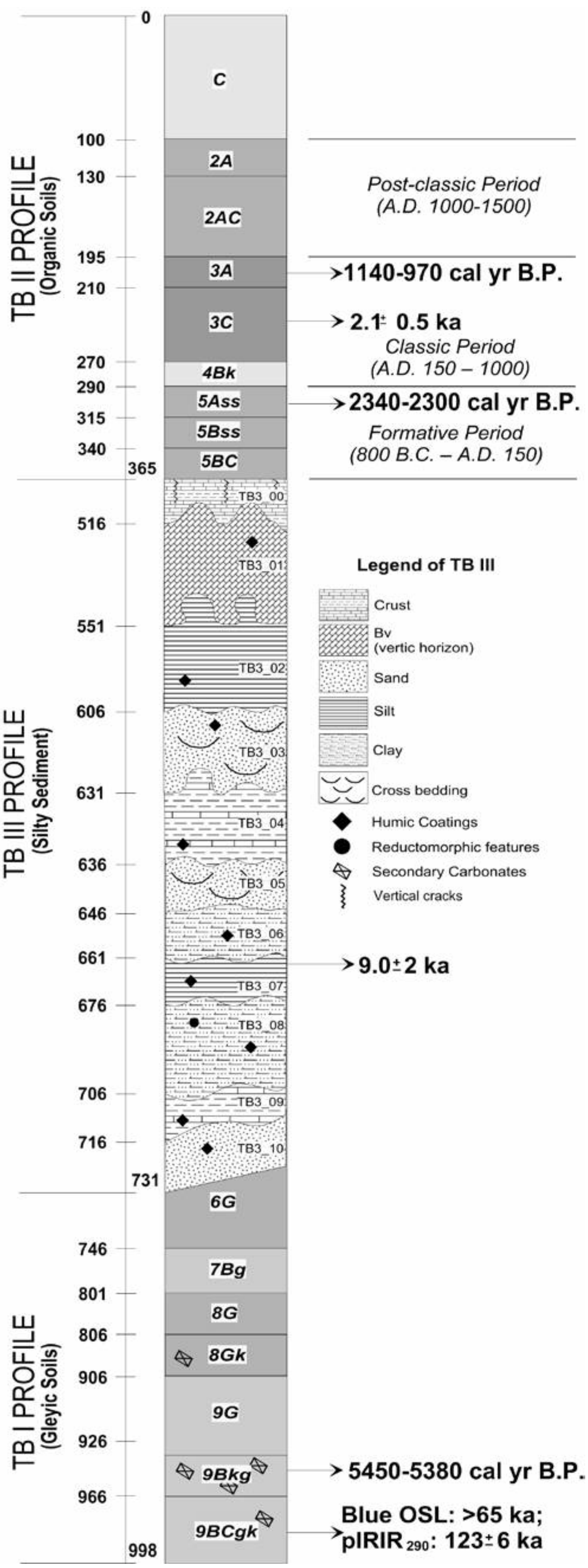
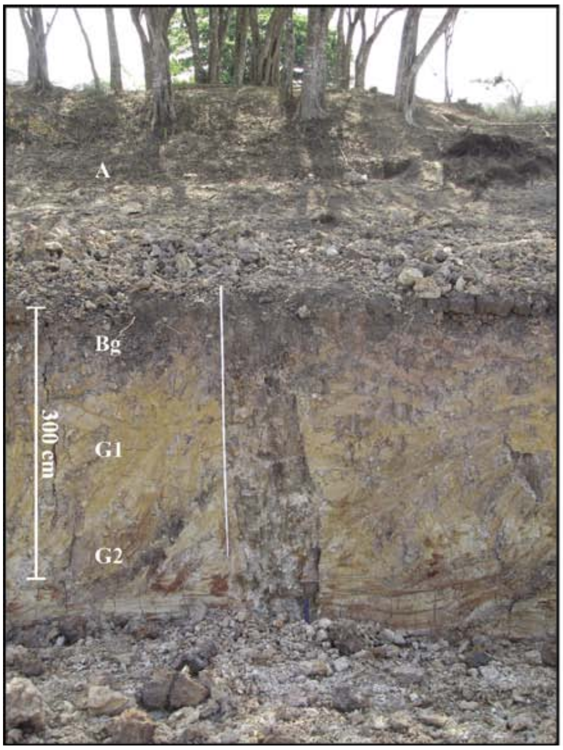


Fig. 3: Tierra Blanca: composite profile and ages.

Abb. 3: Gesamtprofil und Alter für Tierra Blanca.

E&G / Vol. 62 / No. 2 / 2013 / 4–17 / DOI 10.3285/eg.62.2.01 / © Authors / Creative Commons Attribution License



A Horizon (0-10 cm): Sandy material, with very friable subangular blocky structure; dark gray. This horizon is strongly affected by recent human activities, i.e. agriculture and cattle.

Bg Horizon (10-104 cm): Sandy silt with very compact subangular blocky structure. The matrix is gray with red and yellow mottles; slickensides are present. The matrix is free of carbonates and contains traces of large roots (90 cm-lenght) filled of reddish-yellow material. The horizon is moderately friable.

G1 Horizon (104-153 cm): Silty sand and very hard subangular blocky structure that breaks into columns; grayish-green with yellowish and reddish mottles. The matrix is free of carbonates. Slickensides are present.

G2 Horizon (153-260 cm): Silty material with angular blocky structure, which is clearly more friable than G1. It has a green color with mottles in the ped surfaces. On the surfaces of soil fractures there is reddish material, which is friable and silty. The yellowish color is more intense at a depth of 210 cm;where,also Fe concretions and Mn mottles appear

Fig. 4: Balancán: composite profile and field description.
Abb. 4: Gesamtprofil und Geländeaufnahme für Balancán.

doses were also derived from the K-feldspar fraction. A post-IR IRSL protocol was applied using a preheat and cutheat temperature of 320°C, IR stimulation at 50°C (200 s) and post-IR IR stimulation at 290°C (200 s; referred to as pIRIR290) (Thiel et al. 2011; Buylaert et al. 2012). An IR clean-out at 325°C (100 s) complemented the measurement cycle. The initial 2 s minus a background of the last 40 s were used for equivalent dose calculation.

Dosimetry samples were dried and homogenized prior to packing ~50 g into N-type beakers. High-resolution gamma-counting was conducted at the Leibniz Institute for Applied Geophysics (Hannover, Germany). Conversion to dose rates is based on the values given in Guérin et al. (2011). The cosmic ray contribution was calculated using the data given in Prescott & Hutton (1994), and for all samples a water content of 25 ± 5% was used. Equivalent doses, dose rates and ages are listed in Table 1.

4 Results
4.1 Heavy minerals

An overview of the heavy minerals found is shown in Figures 6 and 7. The heavy mineral composition of the paleosols and river sediments of the Usumacinta shows a clear pattern for all studied samples (Figure 5): There is a dominance of opaque minerals. These show signs of weathering (Table 2), indicated by leucoxene whitish rings. These observations are specifically pronounced in the alluvial sediments with concentrations ranging from 14.5% to 59.6%. The samples from the TB II section (the youngest paleosols with strong evidence of human occupation; see Table 2) have the lowest concentration of fresh opaque minerals for all studied samples (including Balancán). The smallest amount is found in horizons 3A and 3C, where it is about 4.5%. The underlying horizons show values between 22% and 33%. Epidote is the second most abundant mineral (1% to 21%), with a notable increase in the lowest horizons (5Bss, 5BC, 5C). Interestingly, there are high concentrations of pyroxene in the three uppermost horizons (AC-2A-2AC) with values between 12% and 22%; these are the highest concentration of all studied profiles (Table 2). Furthermore, these horizons show the highest concentrations of green (11%) and brown amphibole (5% to 9%). In general green amphibole has greater abundance than brown hornblende. The presence of calcite is more or less constant throughout the profile, with the exception of the uppermost horizons (AC-2A-2AC-3A), where the content ranges from 55 to 18%. Chlorite and zoisite were also found; they do not exceed 4.5%, again with the highest concentrations in the uppermost horizons. The lower part of the profile (4Bk-5As-5Bss-5BC-5C) shows remarkable heavy mineral patterns with relatively high concentrations of rutile (1.3% to 2.5%), chromospinel (3.0% to 5.8%), turmaline (1.1% to 4.0%), kyanite (1.4% to 2.0%) and monazite (2.0% to 2.8%). It is interesting to note that the 4Bk horizon is the only layer with well-rounded minerals, including coarse silt size, and the presence of volcanic glass on the surface of amphiboles.

For the alluvial units, the most striking aspect is the high concentration of volcanic material represented by amphibole, which is coated by volcanic glass and pyroxenes with dissolution surfaces. However, is not possible to identify a general pattern throughout the sequence except for the presence of calcite in percentages between 1% and 59% (the major part located in the middle of the sedimentary sequence).

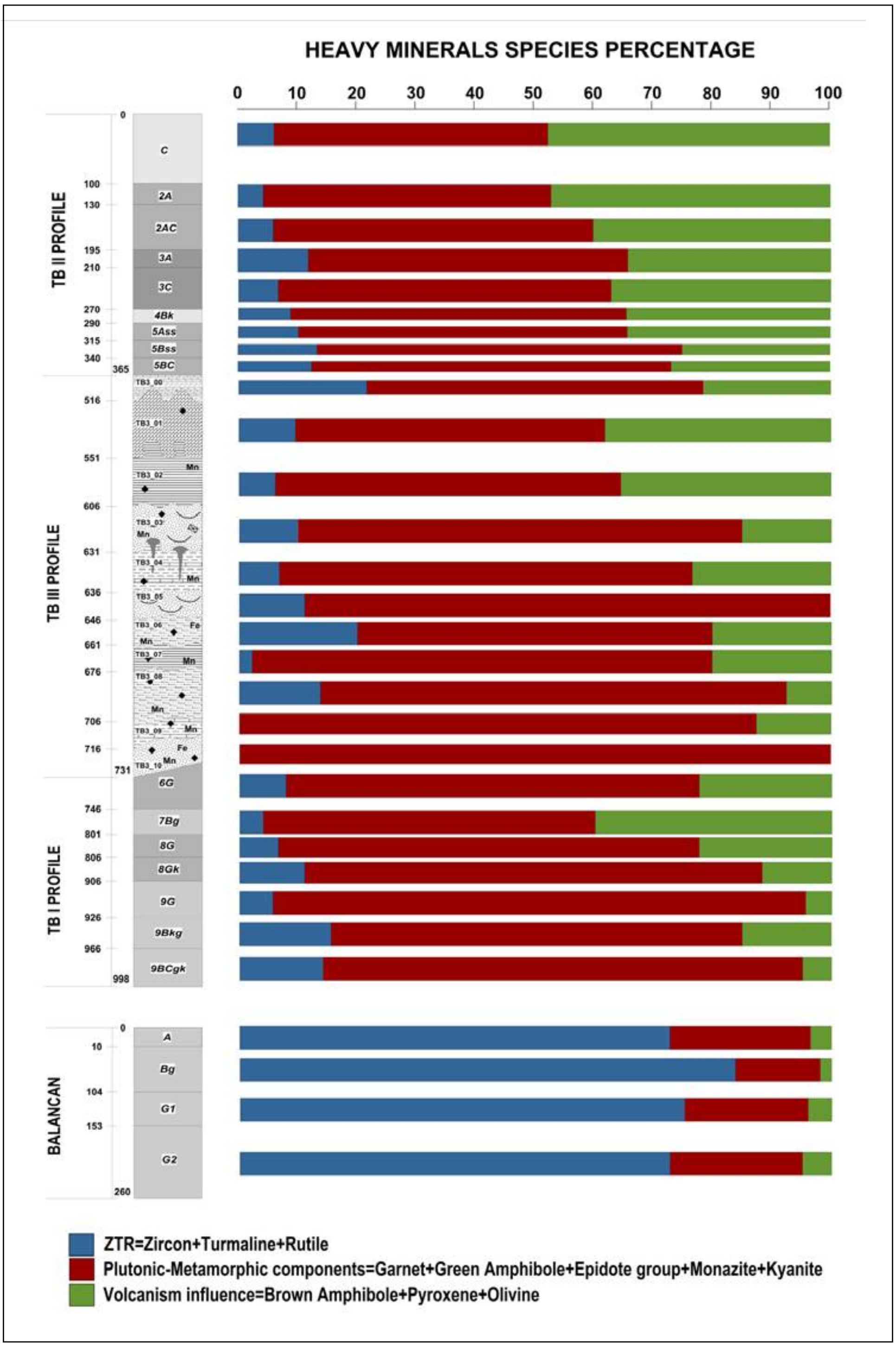


Fig. 5: Tierra Blanca and Balancán profiles and relative abundance of heavy minerals.

Abb. 5: Zusammenstellung der Profile und relative Vorkommen der Schwerminerale für Tierra Blanca und Balancán.

The accumulation of minerals is less homogeneous compared to the soil profiles. There seems to be a weak tendency of enhanced concentrations for green amphibole, epidote, and pyroxene in the bottom of the profile. Garnet is only of importance in the middle part of the profile (3.4% to 6.0%).

The lower part of the TB profile (TB I; Figure 3) shows a more regular pattern in the mineral concentration. The most important characteristic is the highest presence of epidote ranging from 20.8% to 28.3%, and the concentration of stable minerals (garnet, titanite, zircon, zoisite, rutile, chromospinel, monazite, and kyanite) with a decrease of less stable minerals (like amphibole). Many of these minerals have a metamorphic source (from moderate to high grade metamorphic phases). The influence of the volcanic source is less evident, however, pyroxene and olivine show large concentrations (mainly in the upper part of the profile, i.e. 6G-7Bg-8G-8Gk). Horizons 6G and 9G show the largest abundance of opaque minerals (Table 2). There is clearly a change in the mineral composition at the boundary between 6G and the lowermost part of the silty sediment (Figure 3), where the metamorphic components dominate (Figure 3). The amount of calcite is much smaller than for TB II and TB III (0.2% to 3.5%).

The Balancán profile shows clear differences in comparison to the Tierra Blanca sections; there ultrastable minerals are present (Figure 5). The sequence shows very high contents of zircon (17% to 25.5%), rutile (3.4% to 8.4%), and titanite (2.0% to 5.3%). There is only very little epidote and hardly any calcite present (Table 2).

E&G / Vol. 62 / No. 2 / 2013 / 4–17 / DOI 10.3285/eg.62.2.01 / © Authors / Creative Commons Attribution License

Fig. 6: Heavy minerals under the petrographic microscope using plane polarized light.

Abb. 6: Ausgewählte Schwerminerale unter dem petrograpischen Mikroskop unter der Verwendung von eben-polarisiertem Licht.

4.2 Micromorphology of selected horizons

Horizon 3A (TB I) is dominated by a clayey-silty texture; there are only a few sand grains. The structure evidences vertic features (angular blocky structure with porostriated b-fabric; Figure 7a). Weathered volcanic glass is also present (Figure 7b). 9Bkg horizon is very clayey but contains some sand grains, which are mainly composed of quartz (Figures 7c and 7d). A few micas are also present; these are all highly weathered. Clay coatings are frequent. In TB III the most remarkable feature in the silty sediment is the strong lamination that is clearly shown not only in the profile (Figure 2c) but also in the scanned section (Figure 7e). This laminated sediment is dominated by volcanic glass which is angular (Figure 7f).

5 Discussion

5.1 Ages of the paleosol units and pedostratigraphy

The gleyic paleosols (horizons 6 to 9) found in TB I are clearly much older than the overlying succession (TB III and TB II). Horizon 9BCgk was luminescence dated to >65 ka (quartz OSL; sample 2464); the feldspar (pIRIR$_{290}$) yielded an age of 123 ± 6 ka (Table 1). This age represents the age of the parent material of paleosol 9, i.e. the paleosols are younger. One might argue that alluvial sediments are not well-bleached prior to deposition, i.e. the luminescence signal is not reset, which would result in an age overestimate. It is very unlikely that the alluvial sediments at this site carry a large residual dose, which is shown by the youngest sample (horizon 3C; sample 2462): Its luminescence age is in very good agreement with the radiocarbon ages of the over- and underlying layers (Table 1). The radiocarbon age of 5450–5380 cal. B.P. for the lowermost paleosol (horizon 9Bkg; Table 1) was derived from neoformed carbonates; they postdate the age of the sediments. The gleyic paleosols show strong redoximorphic features, leaching (carbonates are absent in the groundmass) and intense clay accumulation (including well preserved clay coatings). All these characteristics point to pedogenesis in a moist environment, sometimes accompanied by water-logging that is hardly compatible with the formation of calcite. Thus, carbonates precipitated much later, after environmental conditions changed. As a consequence, the age of the carbonate concretions (5450–5380 cal. B.P.) cannot be interpreted as the age of the first intensive pedogenetic phase. According to the luminescence ages of the parent material and of the overlying alluvial sequence (sample 2463; cf. Table 1) the soils formed after 123 ± 6 ka but prior to 9 ± 2 ka.

The latter age is the only age estimate for the silt sediment between the two pedocomplexes (TB I and TB II) (cf. Figure 3). The deposition thus took place during the Holocene. The underlying pedocomplex had a very long time for its development (i.e. from 123 ± 6 ka until the Holocene). The presence of several phases of sedimentation and soil formation (to constitute each paleosol in the pedocomplex) take a considerable time span, especially if one takes into account the weathering degree of each paleosol, which is higher than for the soils of the overlying sequence.

However, one has to consider that the migration of the river system might have caused erosion of parts of the Late Pleistocene sequence. Evidence of such erosional phases are as follows: None of the Gleysols have A horizons, and there are changes in the heavy mineral distribution, which clearly reflects discontinuities (Figure 5). Such discontinuities are obvious between 8G/7Bg; 7Bg/6G, and 6G/silty sediment (the latest is the most contrasting).

Solís-Castillo et al. (2013) have presented a chronological framework based on radiocarbon and archeological evidence for the younger paleosols (TB II). They presented an age of 2340–2300 cal B.P. for soil horizon 5Ass (Figure 3), and they found ceramic belonging to the Formative culture, which agrees with the dating result. The presence of Vertisols, which formed during the same period, has been documented in other areas of the Mayan Lowlands (Dahlin et al. 1980; Pope & Dahlin, 1989, 1993; Dunning & Beach, 2004; Beach et al. 2006; Dunning et al. 2006).

Horizon 3A was radiocarbon dated to 1140–970 cal. B.P (Solís-Castillo et al. 2013). The luminescence age of 2.1 ± 0.5 ka for horizon 3C fits well into this chronological framework, and can give some insights about the period of relative landscape stability. The age from the 3C horizon represents the time when the sediment was deposited, that is the maxi-

Tab. 2: Summary of the heavy mineral analysis results (in percentage).

Tab. 2: Zusammenfassung der Ergebnisse der Schwermineralanalyse (angegeben in Prozent)

Horizon	Volcanic		Plutonic-Metamorphic					ZTR (ultra stable)			Opaque Minerals	
	Brown amphibole	Pyroxene	Garnet	Green amphibole	Epidote group	Monazite	Kyanite	Zircon	Turmaline	Rutile	Weathered	Fresh
Tierra Blanca II												
C	8.95	17.02	2.28	11.05	8.07	0.00	0.00	2.28	0.00	1.05	25.26	0.00
2A	5.32	22.20	1.28	11.19	13.03	0.00	0.00	0.73	0.73	1.10	22.02	0.00
2AC	6.52	11.86	7.31	2.17	12.85	0.00	0.59	1.38	0.20	1.19	26.68	0.99
3A	0.00	0.00	0.25	0.75	1.01	0.00	0.00	0.25	0.00	0.00	4.52	5.03
3C	1.67	0.83	0.83	3.33	2.92	0.00	0.00	2.08	0.42	0.00	4.58	0.83
4Ck	1.42	3.30	6.60	5.19	10.85	0.00	0.47	2.36	0.94	0.00	33.02	3.30
5Ass	7.17	7.89	2.15	2.15	10.04	2.51	1.43	6.45	3.94	0.72	27.60	6.09
5Bss	6.31	4.32	1.99	1.33	20.60	1.99	1.99	3.99	1.66	1.33	24.25	6.31
5BC	6.20	5.43	4.65	1.94	17.83	1.94	0.00	3.49	1.16	1.16	29.07	4.26
5C	4.13	6.06	3.31	2.20	20.94	2.75	0.83	6.61	3.31	2.48	27.00	2.75
Tierra Blanca III												
TB3_0	11.01	12.50	0.89	7.74	20.83	1.79	1.19	2.68	2.38	1.19	24.40	1.49
TB3_1	1.74	6.67	2.32	2.32	7.83	0.58	0.00	1.16	0.00	0.29	19.13	7.83
TB3_2	2.54	0.00	1.69	4.24	5.93	0.00	0.00	1.69	0.00	0.00	50.00	16.10
TB3_3	0.78	7.03	1.56	4.69	14.06	0.78	0.00	2.34	0.00	0.00	30.47	17.19
TB3_4	0.00	0.00	0.81	2.42	3.23	0.00	0.00	0.81	0.00	0.00	14.52	16.13
TB3_5	6.78	3.39	3.39	13.56	11.86	0.00	0.00	8.47	1.69	0.00	18.64	3.39
TB3_6	7.69	3.85	8.97	19.23	15.38	0.00	0.00	1.28	0.00	0.00	23.08	2.56
TB3_7	1.82	1.82	5.45	12.73	18.18	0.00	0.00	3.64	3.64	0.00	14.55	1.82
TB3_8	1.75	1.75	0.00	3.51	21.05	0.00	0.00	0.00	0.00	0.00	59.65	7.02
TB3_9	0.00	0.00	3.09	0.00	6.79	0.00	0.00	0.00	0.00	0.00	61.11	27.16
TB3_10	3.55	8.28	2.37	18.93	14.20	1.79	0.00	1.78	2.37	0.00	37.87	4.14
Tierra Blanca I												
6G	2.49	7.21	2.62	0.98	22.62	0.00	0.00	2.30	1.49	0.50	25.87	0.50
7Bg	0.66	2.53	2.11	0.84	28.27	0.00	0.33	2.11	0.33	0.33	37.70	4.92
8G	0.84	2.70	1.96	0.25	26.72	0.98	0.00	2.45	0.00	0.42	38.40	9.28
8Gk	1.96	1.22	6.40	1.22	28.96	1.69	0.00	0.91	0.25	1.96	44.61	0.98
9G	0.00	5.38	6.01	0.95	20.89	1.72	0.00	5.70	0.30	1.22	36.89	10.37
9Bkg	1.90	0.70	6.32	1.75	23.51	0.61	2.85	5.26	0.32	1.58	25.63	13.29
9BCgk	1.05	7.21	2.62	0.98	22.62	0.95	0.35	2.30	0.00	1.05	32.28	4.56
Balancan												
A	1.55	0.00	0.00	7.75	1.55	0.78	0.00	24.42	0.39	7.36	44.96	3.88
Bg	0.62	0.00	0.00	0.62	2.80	0.93	0.62	20.81	0.00	8.39	25.16	30.12
G_1	0.76	0.38	0.00	1.14	2.28	1.14	1.14	19.77	0.00	3.42	46.77	10.27
G_2	1.06	0.53	0.00	3.19	2.66	1.06	0.53	17.02	1.60	6.38	48.40	6.38

mum age of the soil. In contrast, the date obtained from the bulk organic matter of 3A represents the minimum age of the paleosol, just prior to its burial. These ages show that the soil formed within 1000 years (the difference between the age of 3C and 3A horizons: beginning and end of pedogenesis).

5.2 Provenance and landscape evolution: Mineralogical evidences

Mineralogical assemblages are similar among all studied profiles (Figure 5). However, in the upper units, higher amounts of volcanic minerals can be detected. It is clear

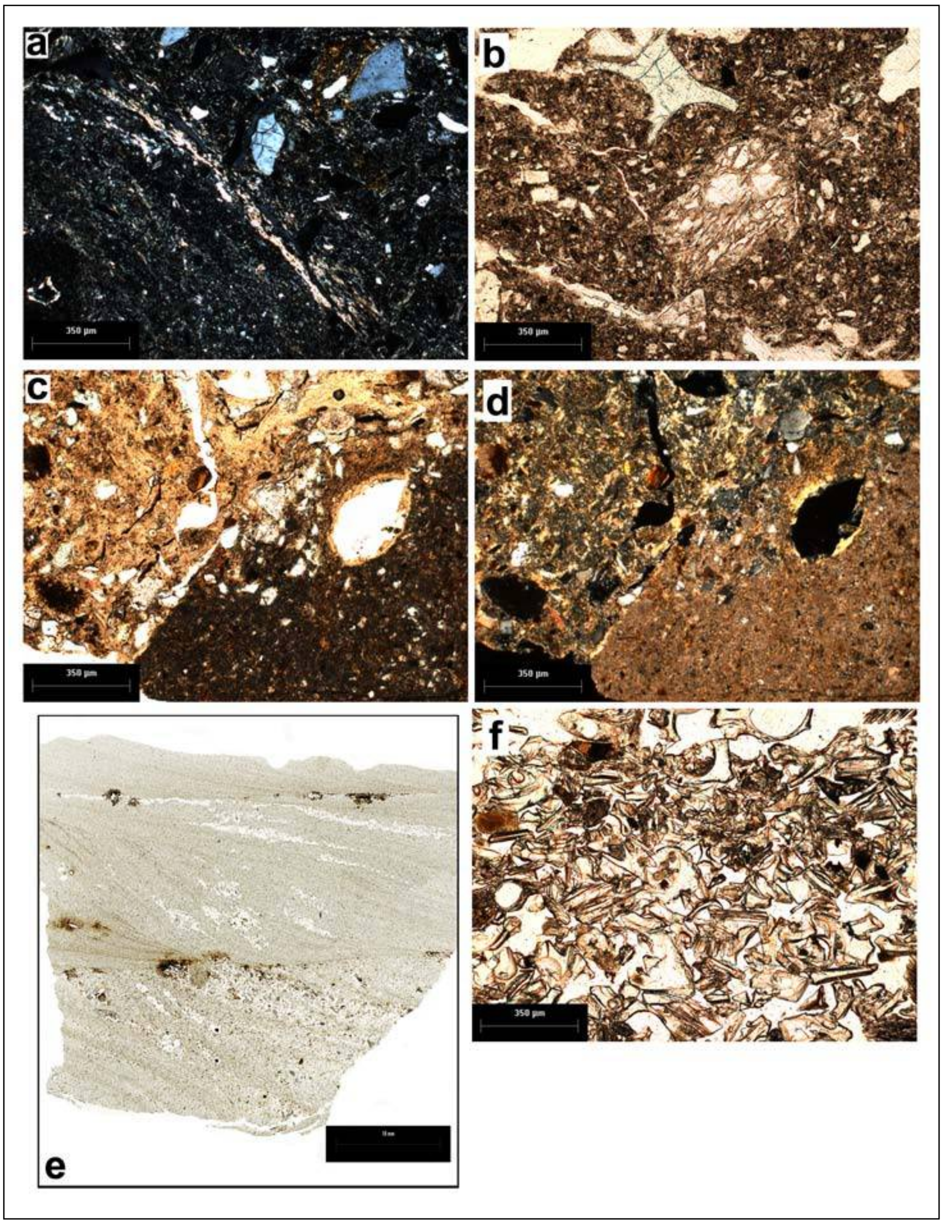


Fig. 7. Micromorphology of selected horizons: (a) porostriated b-fabric in horizon 3A TB I, cross polarized light (XPL); (b) weathered pumice in horizon 3A TB I, plane-polarized light (PPL); (c) Clay coatings and pedogenetic carbonates in 8Bkg horizons (PPL); (d) Clay coatings and pedogenetic carbonates in 8Bkg horizons (XPL); (e) silty sediment from TB III; (f) volcanic glass in the silty sediment of TB III (PPL).

Abb. 7: Mikromorphologie von ausgewählten Horizonten: (a) poro-streifiges b-Fabric aus Horizont 3A TBI, gekreuzt-ploarisiertes Licht (XPL); (b) verwitterter Bims aus Horizont 3A TB1, eben-polarisiertes Licht (PPL); (c)Toncutane und pedogenes Karbonat aus Horizont 8Bkg (PPL); (d) Toncutane und pedogenes Karbonat aus Horizont 8Bkg (XPL); (e) silitiges Sediment aus TB III; (f) vulkanisches Glas im siltigen Sediment aus TB III (PPL).

that the active volcanism in the Central America Volcanic Arc can provide such minerals to the alluvial plain of Tabasco (Figure 1). It is interesting to note that these minerals have angular and subangular shapes suggesting transport by slow river flow. It is likely that they originate from ash falls coming directly from the primary source.

One of the most intriguing materials is the silty sediment in the upper part of TB III (TB3_00). Its sand fraction contains a mixture of volcanic, metamorphic, and plutonic minerals, but in the thin sections, we clearly observe the dominance of laminated volcanic materials, particularly, volcanic glass (Figure 7). Based on the mineralogical data and an age of 9 ± 2 ka of the sediment, in which the minerals were found, we attempt to correlate the mineral assemblage to a possible eruption in the surrounding area. According to Arce (personal communication), it is likely that the Tacana volcano (Figure 1) provided the volcanic material found in the sediment. This volcano had large voluminous eruptions during the Late Pleistocene (Arce et al. 2012). This material can subsequently be reworked over short distances by the river. However, a detailed analysis is needed to draw any final conclusions on the provenance of this sample.

The heavy mineral associations (Figure 8) of the investigated sediments imply a broad range of metamorphic source rocks, suggesting the influence of different tectonic environments. Zircon-Turmaline-Rutile (ZTR) suit minerals (Hubert 1962) are common in acidic to intermediate granitoid rocks as well as in mature siliciclastic sediments and some metamorphic rocks (e.g. von Eynatten & Gaupp 1999). The highest concentrations of ZTR in the Balancán profile can be interpreted as originating from an ancient sedimentary recycling phase, where the dissolution and pedogenesis reduces the less stable minerals (Garzanti & Ando 2007). It is interesting to draw attention to the origin of the rutile phases: The majority of detrital rutile comes from medium to high grade metamorphic rocks (Force 1980; 1991) and recycled sediments. The same mineralogical evidence is found in the metamorphic complex of Southeast Guatemala (garnet, kyanite, rutile schists, and abundant ortho-gneisses, which range from mafic to granitic); this is where the Usumacinta River starts. In consequence, our data suggest that the river transported material from this region.

Additionally, the dominance of euhedral tourmaline indicates proximity to the source rocks and short transport from a predominantly low-grade metamorphic source (Singh et al. 2004). Chlorite and epidote were also derived from low-grade metamorphic series, whereas gneisses, granitoid rocks and recycled sedimentary rocks are possible sources of (ultra) stable minerals like zircon, tourmaline and rutile. Kyanite indicates the presence of high-pressure metamorphic rocks in the catchment; it has to be noted that it is not a dominant mineral in the assemblage. Solari et al. (2011) have documented areas in Central Guatemala with high-pressure metamorphic rocks. As this area is cut northwards by the Chixoy River until it joins with the Passion River (a tributary of the Usumacinta; Figure 1), it is very likely that this is the sediment source for the alluvial plain.

The presence of chromspinel and epidote group minerals are indicative for a source area with ophiolite complexes associated with suture zones. The most important suture zone near the study area is in Guatemala where the Usumacinta River springs (Figure1). At present, this suture zone is part of a major left lateral strike slip boundary between the North American plate to the north (locally known as the Maya block) and the Caribbean plate (locally the Chortís block) to the south (Brueckner et al. 2009).

The units in the Mayan block include the Chuacús metamorphic complex, recently shown to include eclogitic lenses that record a Late Cretaceous event (Ortega-Gutierrez et al. 2004; Martens et al. 2007, 2010), Paleozoic sedimentary rocks of the Santa Rosa Group, low-grade meta-sediments (white mica-chlorite schists, quartzite, and minor marble) associated with antigorite schist/mélange and deformed granites. The Chortís block contains the green schist facies, San Diego phyllite, the amphibolites facies Las Ovejas complex, and relatively undeformed granitoids. Numerous U-Pb zircon ages from granites and their host gneisses north of the fault resulted in Late Proterozoic (Grenville), Carboniferous, and Triassic ages as well as a metamorphic event at c. 70 Ma (Martens et al. 2007, 2010).

5.3 Implication for human land use

Our data can provide some insight into the land use of the region, especially with respect to fluctuations of human occupation and to the ceramic production. It is obvious that the presence of well-drained soils in Tierra Blanca (TB II) favored human occupation. These paleosurfaces were not inundated and represented stable areas for human activities, which were more or less continuous throughout the last 2–3 millennia. In contrast, other archeological sites such as Palenque, even though bigger in size, had less continuous occupation (for details see Liendo et al. 2013).

Further, is interesting to note that the suite of heavy minerals in paleosols and sediments found in Tierra Blanca has also been documented in petrographic studies about the pottery of the region (Obando et al. 2011). It can therefore be deduced that the material at Tierra Blanca is very suitable for the manufacturing of the pottery. The gleyic paleosols at the base provided clay for the clay matrix of the ceramic, while the volcanic glass found in the silty sediment (TB III) could be used as temper. Thus, this area has been of great importance to the humans at this time.

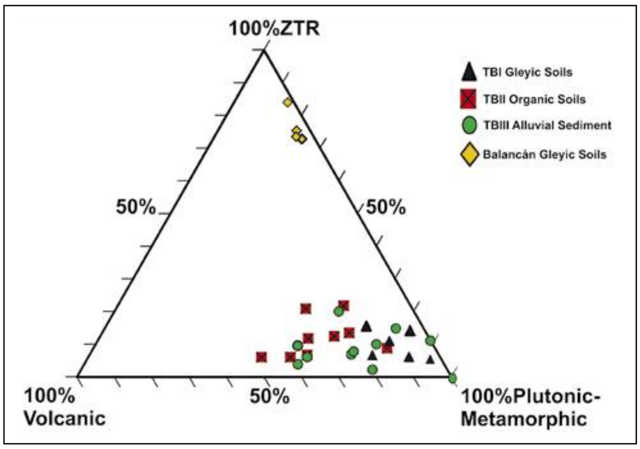


Fig. 8: Ternary diagram with the relative mineralogical suites of heavy minerals. ZTR = zircon + turmaline + rutile; Plutonic-Metamorphic = garnet + green amphibole + epidote group + monazite + kyanite; Volcanic = brown amphibole + pyroxene + olivine.

Abb. 8: Phasendiagramm für die mineralogischen Charakter der Schwerminerale. ZTR = Zirkon + Turmalin + Rutil; plutonisch-metamorph = Granat + grüner Amphibol + Epidotgruppe + Monazit + Kyanit; Vulkanisch = brauner Amphibol + Pyroxen + Olivin.

6 Conclusions

The alluvial terrace system of the Usumacinta River reflects the Late Quaternary pedostratigraphy of the region. On the alluvial Pleistocene terrace, soils with gleyic features are present. On the oldest Holocene terrace (HT2), we found the remnants of the gleyic paleosols in sediment dated to 123 ± 6 ka ($pIRIR_{290}$), while on the younger terraces (HT1, HT0) only less developed paleosols are present.

Metamorphic and plutonic terrains of the south of Mexico and Guatemala were identified as the main source of sediments for the Tierra Blanca area. However, the heavy mineral assemblages reflect some changes in provenance throughout time. Soils located on the older terraces, as in Balancán, show the presence of ultra-stable minerals; these reflect prolonged landscape stability and soil formation. In consequence, this mineralogical set can be used for pedostratigraphic correlation and tracing the oldest terraces in the area.
Larger amounts of volcanic minerals in the younger paleosols may allow for pointing out areas which were affected by eruptions. Further, the mineral compositions, if compared with those of ceramics might make it possible to trace the source regions for ceramic production.

Acknowledgement

This research has been funded by PAPIIT, (grants no. IN117709 and IN110710; E. Solleiro-Rebolledo), a bilateral project (no. CONACYT-DLR J010/0705/09 and CONACYT 166878; E. Solleiro-Rebolledo), and Coordinación de Estudios de Posgrado (UNAM). Funding from the Bundesministerium für Bildung und Forschung, Internationales Büro (German Ministery for Education and Research, International office) in form of the bilateral project MEX 08/002 is very much appreciated. We thank Christina Wiesbeck, Daniel Jäger, Jaime Díaz and Serafín Sánchez for assistance during field work.

References

Arce J.L. Macías J.L., Gardner J.E., Rangel E. (2012). Reconstruction of the Sibinal Pumice, an andesitic Plinian eruption at Tacaná Volcanic Complex, Mexico–Guatemala. Journal of Volcanology and Geothermal Research 217–218: 39–55.

Beach T., Luzzadder-Beach, S., Dunning, N. & Scarborough, V. (2003): Depression soils in the lowland tropics of northwestern Belize. In: Gomez-Pompa, A., Allen, M., Fedick, S.L., Jimenez-Osornio, J.J. (eds.): Lowland Maya Area: Three Millennia at the Human-Wildland Interface: 139–173; Binghamton, NY (Haworth Press).

Beach, T., Dunning, N., Luzzadder-Beach, S., Cook, D.E. & Lohse, J. (2006): Impacts of the ancient Maya on soils and soil erosion in the central Maya Lowlands. – Catena, 65: 166–178.

Brueckner, H.K. & Force, E.R. (1980): The provenance of rutile. – Journal of Sedimentary Petrology, 50: 485–488.

Brueckner, H.K., Avé Lallemant, H.G., Sisson, V.B., Harlow, G.E., Hemming, S.R., Artens, U., Tsujimori, T. & Sorensen, S.S. (2009): Metamorphic reworking of a high pressure–low temperature mélange along the Motagua fault, Guatemala: A record of Neocomian and Maastrichtian transpressional tectonics. – Earth and Planetary Sciences Letters, 284: 228–235.

Bullock, P., Fedoroff, N., Jongerius, A., Stoops, G., Tursina, T. & Babel, U. (1985): Handbook for Soil Thin Section Description. – 152 p.; Waine Research Publications, Wolverhampton, Ukraine.

Buylaert J.-P., Jain, M., Murray, A.S., Thomsen, K.J., Thiel, C. & Sohbati, R. (2012): A robust feldspar luminescence dating method for Middle and Late Pleistocene sediments. – Boreas, 41: 435–451.

Cabadas-Baez, H., Solleiro-Rebolledo, E., Sedov, S., Pi, T. & Gama-Castro J. (2010): Pedosediments of karstic sinkholes in the eolianites of NE Yucatán: a record of Late Quaternary soil development, geomorphic processes and landscape stability. – Geomorphology, 122: 323–337.

Consejo de Recursos Minerales (1999): Monografía Geológico Minera del Estado de Tabasco. – 152 p.; Conabio, Mexico.

Cunningham, A.C. & Wallinga, J. (2010): Selection of integration time intervals for quartz OSL decay curves. – Quaternary Geochronology, 5: 657–666.

Dahlin, B.H., Chambers, M.E. & Foss, J.E. (1980): Project Acalches: Reconstructing the Natural and Cultural History of a Seasonal Swamp at El Mirador Guatemala; Preliminary Results. In: Matheny R. (ed.): El Mirador, Peten, Guatemala: An Interim Report. Publication 45. New World Archaeological Foundation; Provo, Utah.

Donnelly, T.W., Horne, G.S., Finch, R.C. & Lopez, R.E. (1990): Northern Central America: The Maya and Chortis blocks. In: DENGO, G., CASE, J.E. (eds.): The Geology of North America, Vol. H: The Caribbean Region: 37–76; Geological Society of America.

Dunning, N.P. & Beach, T. (2004): Fruit of the Lu'um: Lowland Maya Soil Knowledge and Agricultural Practices. – Mono y Conejo, 2: 1–25.

Dunning N.P., Luzzadder-Beach, S.L., Beach, T., Jones, J.G., Scarborough, V. & Culbert, T.P. (2002): Arising from the Bajos: The Evolution of a Neotropical Landscape and the Rise of Maya Civilization. – Annals of the Association of American Geographers, 92: 267–283.

Dunning N., Beach, T. & Luzzadder-Beach, S. (2006): Environmental variability among bajos in the southern Maya Lowlands and its implications for ancient Maya civilization and archaeology. In: LUCERO, L., FASH, B. (eds.): Pre-Columbian Water Management: 111–133; University of Arizona Press.

Einsele, G. (1992): Sedimentary Basins. – 648 p; Springer (Berlin).

Fedick, S.L., Flores-Delgadillo, M.L., Sedov, S., Solleiro-Rebolledo, E. & Palacios-Mayorga, S. (2008): Adaptation of Maya Homegardens by Container Gardening in Limestone Bedrock Cavities. – Journal of Ethnobiology, 28: 305–317.

Fernandez F., Johnson, K., Terry, R., Nelson, S. & Webster, D. (2005): Soil resources of the Ancient Maya at Piedras Negras, Guatemala. – Soil Science Society of America Journal, 69: 2020–2032.

Force, E.R. (1980): The provenance of rutile. – Journal of Sedimentary Petrology, 50: 485–488.

Force, E.R. (1991): Geology of titanium-mineral deposits. – Geological Society of America Special Paper, 259: 112.

Garzanti, E. & Ando, S. (2007): Heavy mineral concentration in modern sands: implications for provenance interpretation. In: Mange, M.A. & Wright, D.T. (eds.): Heavy Minerals in Use: Developments in Sedimentology, 58: 517–545.

Guérin, G., Mercier, N. & Adamiec, G. (2011): Dose-rate conversion factors: update. – Ancient TL, 29: 5–8.

Hernandez Santana, J.R., Mendez Linares, A.P. & Bollo Manent, M. (2012): Análisis morfoestructural del relieve noroccidental del Estado de Chiapas, México. – Revista Geográfica Venezolana, 53: 57–75.

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

Hodell D.A., Anselmetti, F.S. & Ariztegui, D. (2008): An 85 ka record of climate change in lowland Central America. – Quaternary Science Reviews, 27:1152–1165.

Hubert, J.F. (1962): A zircon–tourmaline–rutile maturity index and the interdependence of the composition of heavy mineral assemblages with the gross composition and texture of sandstones. – Journal of Sedimentary Petrology, 32: 440–450.

Hughes, P.H. (2010): Geomorphology and Quaternary stratigraphy. The roles of morpho-, litho-, and allostratigraphy. – Geomorphology, 123: 189–199.

Komar, P.D. (2007): The entrainment, transport and sorting of heavy minerals by waves and currents. In: Mange, M.A. & Wright, D.T. (eds). Heavy Minerals in use. – Developments in Sedimentology, 58: 3–48.

Konta, J. (1988): Minerals in Rivers. In: Mitteilungen des Geologischen-Paläontologischen Instituts Universität Hamburg, SCOPE/UNEP, 66: 341–365.

Kraus, M.J. (2002): Basin-scale changes in floodplain paleosols: implications for interpreting alluvial architecture. – Journal of Sedimentary Research, 72: 500–509.

Martens, U., Mattinson, C.G., Wooden, J. & Liou, J.G. (2007): Protolith and metamorphic ages of gneiss hosting eclogite in the Chuacús complex, Central Guatemala. – American Geophysical Union (AGU), EOS Transactions, 88(23), Joint Assembly Supplement, Abstract: U53A-08.

Martens, U., Weber, B. & Valencia, V.A. (2010): U/Pb geochronology of Devonian and older Paleozoic beds in the southwestern Maya Block, Central America: its affinity with Peri-Gondwanan terranes. – Geological Society of America Bulletin, 122: 815–829.

Mikesel, L.R., Schaetzl, R. & Velbel, M.A. (2004): Hornblende etching and quartz/feldspar ratios as weathering and soil development indicators in some Michigan soils. – Quaternary Research, 62: 162–171.

Murray, A.S. & Wintle, A.G. (2000): Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. – Radiation Measurements, 32: 57–73.

Ortega-Gutiérrez, F., Solari, L.A., Ortega-Obregón, C., Elías-Herrera, M., Morán-Ical, S., Chiquín, M., Keppie, J.D., Torres de León, R. & Schaaf, P. (2007): The Maya-Chortís boundary: a tectonostratigraphic approach. – International Geology Review, 449: 996–1024.

Ortiz Perez, M.A., Siebe, C. & Cram, S. (2005): Diferenciación ecogeográfica de Tabasco. In: Bueno, J., Álvarez, F. & Santiago, S. (eds.): Biodiversidad del Estado de Tabasco: 305–322; Instituto de Biología, UNAM- CONABIO (Mexico).

Padilla, R. & Sanchez, R.J. (2007): Evolución geológica del sureste mexicano desde el Mesozoico al presente en el contexto regional del Golfo de México. – Boletín de la Sociedad Geológica Mexicana, LIX: 19–42.

Pirkle, F.L., Pirkle, W.A. & Pirkle, E.C. (2007): Heavy Minerals Sands of the Atlantic and Gulf Coastal Plains, USA. In: Mange, M.A. & Wright, D.T. (eds): Heavy Minerals in use. – Developments in Sedimentology, 58: 1145–1234.

Pope, K.D. & Dahlin, B.H. (1989): Ancient Maya Wetland Agriculture. New Insights from Ecological and Remote Sensing. – Journal of Field Archaeology, 16: 87–106.

Prescott, J.R. & Hutton, J.T. (1994): Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long-term variations. – Radiation Measurements, 23: 497–500.

Retallack, G.J. (1990): Soils of the past. An introduction to paleopedology. – 404 p.; Blackwell Science (U. K.).

Rosenmeier, M.F., Hodell, D.A., Brenner, M. & Curtis, J.H. (2002): A 4000-Year Lacustrine Record of Environmental Change in the Southern Maya Lowlands, Petén, Guatemala. – Quaternary Research, 57: 183–190.

Sedov S., Solleiro-Rebolledo, E., Fedick, S.L., Gama-Castro, J., Palacios-Mayorga, S. & Vallejo Gomez, E. (2007): Soil genesis in relation to landscape evolution and ancient sustainable land use in the northeastern Yucatan Peninsula, Mexico. – Atti della Società Toscana de Scienze Naturali di Pisa, Serie A, 112: 115–126.

Schatzl, R. & Anderson, S. (2005): Soils: Genesis and Geomorphology. –791 p; New York.

Singh, B.P., Pawar, J.S. & Karlupia, S.K. (2004): Dense mineral data from the northwest Himalayan foreland sedimentary rocks and recent river

sediments: evaluation of the hinterland. – Journal of Asian Earth Sciences, 23: 25–35.
Solís-Castillo, B., Solleiro-Rebolledo, E., Sedov, S., Liendo, R., Ortiz-Pérez, M.A., López-Rivera, S. (2013): Paleoenvironment and human occupation in the Maya lowlands of the Usumacinta River, Mexico. – Geoarchaeology, 28: 268–288.
Solleiro-Rebolledo, E., Sycheva, S., Sedov, S., McClung de Tapia, E., Rivera-Uria, Y., Salcido-Berkovich, C., Kuznetsova, A., 2011. Fluvial processes and paleopedogenesis in the Teotihuacan Valley, México: Responses to late Quaternary environmental changes. Quaternary International, 233: 40–52.
Thiel, C., Buylaert, J.-P., Murray, A., Terhorst, B., Hofer, I., Tsukamoto, S. & Frechen, M. (2011): Luminescence dating of the Stratzing loess profile (Austria) - Testing the potential of an elevated temperature post-IR IRSL protocol. – Quaternary International, 234: 23–31.
Von Eynatten, H. & Gaupp, R. (1999): Provenance of Cretaceous synorogenic sandstones in the Eastern Alps: constraints from framework petrography, heavy mineral analysis and mineral chemistry. – Sedimentary Geology, 124: 81–111.
West R.C., Psuty, N.P. & Thom, B.G. (1969): The Tabasco lowlands of Southern Mexico. – 88 p.; Louisiana State University Press.
WRB, World Reference Base for soil resources (2006): A framework for international classification, correlation and communication: World Soil Resources Reports 103, Food and Agricultural Organization of the United Nations, Rome.

3.3 Paleoenvironment and Human Occupation in the Maya Lowlands of the Usumacinta River, Southern Mexico

Berenice Solís-Castillo,[1,*] Elizabeth Solleiro-Rebolledo,[2] Sergey Sedov,[2] Rodrigo Liendo,[3] Mario Ortiz-Pérez,[4] and Sara López-Rivera[5]

[1]Posgrado en Ciencias de la Tierra. Instituto de Geología, UNAM, México, D.F.
[2]Instituto de Geología, UNAM, México, D.F.
[3]Instituto de Investigaciones Antropológicas, UNAM, México, D.F.
[4]Instituto de Geografía, UNAM, México, D.F.
[5]Facultad de Ciencias, UNAM, México, D.F.

Correspondence
*Corresponding author;
E-mail: bsolisc.geologia@gmail.com

Received
20 March 2012
Accepted
13 December 2012

Scientific editing by Calla McNamee and Howard Cyr

Published online in Wiley Online Library (wileyonlinelibrary.com).

doi 10.1002/gea.21438

Paleosol sequences along the lowest terraces of the Usumacinta River in southern Mexico were used to reconstruct Holocene environmental changes and examine human–environmental interactions. Study sections were correlated through paleosol morphology, radiocarbon dating, and artifact seriation of Formative, Classic, and Postclassic ceramics. The oldest paleosols have gleyic features. Although they contain hard carbonate concretions dating to 5450–5380 cal. yr B.P., these Gleysols formed in the Late Pleistocene to Early Holocene. Carbonates were deposited later. The uppermost paleosols lack gleyic features, the oldest of which contains vertic features, dating to 2000–2700 cal. yr B.P., and contains abundant Formative period ceramics. The upper two paleosols are morphologically less developed and are strongly affected by human activities; radiocarbon ages and ceramic assemblages indicate that they belong to the Maya Classic and Postclassic periods. Stable carbon isotope values from the decalcified organic matter vary among paleosols of different ages and sites. $\delta^{13}C$ values are highest (−16 to −20‰) in the Formative period paleosol. Although it is possible that maize cultivation could contribute to the isotopic signatures, we believe that the $\delta^{13}C$ values indicate the dominance of drought-resistant C4 and CAM vegetation due to their association with vertic soils. The Classic period paleosol has a slightly lower isotopic value (−20 to −22‰), while the Postclassic paleosol shows the lowest values (−22 to −23‰), suggesting reforestation of the floodplain. These results indicate that the Early Holocene paleosols formed in a humid climate similar to that of today, which transitions toward dryer conditions around 5500 cal. yr B.P. In the Late Holocene (approximately 3000 B.P.) an increase in seasonality occurs. This condition favored the formation of Vertisols, suitable for agriculture.

INTRODUCTION

Landscape evolution is driven by environmental changes both natural and human induced. In particular, land-cover transformations due to long-term human–environment interactions can provide insight into the causes of the rise and decline of ancient civilizations (Dunning et al., 2002), even while the role of climate change is still poorly understood. The integration of information from several sources is required to understand the interaction of coupled human–environment systems (Klepeis & Turner, 2001).

The Maya Lowlands have been studied by several scholars, who have used different proxies to approach the identification of land-use changes, particularly as a product of agricultural practices that include forest clearance, cultivation, terracing, and so forth (e.g., Turner, 1974; Fedick, 1996; Beach et al., 2002, 2009; Dunning et al., 2002; Fernández et al., 2005; Anselmetti et al., 2007; Johnson et al., 2007a; Johnson, Wright, & Terry, 2007b). Most published studies concentrated on sites in Guatemala and Belize (Dahlin, Chambers, & Foss, 1980; Dunning et al., 2002; Beach et al., 2003; Fernández et al., 2005; Dunning, Beach, & Luzzadder-Beach, 2006), and in the northern Yucatan Peninsula (Fedick, 1996; Beach, 1998; Gomez-Pompa et al., 2003; Johnson et al., 2007a; Johnson, Wright, & Terry, 2007b; Fedick et al., 2008).

The Maya Lowlands along the Mexican Gulf Coast are less studied despite the key role this region played in the development of the ancient cultures of Mesoamerica, as well as in the initial peopling of the Americas. Furthermore, the area is now considered a possible region associated with the initial development of agriculture and the domestication of maize (Pope et al., 2001). According to Pope et al. (2001), maize pollen associated with the deltaic landscapes of the Grijalva River and dating to 6200 ^{14}C yr BP. document early agriculture in the area.

Our study presents the results of a paleopedological survey of soils developed in alluvial sediments within Holocene terraces along the Usumacinta River within the Northwest Maya Lowlands. The Northwest Maya Lowlands lie between the coastline of the Gulf of Mexico to the north and the Sierra de Chiapas to the south, and the Candelaria and Grijalva Rivers to the east and west, respectively (Figure 1). Although these spatial and cultural delimitations have been considered homogeneous (Culbert & Rice, 1990), there is much cultural diversity spatially and temporally throughout the region.

This study investigates Holocene environmental change in the region, as well as the potential use of ancient soil resources and the impact of human populations on the landscape. The research is guided by the concept of "soil memory" (Targulian & Goryachkin, 2004), which integrates information from selected soil features that are stable and do not change markedly following burial. Soil morphology (both macro and micro) and grain-size distribution are used as indicators of soil development; total organic carbon and stable carbon isotope signatures are employed proxies of paleovegetation; carbonate content is used to estimate environmental humidity; and magnetic susceptibility is used as an indicator of stratigraphic discontinuities.

Theoretically, the paleosols represent periods of landscape stability, during which pedogenesis alters the alluvial sediments, while the accumulation of alluvium records periods when the alluvial system is more active and soil formation is largely precluded. We concentrate our paleoenvironmental interpretation on the nature and characteristics of the paleosols with a lesser emphasis on the intervening alluvial sediments. These paleosols cover the Holocene and their properties reflect environmental change in the area, as well as the effects of human disturbance (they contain artifacts and burials).

STUDY AREA

The Usumacinta River is located in the southeastern part of Mexico and is one of the largest fluvial systems in the country with a drainage area of 63,804 km^2 (Figure 1) (West, Psuty, & Thom, 1969). Modern climate is warm and humid with an annual precipitation ranging from 1800 mm in the alluvial plain to 2000 mm near the headwaters. Approximately 67% of precipitation occurs in summer. Mean annual temperature is 27°C, with temperatures reaching 30°C during the hottest month (García, 1988). Vegetation is evergreen tropical rainforest. In the floodplain areas, which are inundated for long periods, there are mainly grasses and aquatic species such as *Bactris* and *Ponderia* (Bueno, ALvarez, & Santiago, 2005; Rzedowski, 2006).

Beginning in Guatemala, the Usumacinta River runs northeast to the Bay of Campeche in the Gulf of Mexico (Figure 1). The Usumacinta River crosses through the Sierra de Chiapas, a mountain range formed mostly of folded Tertiary age limestone, with their folding axis oriented northwest-southeast. The limestone bedrock hosts an extensive karst system that includes abundant subterranean drainages and ephemeral surface streams. To the north, the river flows through the State of Tabasco in an alluvial valley that contains Plio-Pleistocene terraces. The terraces have been strongly affected by Neogene tectonic activity that formed a set of normal faults and the development of a horst-graben system (Padilla & Sánchez, 2007). The river has several distributaries named the San Pedro in the eastern part, Chacamax in the center, and Tulijá in the west that follow fault lines (Figure 1).

The system of alluvial terraces covers a timespan from Plio-Pleistocene to Holocene (Ortiz-Perez, Siebe, & Cram, 2005). The oldest terraces are located in the areas more distant from the sea. They consist of large surfaces, slightly inclined toward the sea, dissected by the river that eroded deep V-shaped valleys (West, Psuty, & Thom, 1969). Big urban centers as Palenque, Chinikihá, Pomoná, and Santa Helena (Figure 1) developed on the Pleistocene terraces in the middle Usumacinta. In contrast, Holocene terraces are formed by cut and fill floodplain deposits along the main channel. The channel apparently experienced lateral channel migration rates that varied with environmental changes. Three levels of Holocene terraces (Figure 2) are recognized and labeled from oldest to youngest HT2 (at 15–10 m), HT1 (at 10–5 m), and HT0 (at <5 m).

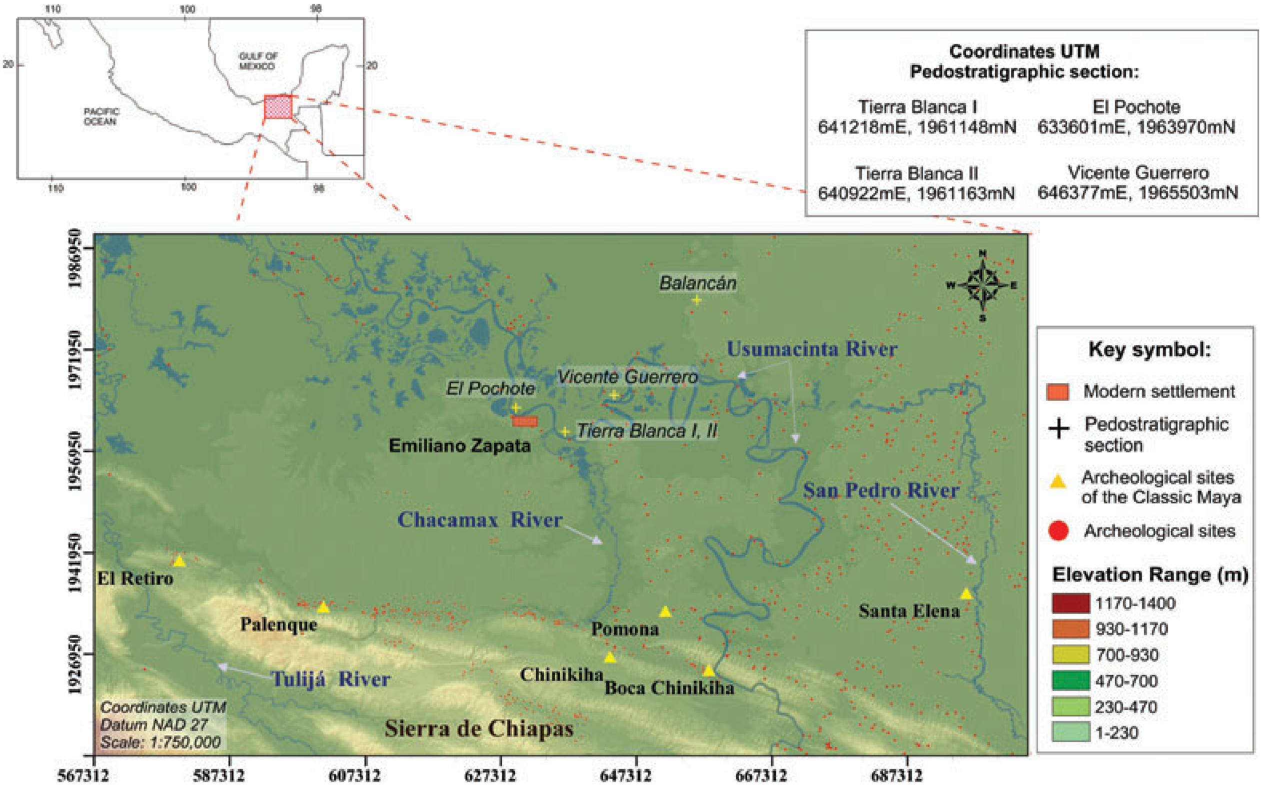


Figure 1 Location of Usumacinta River in the Maya Lowlands and riverbank study sections. Circles represent known archaeological sites; triangles are settlements that increased in size during the Classic period.

Most paleoenvironmental archives used for tracing the environmental history of the Northwest Maya Lowlands are based on lacustrine sediments that originate in neighboring regions such as Lake Petén Itzá, Guatemala (Rosenmeier et al., 2002; Mueller et al., 2009); Lake Amatitlán, highlands of Guatemala (Velez et al., 2011); Lake Chinchancanab, Yucatán (Hodell, Brenner, & Curtis, 2005); Lake Punta Laguna, Quintana Roo (Hodell, Brenner, & Curtis, 2007); Los Tuxtlas, Veracruz (Lozano-García et al., 2007). Other archives include speleothems (Webster et al., 2007) and paleosols, which are mainly concentrated in Belize (Beach et al., 2008, 2009, 2011) and Yucatán (Sedov et al., 2007; Fedick et al., 2008; Cabadas et al., 2010). However, the high spatial variation of Mesoamerican ecosystems limits the reliability of the reconstructions over a broad area. Consequently, the search for local paleoenvironmental proxies is of primary importance.

Paleoenvironmental records indicate that Late Pleistocene climates in southeastern Mexico were quite variable. Sedimentological records from lacustrine basins such as lake Peten-Itza in Guatemala document high climate variability during the last 85,000 years (Hodell, Anselmetti, & Ariztegui, 2008; Correa-Metrio et al., 2012), including variability in precipitation during the Holocene, (Brenner et al., 2002; Hodell, Brenner, & Curtis, 2005).

The reconstruction of Late Holocene paleoenvironmental changes has been mainly based on lacustrine sequences (e.g., Rosenmeier et al., 2002; Hodell, Brenner, & Curtis, 2005; Lozano-García et al., 2007; Velez et al., 2011) and to a lesser extent on paleopedological records in the Maya Lowlands of Belize and Guatemala (Beach et al., 2008, 2009, 2011), and the Yucatan Peninsula (Sedov et al., 2007; Fedick et al., 2008; Cabadas et al., 2010). Available information suggests that humid conditions prevailing in the mid-Holocene changed to a progressively drying trend that began about 4000 years ago (Mueller et al., 2009), with droughts that affected Maya populations (Hodell, Curtis, & Brenner, 1995; Gill, 2000; Haug et al., 2003; Hodell, Brenner, & Curtis, 2005). A general pattern of increasing aridity has been recognized in some studies to have begun about 3000 years ago (Brenner et al., 2002); however other studies indicate that particularly severe pulses of aridity occurred during the ends of the Late Pre-Classic and Classic periods

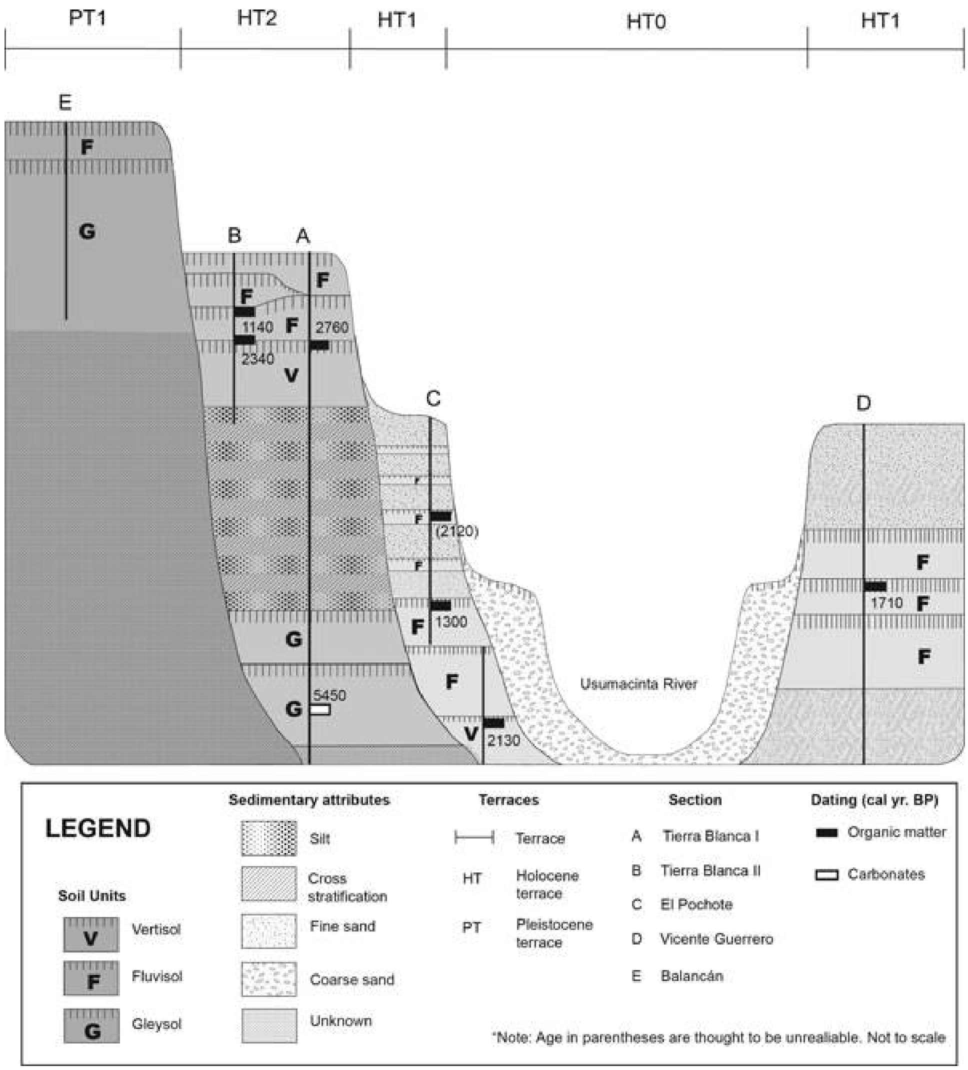


Figure 2 Schematic cross section of the paleosol-sedimentary sequences at the Usumacinta riverbank, showing different alluvial terraces and the location of every study section. Not to scale.

(Gunn, Folan, & Robichaux, 1995; Hodell et al., 2001; Velez et al., 2011). This interpretation is in a good agreement with the stalagmite studies in the Macal Chasm caves in Belize (Webster et al., 2007), as well as the sedimentary record of the Ix Chel cave in Belize, which suggest two drought events occurred in the same periods (Polk, van Beynen, & Reeder, 2007).

According to Dunning and Beach (2010), paleoenvironmental information records intense drought in the Maya Lowlands during the 4th century B.C., and the 2nd, 6th, 9th, and 11th centuries A.D., as well as during the Little Ice Age. Hurricanes have also a large influence on the climate of the area, causing disasters and migrations. However, humans in ancient Mesoamerica adapted to environmental changes and ultimately transformed the forest to cultivated fields and grassland over several periods of retreat and expansion (Brenner, Leyden, & Binford, 1990).

CULTURAL HISTORY OF THE NORTHERN MAYA LOWLANDS

The rich alluvial banks of the Usumacinta River contain many of the earliest sites reported for the Northwestern Lowlands. Several factors may account for the high frequency of pre-Hispanic sites close to the Usumacinta River and its tributaries, the Rio San Pedro, and Chacamax. These include the existence of rich alluvial soils, the lack of evidence for destructive floods on natural banks, and the rich variety of water resources available to pre-Hispanic inhabitants of the region.

In the Lower Usumacinta, the Middle Formative (800–300 B.C.) generally seems to have been a remarkable period of population growth. Research has detected a significant occupation in Trinidad and Tierra Blanca, Tabasco, during the Middle Formative period (Rands, 1977). Major sites at Tierra Blanca, Balancan, and Zapata (Figure 1) are located on the rich alluvial banks of the Usumacinta River. In this vast natural terrace, Povictuc, La Carmelita, and Tierra Blanca appear to have functioned as important centers, as indicated by a series of small mounds located on both banks of the Usumacinta (Ochoa-Salas, 1978).

This scenario differs radically from the Sierra de Chiapas region (Figure 1) where no Formative settlements have been found so far. Recently, our own surveys have identified about 32 sites with abundant evidence of ceramics belonging to the Late Formative (300 B.C.–A.D. 150) Chicanel period along the foothills of the Sierra de Chiapas and along the Chacamax River. If we compare the abundance of early ceramic contexts in Balancan-Zapata with the few contexts in the Sierra, we might argue for marginal demographic development at a regional scale for the Formative period. It is highly probable that during the Early and Middle Formative periods, the Sierra region remained sparsely populated and visited sporadically by groups of individuals with permanent residency in the northern plains.

The next period is known as Early Classic in the archaeological literature (A.D. 150–550). For the first time, the archaeological record for the region shows a clear population concentration within a small number of centers along the foothills of the Sierra de Chiapas and intermountain valleys: Chinikiha, Palenque, Santa Isabel, La Cascada, San Juan Chancalaíto, La Reforma, El Retiro, Nututun, Sulusum, and Miraflores, are examples of settlements from this period (Liendo 2011). Along the Usumacinta and San Pedro rivers, there are several important sites with evidence of occupation for this period, including Pomona, Morales-Reforma, San Claudio, and Santa Elena. The Usumacinta River and the Rio San Pedro seem to have exerted a strong force of attraction to people seeking appropriate communication routes. In general terms, the Early Classic period represents a time of significant population growth along the Usumacinta River and the Sierra region. It also represents the time of emergence of important local dynasties like Palenque, Piedras Negras, Yaxchilan, Pomona, Reforma, and Chinikiha, all sites with great influence in later times.

In the Late Classic (A.D. 550–850), there is a clearly distinguishable change in the correlation between the populations living within larger settlements and overall population in the region. The archaeological surveys conducted in the region show patterns of population concentrations within a small number of sites, leaving vast areas empty of settlements (Figure 1). Although some researchers (Rands, 1987; Bishop, 1992 suggest that this represents a marked increase in population during the Late Classic, Liendo (2002) considers this phenomenon to indicate a concentration of populations within major sites. The settlement pattern during the last 100 years of regional development (A.D. 750/850) indicates a new trend toward the abandonment of nucleated settlements, which created a more dispersed pattern than evidenced in the Early Classic. This phenomenon is more clearly expressed in the Palenque and remains to be demonstrated elsewhere in the Northwest lowlands.

The following Terminal Classic period is characterized by the introduction of a fine paste ceramic tradition, characterized primarily by orange ceramic groups related to the Altar, Balancan, and Silho ceramic types (Rands, 1977). This ceramic phase is underrepresented in the Sierra region, with only a few sherds found at Palenque, Miraflores, and Pomona and none found at Chinikiha. It is evident that the Terminal Classic was a period of substantial decrease in population levels throughout the Northwest Maya Lowlands. Although sites located near the Usumacinta River, specifically Balancan, Calatrava, and Trinidad, appear to have thrived into Postclassic times, the Terminal Classic seems to represent the end of sites such as Palenque, Piedras Negras, Yaxchilan, Pomona, Morales-Reforma, and Chinikiha as centers of political importance in the region.

MATERIALS AND METHODS

Detailed studies of Holocene pedostratigraphy were conducted along the Usumacinta River, near the town of Emiliano Zapata. Four sections were described and sampled (Figures 1 and 2). Two are from the oldest Holocene terrace, HT2: Tierra Blanca I (TBI) and Tierra Blanca II (TBII); and two from the middle terrace, HT1: El Pochote (POCH) and Vicente Guerrero (VG). Sections from the modern floodplain terrace, HT0, were not sampled due to the apparent high rates of recent sedimentation, which has resulted in a lack of buried soils within the alluvium. Soils were described following the International Union of Soil Sciences (IUSS Working Group WRB, 2006) and Retallack (1990). The field description of the morphological characteristics of each profile was made based on the identification of paleosols and their diagnostic horizons.

Laboratory analysis was limited to properties associated with the soil memory concept that could provide data for paleoenvironmental reconstructions. These included grain-size distribution, pH, total organic carbon,

carbon stable isotope signature, carbonate content, and magnetic susceptibility. Grain-size distribution was evaluated in order to verify differences in soil processes and detect discontinuities. The sand fraction (2–0.063 mm) was separated by sieving; silt (0.063–0.002 mm) and clay (<0.002 mm) fractions by gravity sedimentation and pipette sampling. Pretreatments for destruction of aggregating agents include 15% H_2O_2 for soil organic matter (SOM), dithionite-citrate-bicarbonate for iron oxides, and 10% HCl for carbonates. pH was measured in H_2O in a 1:2 soil paste (USDA 2009). Total organic carbon (TOC) was determined only in A horizons, using a CHNS/O analyzer, PerkinElmer 2400, Series II. Prior to TOC analysis, inorganic carbonates were removed using 10% HCl.

For stable isotope composition ($\delta^{13}C$), samples from SOM of the A horizons were acidified with 1M HCl at 70°C to remove carbonates that would interfere with analysis (Midwood & Boutton, 1998). The $^{13}C/^{12}C$ ratio was then determined in the Laboratory of Mass Spectrometry of Stable Isotopes of Instituto de Geología, Universidad Nacional Autónoma de México (UNAM), by using a combustion method slightly modified from that described by Sofer (1980). The modification consists in the addition of metallic copper Cu° to eliminate NO_2 (Mook & Jongsma, 1987). All the analyses of the $^{13}C/^{12}C$ ratios are reported as $\delta^{13}C$ in ‰ relative to the international PDB standard (CO_2 from carbonate shell of a Cretaceous mollusk, Beleminitella Americana, from the Pee Dee Formation in South Carolina) (Craig, 1953). $^{13}C/^{12}C$ ratios from pedogenic carbonates were obtained from the accelerator mass spectrometry (AMS) radiocarbon analysis conducted by Beta Analytic.

The carbonate content was determined by weight loss after dissolution with HCl. Samples were dried at 105°C for 72 hours, weighed, and acidified with 25 mL of 0.5 M HCl to destroy carbonates. The samples were then washed with distillated water, dried at 105°C for 48 hours, and weighed. Percentage carbonate content was calculated by the difference between the initial weight prior destruction and weight after carbonates elimination.

Mass-specific low-field magnetic susceptibility (χ) was measured in all paleosol horizons. Rock magnetism parameters have proven useful to differentiate soil horizons and detect sediment layers (Rivas et al., 2006). Samples were homogenized, and placed in 8 cm^3 acrylic boxes for magnetic measurements at low (0.47 kHz) frequency with a Bartington MS2B dual sensor. The obtained χ was plotted in SI (a dimensionless system).

Pedostratigraphy was established using three approaches: radiocarbon dating, archaeological and cultural evidences (presence of ceramics or other kind of artifacts), and soil morphology. Radiocarbon ages were obtained from bulk SOM of selected A horizons by Beta Analytic Laboratory (Miami, Florida USA). The dates are reported in calibrated ages according to data sent by the laboratory. Note that radiocarbon ages of SOM in A horizons represent the minimum age of the soil, essentially marking the end of soil development at the time of burial.

RESULTS

Morphology, Physical, and Chemical Properties

Tierra Blanca I and II (TBI, TBII)

The Tierra Blanca I profile represents the most complete stratigraphic section of the HT2 terrace (Figures 2 and 3). The section contains two distinct types of paleosol development clearly separated by alluvial sediments. Overlying sandy Pleistocene-age alluvium, the lower part contains four paleosols (numbered 4, 5, 6, 7) that formed during the pre-occupation period. We have recognized the following horizons: 4G, 5Bg, 6G, 6Gk, 7G, 7Bkg, and 7BCgk, with a total thickness of 363 cm (Figures 3A and 4). None of these paleosols contain A horizons, which we interpret as the result of erosional processes stripping the surface soil as the next depositional phase was beginning. There are not C horizons separating every paleosol, but differences in soil morphology (Table I) helped identify the discontinuities (Figure 3A). Consequently, the complete sequence contains multiple stacked paleosols that constitute a pedocomplex. Paleosol 7, at the base, shows the most complete profile with parent material still recognizable (alluvial sediment). One of the most remarkable features in this profile is the presence of hard, carbonate concretions, around 5–10 cm in diameter. These concretions are resistant to erosion and represent a hard surface easily identified along the river margin. All horizons exhibit strong gleyic features expressed as grayish-brown colors with reddish-yellowish-greenish mottles (Table I), coarse subangular blocky structure, and Fe concretions and/or spots and dendritic Mn. The strongest gleyic features are observed in paleosol 6 where slickensides are also present.

At the contact with 4G, the overlying paleosol, paleosol 3, contains multiple horizons, labeled 3A, 3AB, 3BC, 3C horizons. The 3C horizon is laminated (Figure 3B) and silt rich but also contains a high proportion of clay (Figure 4). The middle part of the 3C horizon combines lamination with crossed stratification. Its upper part is also laminated, although there are vertical cracks 40 cm deep across the sediment layer. The material of all laminated strata reacts intensively with HCl. The uppermost paleosol, paleosol 2, consists of horizons 2A, 2AB, 2C (Figures 3C and 4; Table I). There is a strong contrast between the morphology of paleosols 2 and 3 and that

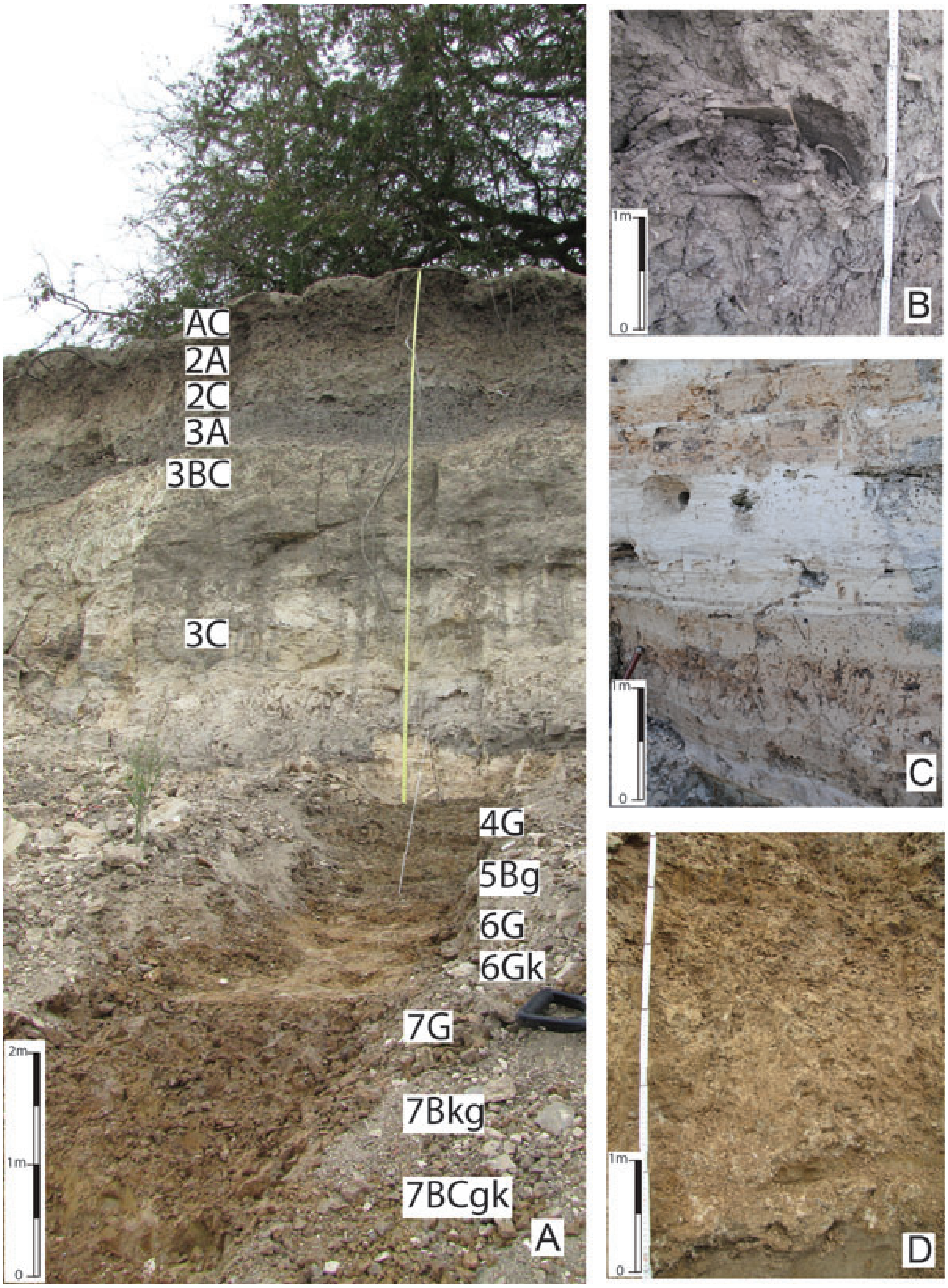


Figure 3 (A) Tierra Blanca I profile, Usumacinta River, Holocene Terrace 2 (HT2); (B) Late Holocene paleosols with humic horizons and cultural artifacts; (C) Silty sediments with cross lamination located mid-profile, and (D) Gleysols in the lower section of the profile.

of paleosols 4 through 7. Paleosols 2 and 3 lack gleyic or redoximorphic features. Their main morphological characteristic is the presence of dark SOM (humus) horizons. Both 2A and 3A have a very hard and compact angular blocky structure. Paleosol 3A also exhibits slickensides on ped surfaces. Paleosol 2A contains abundant artifacts including ceramics and human bones from both the Classic and Postclassic periods. The modern surface exhibits a weakly developed soil with an Ap horizon approximately 20-cm thick.

The modern surface of the TBII profile consists of 100 cm of alluvial sediment little affected by pedogenesis. Carbonates are found throughout the profile, present as white spots and accumulations filling fractures and

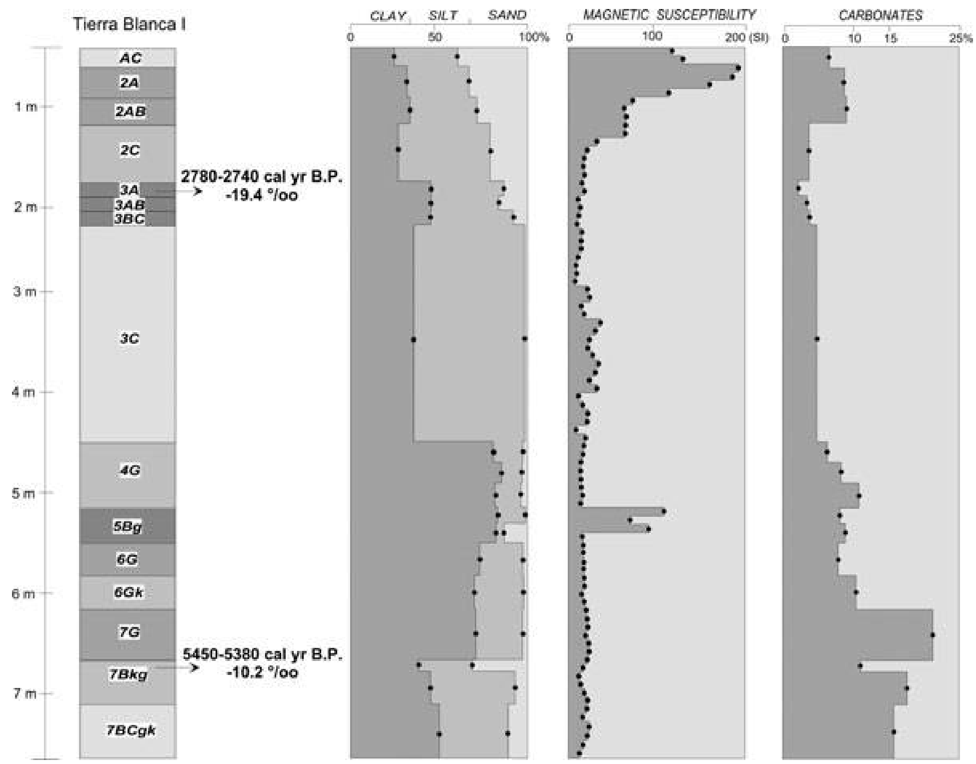


Figure 4 Selected properties of the Tierra Blanca I profile: grain-size distribution (%); total organic carbon (%); magnetic susceptibility (10^{-6} SI); carbonates (%).

pores. The upper paleosols identified in section TBI are better expressed in TBII (Figures 2, 5A, and 6). Although located only 50 m east of TBI, the TBII profile contains four paleosols (paleosols 2, 3, 4, and 5) (Figures 5A and 6). TBII paleosols 2 and 3 contain similar soil profiles, characterized as 2A-2AC and 3A-3C, but are less developed than paleosol 5 (Table I, Figures 5A and 6). Abundant artifacts have been found in both paleosols, with Postclassic artifacts present in horizons 2A and 2C (Figure 5B) and Classic artifacts in horizons 3A and 3C (Figure 5C). In the TBII stratigraphic section, paleosols 2 and 3 are separated by parent material while in TBI, they are welded into a single horizon, horizon 2A.

In TBII, paleosol 4 (4Bk; Table I, Figures 5A and 6) represents a pedosediment composed of fragments of soil and hard carbonate concretions that are broken and horizontally aligned. Paleosol 5 has the strongest morphological expression of any of the paleosols in both the TBI and TBII sections. Its horizonation is 5Ass, 5Bss, 5BC, and 5C, with a solum greater than 1-m thick. Paleosol 5 contains Formative period ceramics (Figure 5D) and exhibits strong vertic features, including slickensides, hard angular blocky structure, and vertical cracks.

The laboratory results provide the following set of characteristics. The gleyic paleosols (TBI) are very clayey, reaching the highest proportion in paleosols 4 and 5 (> 80% of clay, Figure 4) and showing pH values ranging from 6.8 to 7.5 (Table I). We did not measure TOC content for these paleosols due to the lack of A or AB/AC horizons. In paleosol 7, the total amount of sand and silt increases in comparison to other gleyic paleosols, confirming the presence of a discontinuity between paleosols 6 and 7 (Figure 4). Paleosol 7 also contains the highest proportion of carbonate (11–21%), which coincides with a slightly alkaline pH (Figure 4, Table I). Magnetic susceptibility values are the lowest in the gleyic paleosols of TBI; however, in paleosol 5 (5Bg) this parameter increases dramatically from 13 to 100 SI × 10^{-6}, suggesting the presence of another discontinuity (Figure 4).

The upper paleosols in TBI and TBII are more silt rich, with textures ranging from 37% to 43% silt. The maximum contribution of clay occurs in 5Ass and 5Bss of TBII (57% and 55%, respectively) (Figure 6), while TBI paleosols contain less clay. The modern surface in both sections is very sandy.

The 2A and 3A horizons in TBI have TOC values of 0.65% and 0.35%, respectively (Table I). In TBII, 2A has

Table I Morphological descriptions and selected chemical properties of the study paleosols in Tierra Blanca I and II; El Pochote and Vicente Guerrero

Horizon	Depth (cm)	Color dry	pH	TOC[a] (%)	δ^{13}C (‰)	Cultural period	Features
Tierra Blanca I (TBI)							
AC	0–20	10YR 4/2	7.05	1.31	−21.9		Sandy material, with a very friable structure; strongly affected by recent human activities.
2A	20–52	10YR 5/2	6.98	0.65	−20.2	Early Classic-Postclassic (A.D. 150–1500 A.D.)	Dark Brown. Very hard and compact subangular blocky structure. There are many artifacts (ceramic and burials).
2AB	52–80	10YR 6/2	7.54	na	na		Dark gray showing charred organic matter. Very hard, subangular blocky structure, no roots and abundant artifacts.
2C	80–140	2.5Y 6/2	7.70	na	na		Colluvial material, with no pedogenic structure.
3A	140–155	2.5Y 7/1	7.56	0.35	−19.4	Early-Middle Formative (1800 B.C.–300 B.C.)	Dark gray. Silty clay. Fine and very hard subangular blocky structure; slickensides are present in ped surfaces.
3AB	155–170	2.5Y 7/2	7.43	na	na		Gray. Silty loam. Fine and very hard subangular blocky structure.
3BC	170–185	2.5Y 8/2	7.14	na	na		Less structured, friable, silty.
3C	185–451	2.5Y 8/2	7.35	na	na		Light yellowish silty sediment. There are five strata showing differences in the kind of stratification. In the base the sediment is laminated. The middle part combines the lamination with crossed stratification. The upper part is laminated with vertical cracks, 40 cm depth, crossing the sediment
4G	451–519	2.5Y 7/4	6.84	na	na		Clayey, greenish gray, with reddish mottles; structure in subangular blocks very friable. Dendritic Mn as well as Mn spots, especially in the base of this horizon. The contact with the underlying horizon is ondulated and shows the highest concentration of Mn.
5Bg	519–556	10YR 7/6	7.53	na	na		Yellowish brown. Subangular blocky structure. Matrix is free of carbonates. Dendritic Mn.
6G	556–590	2.5Y 7/8	7.45	na	na		Clayey. Coarse subangular blocky structure. Strong gleyic features. Dendritic Mn. Slickensides are frequent.
6Gk	590–625	2.5Y 7/6	7.11	na	na		Clayey. Slickensides are less prominent. Here carbonates are frequent.
7G	625–678	10YR 7/6	7.67	na	na		Clayey. Prismatic structure breaking into subangular blocks. Mn films are abundant. Abundant concentrations of carbonates. Soil matrix is free of them.
7Bkg	678–758	2.5Y 7/3	7.45	na	−10.2[b]		Clayey. Mottled, with Mn films on ped surfaces. Main feature is the presence of very hard carbonate concretions 5 to 7 cm diameter.
7BCgk	758–814	2.5Y 7/4	7.38	na	na		Matrix is free of carbonates, but they appear in concentrations along the ped surfaces.
Tierra Blanca II (TBII)							
AC	0–100	10YR 4/2	7.00	na	na		Alluvial sediment poorly affected by pedogenesis
2A	100–130	2.5Y 4/2	7.64	0.73	−22.6	Postclassic (A.D. 1000–A.D. 1500)	Dark gray, silty. Structure is well developed, with fine subangular blocks. Presence of ceramis belonging to the Postclassic
2AC	130–195	10YR 4/3	6.50	na	na		More Sandy and less structured.
3A	195–210	2.5Y 5/3	7.92	0.29	−20.3 −25.0[c]	Classic (A.D. 150–A.D. 830)	More clayey. Brownish gray. subangular blocky structure, compact. Presence of ceramic of Maya Classic
3C	210–270	2.5Y 5/3	8.10	na	na		More sandy and less structured.
4Bk	270–290	2.5Y 3/3	6.20	na	na		Yellowish brown. Silty material with a lot of reworked concretions, horizontally alignment, and showing little pedogenesis.
5Ass	290–315	2.5Y 4/1	7.75	0.49	−16.5	Middle Formative (800 B.C.–300 B.C.)	Dark brown to black. Clayey. Structure in angular blocks, slikensides, and carbonate concentrations. Ceramic of the Formative period.
5Bss	315–340	2.5Y 5/3	7.76	0.33	−18.3 −10.0[b]		Clayey. Grayish brown, slickensides. Concentrations of carbonates in the ped surfaces along fractures.
5BC	340–365	2.5Y 5/3	7.66	na	na		More silty. Here, there are also abundant ceramic fragments.
5C	365–515	2.5Y 5/2	8.16	na	na		Colluvial sediment. Silty sand. It has incorporated rests of gleyic soils as well as the hard carbonate concretions found in 9Bkg of TBI.

Geoarchaeology: An International Journal **28** (2013) 268–288

Table I Continued

Horizon	Depth (cm)	Color dry	pH	TOC[a] (%)	$\delta^{13}C$ (‰)	Cultural period	Features
El Pochote (PC)							
C	0–38	2.5Y 5/3	7.85	na	na		Sandy, with low pedogenesis. At a 24 cm depth there is a line of charred organic matter.
2AC	38–50	10YR 7/4	7.77	0.31	−22.9		Yellowish brown. Low structured. Sandy
2C	50–71	2.5Y 6/4	7.92	na	na		Sandy, with no structure. Laminated sediment.
3A	71–88	2.5Y 5/3	7.68	na	na		Dark brown. Sandy, with a weak structure.
3C	88–120	2.5Y 6/3	7.77	na	na		Light brown, sandy, with no structure
4A	120–160-	2.5Y 7/3	7.68	0.49	−21.9		Dark brown, with yellowish mottles sandy. Subangular blocky structure, friable, abundant charcoal fragments.
4AC	160–176	2.5Y 7/3	7.46	na	na		Dark brown, with yellowish mottles sandy. Coarser subangular blocky structure, friable.
4C	176–326	2.5Y 6/4	7.76	na	na		Sandy, laminated sediment.
5Bg	326–356	2.5Y 7/3	7.87	na	na		Brown, with reddish-yellowish mottles. Sandy silt. Frable subangular blocks. In the limit with 5Bgk there is a layer of coarser material.
6Bgk	356–446	2.5Y 7/3	7.66	na	na		Dark grayish brown. Clayey. Prismatic to columnar structure, very hard and very well developed, with small carbonate hard concretions. Some shells are present. Mottles and Fe concretions. Matrix contains carbonates.
6BCg	446–476	2.5Y 7/3	7.65	na	na		Dark brown, less mottles. Subangular blocky structure, very hard and with coarser texture.
7Ass	476–528	2.5Y 6/2	7.37	0.86	−17.6	Classic (A.D. 150 B.C.–A.D. 830)	Very dark gray, columnar to prismatic structure, breaks into angular blocks. Clayey. Matrix is free of carbonates, but there are small concretions. There are also Fe concretions. Slickensides.
7Bg	528–616	2.5Y 7/2	7.85	na	na		Dark brown with reddish mottels. Clayey. Subangular blocky structure more friable than 7Ass. dense and showing reaction to HCl.
8Ass	616–628	2.5Y 6/1	7.58	0.71	−17.6	Late Formative (300 B.C.–A.D. 150)	Very dark gray. Very hard, angular blocky structure, very clayey and with slickensides.
8Bg	628–672	2.5Y 7/3	7.27	na	na		Grayish brown. Clayey. Subangular blocky structure. Slickensides. Gypsum is present in small crystals.
8G	672–702	2.5Y 5/3	7.18	na	na		Grayish brown with mottling. More sandy. Pores are filled by brown material. Fe concretions.
Vicente Guerrero (VG)							
C	0–100	2.5Y 6/4	7.98	na	na		Sandy sediment with no structure and low pedogenesis. At a depth of 45 cm, there is a 1 cm.thick white volcanic ash layer.
2Ag	100–128	2.5Y 7/3	7.73	0.80	−23.4	Postclassic (A.D. 1000–A.D. 1500)	Grayish brown, silty sand, very hard, columnas structure. There are abundant shells.
2ACg	128–146	2.5Y 7/3	7.86	na	na		It is more loose than previous and more sandy.
3A	146–180	2.5Y 7/4	7.78	0.50	−23.5	Classic (A.D. 150–A.D. 850)	Dark brown, structure in subangular blocks, more clayey than previous. It has carbonates and shells.
3BCg	180–200	2.5Y 7/3	7.7	na	na		Brownish gray with mottles.
4A	200–260	2.5Y 6/3	7.42	0.75	−22.4		Very dark brown-balck with columnar structure, very hard. Many shells and Fe concretions. Clayey. Charcoal. Slickensides. Coprolites in biopores-
4BAgk	260–290	2.5Y 7/3	7.62	na	na		Brown, prismatic structure. Mottles. Slickensides, abundant coprolites in biopores.
5Agk	290–360	2.5Y 8/3	7.77	0.29	−20.3	Middle Formative (800 B.C.–300 B.C.)	Dark brown, subangular blocky structure. Matrix has carbonates. They also appear as abundant shells and small concretions. Charcoal. Silty sand.
5C	360–440	2.5Y 6/4	7.84	na	na		Sandy, with no structure, laminated in the contact with 5Agk horizon. Matrix has carbonates.

[a]Total Organic Carbon
[b]From carbonates (Beta Analytic)
[c]From charcoal (Beta Analytic)
na – not available

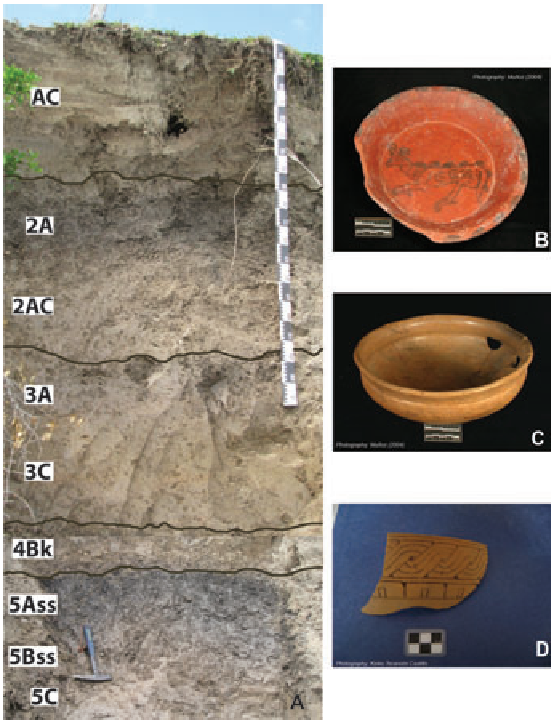


Figure 5 (A) Tierra Blanca II profile, 50 m East of TBI, Usumacinta River, Holocene Terrace 2 (HT2); (B–D) Ceramics found within Late Holocene paleosols; (B) Postclassic Period ceramic; (C) Classic Period ceramic; (D) Formative Period ceramic.

the highest proportion of TOC (0.73%) and 3A the lowest (0.35%). The TOC of 5Ass is 0.49%. pH values are slightly alkaline, ranging from 7 to 8. Carbonate concentrations, measuring less than 15%, are greatest in TBII horizons 2A, 3A, 5Ass, and 5Bss (Figure 6).

In the TBI profile, paleosol 3 exhibits low magnetic susceptibility values (10–15 SI x 10^{-6}), while paleosol 2 contains the highest (177 SI x 10^{-6}). Charcoal and charred organic matter associated with human burials has been detected in paleosol 2, which likely accounts for the high magnetic susceptibility. In TBII, the magnetic susceptibility pattern is very homogeneous down profile. Although values are low in all paleosols, magnetic susceptibility values for paleosols 2 and 3 are two times higher than those of paleosol 5. A clear difference is observed in the surface AC horizon, where the highest values have been detected (1000 SI $\times$ 10^{-6}) (Figure 6).

The stable carbon isotope signatures from TBI show little difference among the modern and buried A horizons. The modern surface contains a $\delta^{13}C$ composition of $-21.9‰$. Paleosols 2A and 3A contain values of -20.2 and $-19.4‰$, respectively. Although we did not evaluate the isotopic composition of the gleyic paleosols, the $\delta^{13}C$ values of the calcium carbonate concretions found in 7Bgk (analyzed by Beta Analytic, BETA-277572) measured $-10‰$. In TBII, $\delta^{13}C$ values decrease with depth (Table I), with the lowest values occurring

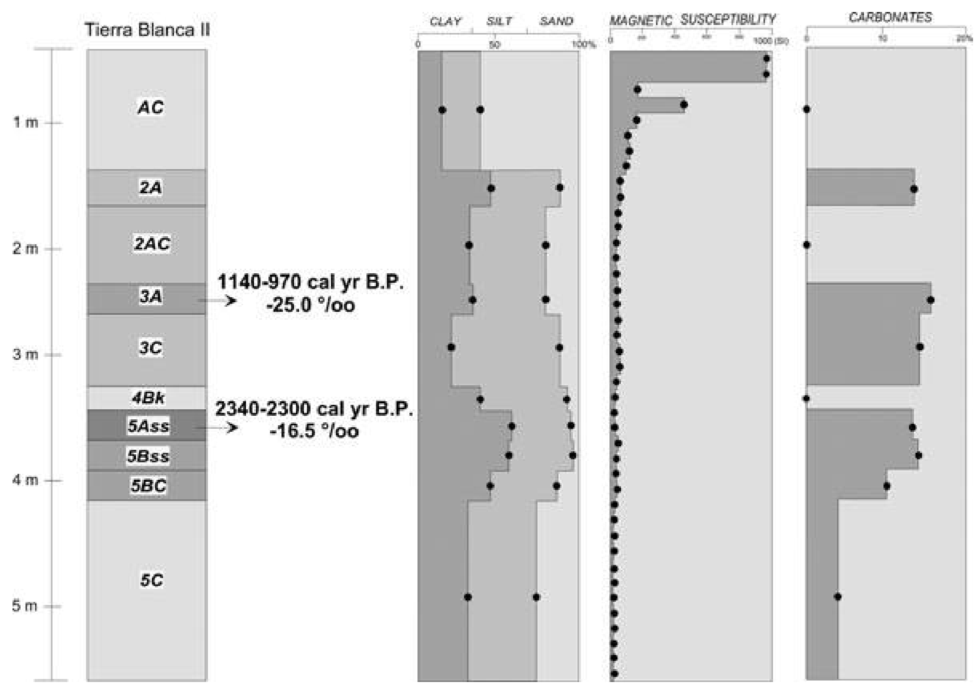


Figure 6 Selected properties of the Tierra Blanca II profile: grain-size distribution (%); total organic carbon (%); magnetic susceptibility (10^{-6} SI); carbonates (%).

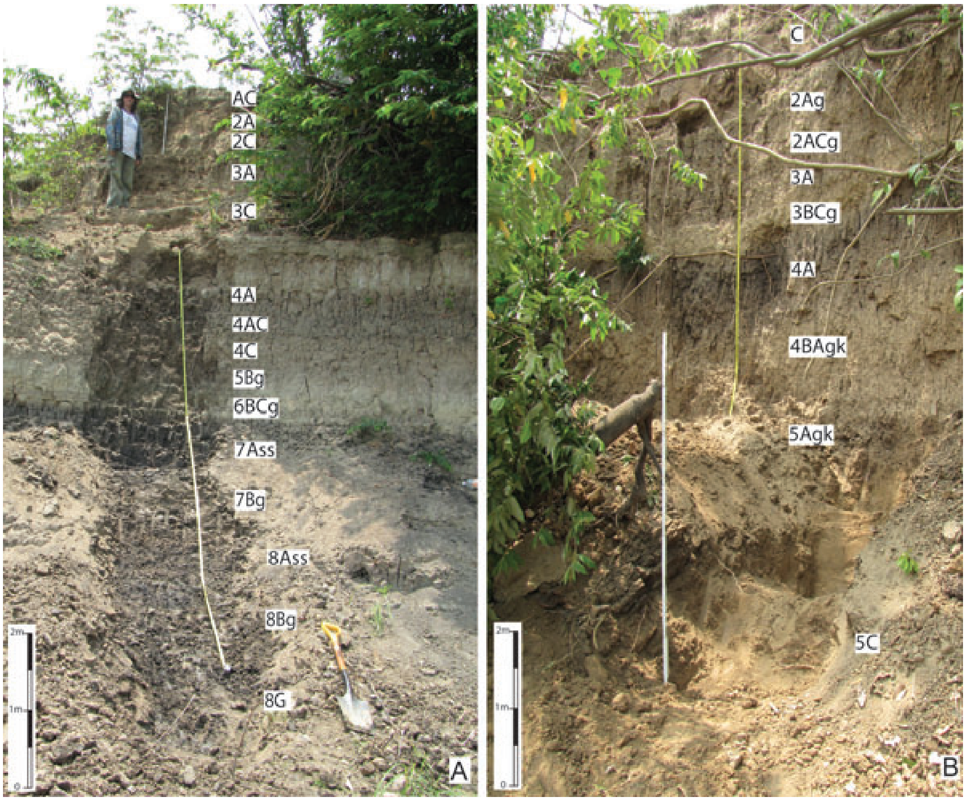


Figure 7 Paleosols exposed at profile at the riverbank of Usumacinta (Holocene Terrace 1 – HT1) (A) El Pochote to the west of Tierra Blanca and (B) Vicente Guerrero to the east of Tierra Blanca.

in 2A (−22.6‰) and the highest in 5Ass (−16.5‰). In 5Bss, the SOM δ^{13}C values measured −18.3‰. Carbonates found in ped surfaces and fractures of this horizon have a stable carbon isotope composition of −10‰ (Table I).

El pochote (POCH)

The El Pochote section, located in the younger terrace HT1 (Figure 2), contains seven paleosols, numbered 2, 3, 4, 5, 6, 7, and 8 (Figure 7A). The modern soil consists of a single AC horizon that preserves the sedimentary characteristics of the sandy alluvium parent material. The uppermost paleosols (paleosols 2, 3, and 4) are weakly developed, showing loose structure and light colors, but darker and clearly expressed A horizons. Paleosol 4 is slightly better developed and contains abundant charcoal fragments. In contrast, the underlying paleosols 5, 6, 7, and 8 are well developed, exhibit greater horizonation (5Bg, 6Bgk, 6BCg, 7Ass, 7Bg, 8Ass, 8Bg, and 8G) and contain gleyic features such as reddish mottling and Fe concretions. A horizons associated with paleosols 7 and 8 (7Ass and 8Ass) are very dark, compact, and dense with angular blocky structure (Figure 7A, Table I).

The upper paleosols 2 and 3 contain elevated proportions of sand (60–70%), while paleosol 4 is more silt rich (Figure 8). TOC content for 2AC measures 0.31% and 0.49% for 4A (Table I, Figure 8). pH values range from 7.5 to 7.9; the percentage of carbonate is 15% in all horizons, except in 4AC where it reaches 38%.

The lower paleosols (paleosols 5, 6, 7, and 8) are more clayey, with the highest clay content recorded in paleosols 7 and 8 (values reaching 50%). Although clay-rich, silt fractions measured high with values varying from 30% to 70%. An exception was found in 5Bg where a high proportion of sand was detected (Figure 8). TOC values (Table I) are more elevated in 7Ass and 8Ass (0.86% and 0.71% respectively). This part of the section shows neutral to slightly alkaline pH (Table I). Carbonate content is relatively high (greater than 20%) in 6Bgk, 7Ag, and 8Bg.

Magnetic susceptibility differs between the upper and lower paleosols in this section. C horizons in the surface as well as paleosols 2, 3, and 4 exhibit the highest values, reaching 300 SI × 10^{-6}. Vertic paleosols located in the base (paleosols 7 and 8) exhibit lower values that range from 10 to 25 SI × 10^{-6}. These values are similar to those observed in the vertic paleosol (paleosol 5) of TBII. SOM

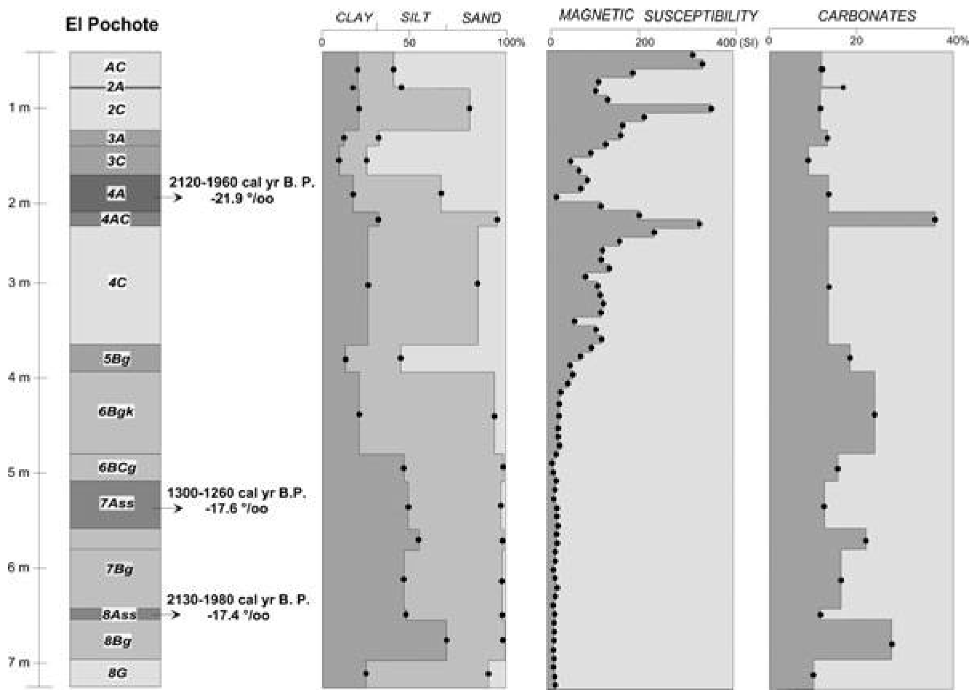


Figure 8 Selected properties of the El Pochote profile: grain-size distribution (%); total organic carbon (%); magnetic susceptibility (10^{-6} SI); carbonates (%).

δ^{13}C values are lowest in the uppermost paleosols (−22.9 and −21.9‰ for 2A and 4A, respectively). The highest values correspond to paleosols 6 and 7, both measuring −17.6‰ (Table I).

Vicente Guerrero (VG)

The Vicente Guerrero (VG) profile (Figure 7B), exposed in terrace HT1, contains fewer paleosols (paleosols 2, 3, 4, and 5), all of which are more weakly developed than those represented in the TBI, TBII, and POCH sections. The modern surface, represented by horizon C, is approximately 1-m thick and consists of silt-rich (∼80% silt) alluvium. Horizon C contains a 1-cm thick layer of white volcanic ash 45 cm below surface (cmbs). A number of buried soil horizons underlie the modern alluvium. These include horizons 2Ag, 2ACg, 3A, 3BCg, 4A, 4BAgk, 5Agk, and 5C (Figure 7B). All horizons exhibit yellowish-to-brown colors, friable consistence, and subangular blocky structure. Horizon 4A, however, exhibits an angular blocky structure with hard consistence and slickensides along ped faces.

The 2Ag, 3A, 4A, and 5Agk horizons contain 0.8%, 0.5%, 0.7%, and 0.3% organic carbon, respectively. The VG paleosols contain the lowest SOM δ^{13}C values (−23‰) of the sections investigated. These values become more positive with depth, reaching −20‰ in 5Agk (Table II). pH is slightly alkaline with carbonate concentrations measuring approximately 15% (Table I, Figure 9). However, the carbonate concentrations may be overestimated based on the presence of mollusk shells found throughout the profile. Although the VG paleosols exhibit greater magnetic susceptibility values than the paleosols of the other sections, their values fluctuate down profile. The uppermost part of the section, characterized by the modern surface/C horizon, has the highest values and greatest degree of variability (Figure 9).

Dating of the Study Sections

Stratigraphic chronologies were obtained through AMS radiocarbon dating of bulk SOM collected from 3A in TBI, 5Ass in TBII, and 4A, 7Ass, and 8A in POCH, as well as carbonate concretions from 7Bkg of TBI, carbonate accumulations from 5Bss of TBII, and charcoal fragments from 3A in TBII. Results are listed in Table II. In addition, we have also documented ceramic assemblages contained in TBI and TBII sections.

The oldest date, 5450–5380 cal. yr B.P. (3240–3110 B.C.), corresponds to the hard carbonate concretions in 7Bkg at TBI. No other datable material was present in the gleyic sequence. The mean age of SOM in 5Ass at TBII

Table II Radiocarbon ages from selected paleosol materials in the Usumacinta riverbank.

Section	Depth of Collected Material (cm)	Horizon	Type of Material	Laboratory Sample	Age (^{14}C yr B.P.)	Calibrated Age (2σ) cal yr B.P.	Calendrical Age (2σ) (B.C/A.D)
TBI	140–155	3A	Humus	BETA-300446	2640 ± 30	2780–2740	830–790 B.C.
TBI	678–758	7Bkg	$CaCO_3$	BETA-277572	4580 ± 50	5450–5380	3500–3430 B.C.
TBII	195–310	3A	Charcoal	BETA-300447	1140 ± 30	1140–970	A.D.810–980
TBII	290–315	5A	Humus	BETA-300448	2260 ± 30	2340–2300	390–350 B.C.
TBII	315–340	5Bss	$CaCO_3$	BETA-300449	750 ± 30	720–660	A.D 1230–1290.
POCH	120–160	4A	Humus	BETA-300443	2070 ± 30	2120–1960	170–10 B.C.
POCH	476–528	7Ass	Humus	BETA-300444	1350 ± 30	1300–1260	A.D.640–690
POCH	616–628	8Ass	Humus	BETA-300445	2080 ± 30	2130–1980	180–30 B.C.
VG	146–180	3A	Humus	BETA-300450	173,030	1710–1560	A.D.240–390

is 2340–2300 cal. yr B.P. (390–350 B.C.). The carbonates accumulated in the 5Bss horizon give a much younger age, 720–660 cal. yr B.P. (1230–1290 A.D.). However, ceramics found in this paleosol date to the Formative period, confirming the earlier SOM date from 5Ass and indicating that the carbonates in 5Bss formed later. Humus from 3A in TBI dates to 2780–2740 cal. yr B.P. (830–790 B.C.), in accordance with the Formative period ceramics found in this horizon. Radiocarbon analysis of charcoal fragments collected from 3A at TBII provides an age of 1140–970 cal. yr B.P. (810–980 A.D.). In 2A at TBI, there is a mixture of archaeological material belonging to both the Classic and Postclassic periods.

No archaeological material was found in association with the buried soils from either the POCH or VG sections. In the POCH section, horizon 4A dates to 2120–1960 cal. yr B.P. (170–10 B.C.), 7Ass dates to 1300–1260 cal. yr B.P. (640–690 A.D.); and 8Ass dating to 2130–1980 yr. B.P. (180–30 B.C.). In the VG profile, horizon 3A dates to 1710–1560 cal. yr B.P. (240–390 A.D.).

DISCUSSION

Pedostratigraphic Correlation

We propose a correlation between the four study sections based on the AMS dating, the presence of ceramic and other cultural materials, and the paleosol morphology (Figure 10). The gleyic paleosols (Gleysols paleosols

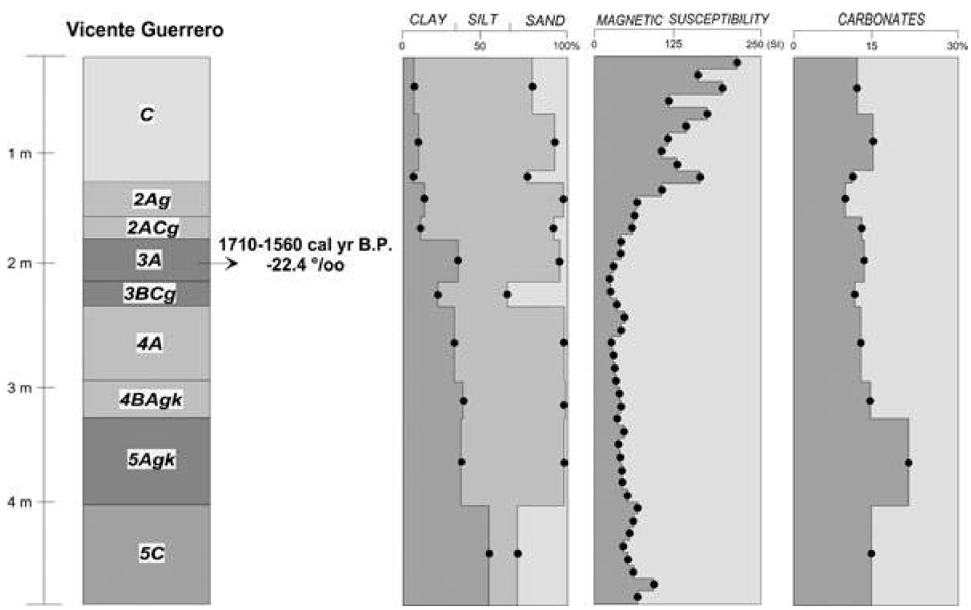


Figure 9 Selected properties of the Vicente Guerrero profile: grain-size distribution (%); total organic carbon (%); magnetic susceptibility (10^{-6} SI); carbonates (%).

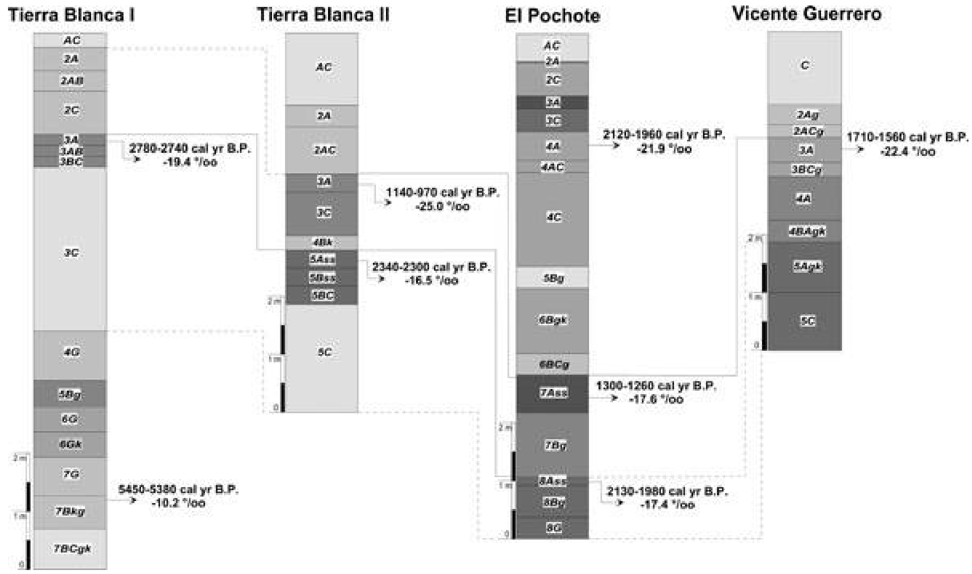


Figure 10 Pedostratigraphy and chronology along the Middle Usumacinta with proposed correlation of paleosols.

4–7) found in TBI are the oldest of the study site. The only radiometric age estimation for this unit is derived from the neoformed carbonates, which we believe post-date the groundmass formation. Our conclusion is based on the type of pedogenetic processes. The gleyic paleosols demonstrate strong redoximorphic features, leaching (carbonates are absent in the groundmass), and high clay accumulation. All these characteristics point to pedogenesis in a moist environment, sometimes accompanied by waterlogging that is not compatible with the formation of calcium carbonate. We conclude that carbonates precipitated later, after environmental conditions changed. Thus the age of the calcium carbonate concretions (5450–5380 cal. yr B.P.) indicates that the gleyic paleosols were formed earlier, probably during the Late Pleistocene to Early Holocene. Although, we have found no evidence of similar soils in the riverbanks, they are well preserved in the upper terraces, presumably of Pleistocene age, in Balancan (Figures 1 and 2).

We have coordinated the pedostratigraphy of the younger paleosols according to their associated AMS ages and artifact assemblages. We propose that soils 5Ass at TBII (2340–2300 cal. yr B.P.), 8Ass at POCH, (2130–1980 cal. yr B.P.), and 3A in TBI (2780–2740 cal. yr B.P), all of which contain Formative period ceramics, formed during the same period (Figure 10). These paleosols contain well-developed vertic features. In the VG profile, paleosol 4 (4A and 4Bgk) is associated with this period because of similar vertic features and because the upper paleosol date corresponds to the Classic period. The presence of Vertisols has been documented in other areas of the Maya Lowlands and is considered to have formed during the same period (Dahlin, Chambers, & Foss, 1980; Pope & Dahlin, 1989, 1993; Beach et al., 2006; Dunning, Beach, & Luzzadder-Beach, 2006). These Vertisols (or Mollisols in some instances) constitute a paleosol designated as *Eklu'um*, the Mayan term for ''black earth'' (Dunning & Beach, 2004), and are commonly found under Maya structures (Beach et al., 2006).

The 2A horizon at TBI contains ceramics from both the Maya Classic and Postclassic periods that correlates with 7Ass at POCH (1300–1260 cal. yr B.P.). The 3A horizon at TBII (1140–970 cal. yr B.P.) likely correlates with the 2A horizon at TBII (with no instrumental age) that contains Postclassic ceramics. Although the age is somewhat older, we correlate these horizons with the 3A horizon at VG (1710–1560 cal. yr B.P.). The difference in age is explained by the geomorphic position of the HT1 terrace within which the VG profile is located (Figure 2). In this location, the river migrated laterally away and buried soil 3A earlier than in the other sections. The lateral migration that affected rates of sedimentation and erosion best explains the timespan represented by these horizons.

Figure 2 shows the reconstruction of the alluvial terrace system, indicating the pedostratigraphy. It is clear that in the alluvial Pleistocene terrace, soils with gleyic features are present. In the oldest Holocene terrace (HT2), where we studied TBI and TBII sections, we have also found gleyic paleosols in the base, while in younger terraces (HT1, HT0) paleosols and soils with less development occur.

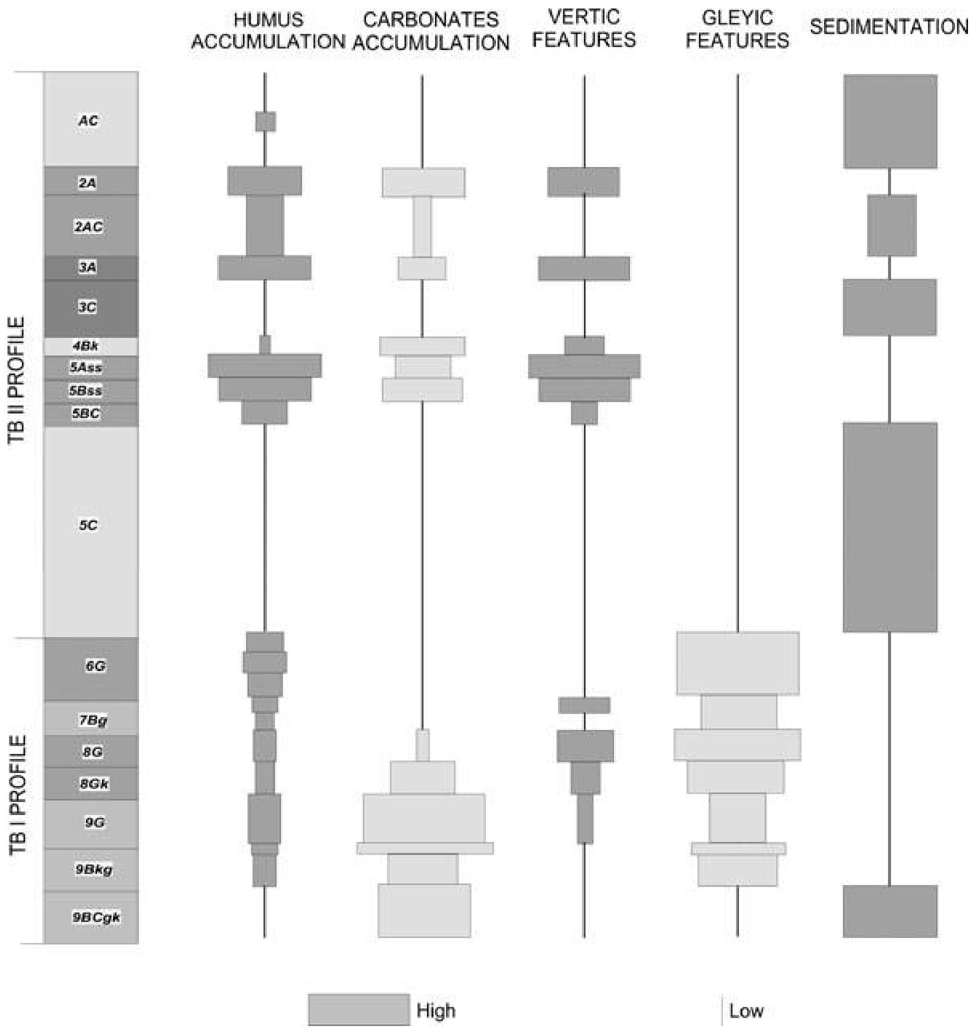


Figure 11 Qualitative differences in the morphological properties of Tierra Blanca I paleosols and rates of alluvial sedimentation.

Environmental Reconstruction and Land-Use Change

Figure 11 shows qualitative differences in the morphology of the studied paleosols in Tierra Blanca, interpreting them in terms of the dominance of pedogenic processes. In the oldest paleosols, we recognize the dominance of processes related to an environment with a high water table, namely weathering and gleyzation. These soils are very similar to those observed today in the higher terraces of the alluvial plain in Balancan (Figure 2). Evidence of humid conditions in the Early Holocene is also reported in other sites of the Maya Lowlands. For instance in northern Guatemala, Islebe et al. (1996) and Mueller et al. (2009) document the presence of wet conditions associated with forest taxa pollen in Lake Petén Itzá. Similar conditions are reported in other lacustrine records as in Salpetén and Quexil, north Guatemala (Leyden, 1984, 1987, 2002; Islebe et al., 1996); Cobá (Whitmore et al., 1996), and Chichancanab (Hodell et al., 2001; Hodell, Brenner, & Curtis, 2007).

A conspicuous feature corresponding to the Middle Holocene is the presence of carbonate concretions, formed during the final stage of development of the gleyic paleosols. We associate these concretions with the vertic features, such as cracks with slickensides that dissect and deform gleyic groundmass, clearly observed in the TBI 4G horizon. However, they can also be related to the Formative vertic paleosol. Differences in age between SOM in this paleosol and the carbonate concretions are due to the soil-forming processes. The combination of carbonates and vertic features point to fluctuating environmental conditions that represent a transition toward a drier climate with strong seasonality. We suggest that this local change is related to a major drying trend evidenced at different geographic scales dating to the beginning of the Middle Holocene. In Mesoamerica, this trend left signals both in the mountainous regions, as well as in the tropical lowlands. In the overview of the Late Quaternary lacustrine proxies of the Central Mexican Highlands, Metcalfe et al. (2000) point to a dry period with strong oscillations at 6000 and 5000 cal. yr B.P. Similarly, Islebe et al. (1996) report diminishing tropical pollen in Lake Petén Itzá around 5600 cal. yr B.P., associated with either climatic drying or vegetation clearance. Mueller et al. (2009) document a progressive drying trend that began about 4500 years ago in northern Guatemala. In Tzib, Yucatán, changes in vegetation reflect the same tendency toward dry climates in the Middle Holocene (Carrillo-Bastos et al., 2010). On a global scale, it is well known that a decrease in atmospheric moisture in the subtropical zones of the northern hemisphere occurred between 6500 and 4500 cal. yr B.P., which led to the development of the Sahara, Arabia, and Thar deserts (Ritchie, Eyles, & Haynes, 1985).

The presence of silt-rich sediment in TBI (horizon 3C) documents an activation of the terrace related to changes in the fluvial system perhaps induced by climatic changes in the region. In TBII, this silty sediment correlates with an alluvial-colluvial material, horizon 5C, at the base of paleosol 5. The change in the lamination pattern and secondary features indicates that deposition of the unit occurred under unstable, sharply fluctuating environmental conditions. Pulses of alluvial sedimentation point to strong floods whereas desiccation cracks and the abundance of carbonates evidence dry conditions. We associate this unit with the Middle Holocene period of climatic variability (Metcalfe et al., 2000) reported in other localities in southern Mexico and Central America (Islebe et al., 1996; Mueller, Joyce, & Borejsza, 2012).

Vertic paleosols formed during the Formative period are found in all the study sections and clearly reflect a shift to widespread land surface stability and pedogenesis under a seasonal climate with periodic episodes of aridity. Stable carbon isotope compositions of SOM associated with these Formative period vertic paleosols contain the most positive $\delta^{13}C$ values, −16.5‰. Although it is possible that maize cultivation could contribute to the isotopic signatures, we believe that the $\delta^{13}C$ values indicate the dominance of drought resistant C4 and CAM vegetation due to their association with vertic soils.

Fernández et al. (2005) and Johnson et al. (2007a; Johnson, Wright, & Terry, 2007b) document $\delta^{13}C$ signatures for surface SOM in the Usumacinta area in Guatemala that range from −26 to −30‰, which reflects the dominance of C3 tropical forest plants present in the area today (Bueno, ALvarez, & Santiago, 2005). This is in contrast to the less negative $\delta^{13}C$ values found in buried A horizons of some sections (2A, 3A–TBI; 3A, 5Ass, 5Bss TBII; 7Ass, 8Ass-POCH; 5Agk-VG (ranging between −17 to −20‰). Similar to observations made by Beach (1998) and Fernández et al. (2005), we view the relative decrease in $\delta^{13}C$ values, indicative of an increase in C4 plants, to be the result of ancient agricultural practices associated with maize production during the Maya occupation. However, we suggest that the large isotopic differences observed in the Classic and Formative period soils of the study area (Table I) represent the differential increase of C4 and CAM plants due to a general decrease in moisture and increase in seasonality. Lounejeva et al. (2006) demonstrate that CAM plants in the Teotihuacan valley have signatures around −14‰. This increase in aridity compares well with research conducted at Lake Amatitlan, Guatemala by Velez et al. (2011), who interpret low lake levels between 250 B.C. and A.D. 125 as evidence of dryer climates. As with Velez et al. (2011), who also consider the impacts that the construction of drainage systems for agriculture had on lake levels, we cannot exclude the influence of maize cultivation on $\delta^{13}C$ values of the Classic and Formative period soils.

Paleosol development during the Classic and Postclassic indicates a more dynamic environment, where sedimentation was more pronounced and rates of pedogenesis were lower. The soil-forming processes were largely limited to humus accumulation and development of dark A horizons. The $\delta^{13}C$ values of SOM in these cases are much lower (−19 to −20‰) and point to a higher proportion of C3 plants typical of humid environments. A drier interval is likely marked by the second generation of the calcite concretions. Although the concretions occur in the vertic paleosols, their age is much younger (720–660 cal. yr B.P., A.D. 1230–1290) and they were likely developed by carbonate illuviation from the Postclassic paleosol. This interpretation is based on the model proposed by Cerling and Quade (1993), where a value of $\delta^{13}C$ of −10‰ in pedogenic carbonates corresponds to a signature of −23‰, due to the isotopic fractionation process between soil CO_2 and carbonate, which result in a total enrichment of −13‰ (at a temperature of 25°C). The $\delta^{13}C$ composition in 2A of TBII of −22.6‰ confirms this interpretation.

The environmental variability evidenced in the soil data provides interesting links between environmental conditions and agricultural development in the area. First, we would like to draw attention to the striking similarity of the chronology of the Middle Holocene dry period marked in the studied sequence by the carbonate concretions and carbonate rich alluvial stratum. Although the earliest evidence of cultivated maize is somewhat older, the major abundance of the pollen from fully domesticated varieties corresponds to approximately 6000 cal. yr B.P. (Pope et al., 2001), close to the beginning of aridity. This suggests a possible connection between increased xeric conditions, plant domestication, and a shift to an agricultural economy, an idea first formulated by Childe (1926) and then extensively discussed worldwide (Byrne, 1987). Although the issue of climate-culture relations in the Middle Holocene in Mesoamerica is still problematic due to the limited number of precisely dated records (Voorheis & Metcalfe, 2007), the possible influence of climate change, specifically an increase in aridity, on the spread of agriculture in the tropical lowlands of the Gulf of Mexico coast deserves more attention.

Further inferences concerning human–landscape interactions require investigations at the local scale, such as the alluvial sequences studied here. Abundant archaeological materials are present in many terrace levels. In fact the river terraces HT2 and HT1, which are periodically flooded, contain evidence of the longest occupation, starting in the Formative period, extending through the Classic period, and surviving the terminal Classic collapse. We believe that soil resources were a major attractor for humans in this otherwise highly dynamic and unpredictable valley bottom. Here people settled on flat alluvial terraces covered by thick, cumulic Fluvisols rich in humus and nutrients. The high quality of these alluvial soils proved much more productive than the leached soils in the uplands. Concentrations of the archaeological findings are clearly associated with the buried alluvial paleosols that show vertic features and humus accumulation (Figure 11). The paleosols mark the periods of major land surface stability that provided edaphic conditions suitable for settlement and population subsistence and growth.

CONCLUSION

This paleopedological study conducted in the Maya Lowlands investigated alluvial paleosols buried and preserved in terraces of the Usumacinta River. The paleosol sequences record environmental changes along the Mexican border of the Usumacinta River valley that appear to agree chronologically and environmentally with records in the neighboring areas of Guatemala and Belize (Beach, 1998; Fernández et al., 2005; Mueller et al., 2009; Velez et al., 2011).

We propose that specific paleosols, with their peculiar morphology, can serve as field indicators for tracing occupation surfaces. In particular, vertic soils are associated with Formative period occupation, while soils dominated by humus accumulation are associated with Classic and Postclassic period. The vertic soils are the most well developed, and we interpret their formation as the product of longer periods of landscape stability and pedogenesis under seasonal climates. Classic and Postclassic paleosols are less developed and are affected by erosion and sedimentation processes. Vertic soils, characterized by dark A horizons, a hard and well-developed blocky structure, and slickensides, can guide archaeological prospection in searching Formative period occupational landscapes.

In addition, the area has experienced a change in vegetation cover. The $\delta^{13}C$ signatures of the A horizons of the Formative and Classic paleosols are indicative of the dominance of C4 plants (-16 to $-19‰$), while the youngest soil surfaces have lower values (-22 to $-23‰$), indicative of C3 vegetation. The highest values correspond to the Formative paleosol, which have been interpreted as a consequence of a dryer climate with high seasonality.

This research has been funded by PAPIIT, grants No. IN117709 and IN110710 (E. Solleiro-Rebolledo); CONACYT-DLR J010/0705/09; and CONACYT 166878 (E. Solleiro-Rebolledo), and Coordinación de Estudios de Posgrado (UNAM). We highly acknowledge the Wenner-Gren Foundation for providing travel funding to the 2011 DIG conference. We appreciate the valuable collaboration of Keiko Teranishi, who has recorded the cultural history in Tierra Blanca. The reviews of the two anonymous referees as well as the suggestions and corrections made by Peter Jacobs have contributed to improve the document. We acknowledge the support of César Salcido, Birgit Terhost, and Bodo Damm, during the fieldwork. Jaime Díaz, Kumiko Shimada, and René Alcalá contributed to the soil analyses. To Ana Ma. Rocha for technical assistance. Edith Cienfugos and Pedro Morales evaluated the carbon stable isotopic composition.

REFERENCES

Anselmetti, F., Ariztegui, D., Brenner, M., Hodell, D., & Rosenmeier, M. (2007). Quantification of soil erosion rates related to ancient Maya deforestation. Geology, 35, 915–918.

Beach, T. (1998). Soil constraints on Northwest Yucatán, Mexico: Pedoarchaeology and Maya subsistence at Chunchucmil. Geoarchaeology, 13, 759–791.

Beach, T., Luzzadder-Beach, S., Dunning, N., Hageman, J., & Lohse, J. (2002). Upland agriculture in the Maya Lowlands: Ancient Maya soil conservation in northwestern Belize. Geographical Review, 92, 372–397.

Beach, T., Luzzadder-Beach, S., Dunning, N., & Scarborough, V. (2003). Depression soils in the lowland tropics of northwestern Belize. In A. Gómez-Pompa, M. Allen, S.L. Fedick, & J.J. Jiménez-Osornio (Eds.), Lowland Maya area: Three millennia at the human–wildland interface (pp. 139–173). Binghamton, NY: Haworth Press.

Beach, T., Dunning, N., Luzzadder-Beach, S., Cook, D.E., & Lohse, J. (2006). Impacts of the ancient Maya on soils and soil erosion in the central Maya Lowlands. Catena, 65, 166–178.

Beach, T., Luzzadder-Beach, L., Dunning, N., & Cook, D.E. (2008). Human and natural impacts on fluvial and karst depresions of the Maya Lowlands. Geomorphology, 101, 308–331.

Beach, T., Luzzadder-Beach, S., Dunning, N., Jones, J., Lohse, J., Guderjan, T., Bozarth, S., Millspaugh, S., & Bhattacharya, T. (2009). A review of human and natural changes in Maya Lowland wetlands over the Holocene. Quaternary Science Reviews, 28, 1710–1724.

Beach, T., Luzzadder-Beach, S., Terry, R., Dunning, N., Houston, S., & Garrison, T. (2011). Carbon isotopic ratios of wetland and terrace soil sequences in the Maya Lowlands of Belize and Guatemala. Catena, 85, 109–118.

Bishop, R.L. (1992). Pre-Columbian pottery: Research in the Maya region. In D.A. Scott, & P. Meyers (Eds.), Archaeometry of pre-Columbian sites and artifacts (pp. 15–65). Los Angeles: The Getty Conservation Institute.

Brenner, M., Leyden, B.W., & Binford, M.W. (1990). Recent sedimentary histories of shallow lakes in the Guatemalan savannas. Journal of Paleolimnology, 4, 239–252.

Brenner, M., Rosenmeier, M.F., Hodell, D.A., & Curtis, J. (2002). Paleolimnology of the Maya Lowlands. Ancient Mesoamerica, 13, 41–157.

Bueno, J., ALvarez, F., & Santiago, S. (2005). Biodiversidad del Estado de Tabasco. México: Instituto de Biología, UNAM. 333 p.

Byrne R. (1987). Climatic change and the origins of agriculture. In: Manzanilla L. (Ed.), Studies in the Neolithic and urban revolutions (pp. 21–34). British Archaeological Reports, Oxford, UK: Oxford Press.

Cabadas-Báez, H., Solleiro-Rebolledo, E., Sedov, S., Pi, T., & Gama-Castro, J. (2010). Pedosediments of karstic sinkholes in the eolianites of NE Yucatán: A record of Late Quaternary soil development, geomorphic processes and landscape stability. Geomorphology, 122, 323–337.

Carrillo-Bastos, A., Islebe, G.A., Torrescano-Valle, N., & González N.E. (2010). Holocene vegetation and climate history of central Quintana Roo, Yucatán Peninsula, Mexico. Review of Palaeobotany and Palynology, 160, 189–196.

Cerling, T.E., & Quade, J. (1993). Stable carbon and oxygen isotopes in soil carbonates. In P.K. Swart, K.C. Lohmann, J. McKenzie, & S. Savin (Eds.), Climate Change in Continental Isotopic Records: Geophysical Monograph, 78, 217–231. American Geophysical Union.

Childe, V.G. (1926). The most ancient Near East. London: Routledge and Kegan Paul.

Correa-Metrio, A., Bush, M.B., Cabrera, K.R., Sully, S., Brenner, M., Hodell, D.A., Escobar, J., & Guilderson, T. (2012). Rapid climate change and no-analog vegetation in lowland Central America during the last 86,000 years. Quaternary Science Reviews, 38, 63–75.

Craig, H. (1953). The geochemistry of the stable carbon isotopes. Geochimica et Cosmochimica Acta, 12, 133–149.

Culbert, P., & Rice D. (1990). Precolumbian population history in the Mayan Lowland. Albuquerque: University New Mexico Press.

Dahlin, B.H., Chambers, M.E. & Foss, J.E. (1980). Project Acalches: Reconstructing the natural and cultural history of a seasonal swamp at El Mirador, Guatemala; preliminary results. In R. Matheny (Ed.), El Mirador, Peten, Guatemala: An interim report, Publication 45 (pp. 37–58). Provo, Utah: New World Archaeological Foundation.

Dunning, N.P., & Beach, T. (2004). Fruit of the *Lu'um*: Lowland Maya soil knowledge and agricultural practices. Mono y Conejo, 2, 1–25.

Dunning, N.P., & Beach, T. (2010). Farms and forests: Spatial and temporal perspectives on ancient Maya landscapes. In I.P. Martini, & W. Chesworth (Eds.), Landscapes and societies (pp. 369–389). Springer Science Business Media B.V. New York.

Dunning, N.P., Luzzadder-Beach, S.L., Beach, T., Jones, J.G., Scarborough, V., & Culbert, T.P. (2002). Arising from the Bajos: The evolution of a neotropical landscape and the rise of Maya civilization. Annals of the Association of American Geographers, 92, 267–283

Dunning, N., Beach, T., & Luzzadder-Beach, S. (2006). Environmental variability among *bajos* in the southern Maya Lowlands and its implications for ancient Maya civilization and archaeology. In L. Lucero, & B. Fash (Eds.), Pre-Columbian water management (pp. 111–133). Tucson, Arizona: University of Arizona Press.

Fedick, S.L., (Ed.) (1996). The managed mosaic: Ancient Maya agriculture and resource use. Salt Lake City: University of Utah Press.

Fedick, S.L, Flores-Delgadillo, M.L., Sedov, S., Solleiro-Rebolledo, E., & Palacios-Mayorga, S. (2008). Adaptation of Maya homegardens by container gardening in limestone bedrock cavities. Journal of Ethnobiology, 28, 2:290–304.

Fernández, F., Johnson, K., Terry, R., Nelson, S., & Webster, D. (2005). Soil resources of the Ancient Maya at Piedras Negras, Guatemala. Soil Science Society of America Journal, 69, 2020–2032.

García, E. (1988). Modificaciones al Sistema de Clasificación Climática de Köppen. México: Offset Larios, 219 p.

Gill, R.B. (2000). The great Maya droughts. Albuquerque: University of New Mexico Press.

Gomez-Pompa, A., Allen, M.F., Fedick, S.L., & Jiménez-Osornio, J.J. (2003). The lowland Maya area: Three millennia at the human-wildland interface. New York: Haworth Press.

Gunn, J.D., Folan, W.J., & Robichaux, H.R. (1995). A landscape analysis of the Candelaria watershed in Mexico: Insights into paleoclimates affecting upland horticulture in the Southern Yucatan Peninsula semi-karst. Geoarchaeology, 10, 3–42.

Haug, G., Gunther, D., Peterson, L., Sigman, D., Hughen, K., & Aeshlimman, B. (2003). Climate and collapse of Maya civilization. Science, 299, 1731–1735.

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

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

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

Hodell, D.A., Brenner, M., & Curtis, J.H. (2007). Climate and cultural history of the Northeastern Yucatán Peninsula, Quintana Roo, Mexico. Climatic Change, 83, 215–240.

Hodell, D.A., Anselmetti, F.S., & Ariztegui, D. (2008). An 85-ka record of climate change in lowland Central America. Quaternary Science Reviews, 27, 1152–1165.

Islebe, G.A., Hooghiemstra, H., Brenner, M., Curtis, J.H., & Hodell, D.A. (1996). A Holocene vegetation history from lowland Guatemala. Holocene, 6, 265–271.

IUSS Working Group WRB. (2006). World Reference Base for soil resources. World Soil Resources Reports 103. Rome: Food and Agricultural Organization of the United Nations, 2nd ed., 102 p.

Johnson, K.D., Terry, R.E., Jackson, M.W., & Golden, C. (2007a). Ancient soil resources of the Usumacinta River region, Guatemala. Journal of Archaeological Science, 34, 1117–1129.

Johnson, K.D., Wright, D.R., & Terry, R.E. (2007b). Application of carbon isotope analysis to ancient maize agriculture in the Petexbatún region of Guatemala. Geoarchaelogy, 22, 313–336.

Klepeis, P., & Turner II, B.L. (2001). Integrated land history and global change science: The example of the Southern Yucatán peninsular region project. Land Use Policy 18, 27–39.

Leyden, B.W. (1984). Guatemalan forest synthesis after Pleistocene aridity. Proceedings of the National Academy of Sciences, USA, 81, 4856–4859.

Leyden, B.W. (1987). Man and climate in the Maya Lowlands. Quaternary Research, 28, 407–414.

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

Liendo, R. (2002). The organization of agricultural production at a Maya center. Settlement patterns in the Palenque region, Chiapas, Mexico. Serie Arqueología de México. University of Pittsburgh Latin American Archaeological Publications/INAH, Mexico.

Liendo, R. (2011). B'aakal. Arqueología de la región de Palenque, Chipas, México. In R. Liendo (Ed.), Paris Monographs in American Archaeology 26. BAR International Series 2203 (pp. 297). Oxford, Inglaterra: Archaeopress.

Lounejeva, E., Morales-Puente, P., Cabadas-Báez, H., Cienfuegos-Alvarado, E., Sedov, S., Vallejo-Gómez, E., & Solleiro-Rebolledo, E. (2006). Late Pleistocene to Holocene environmental changes from δ^{13}C determinations in soils at Teotihuacan, Mexico. Geofísica Internacional, 45, 85–98.

Lozano-García, S., Caballero, M., Ortega, B., Rodríguez, A., & Sosa, S. (2007). Tracing the effects of the Little Ice Age in the tropical lowlands of eastern Mesoamerica. Proceedings of the National Academy of Science, USA, 104, 16200–16203.

Metcalfe, S.E., O'Hara, S.L., Caballero, M., & Davis, S.J. (2000). Records of late Pleistocene-Holocene in Mexico -a review. Quaternary Science Reviews, 19, 699–721.

Midwood, A.J., & Boutton, T.W. (1998). Soil carbonate decomposition by acid has little effect on δ^{13}C of organic matter. Soil Biology Biochemistry, 30, 1301–1307.

Mook, W.G., & Jongsma, J. (1987). Measurement of the N_2O corrections for $^{13}C\delta^{12}C$ ratios of atmospheric CO_2 by removal of N_2O. Tellus, 39B, 96–99.

Mueller, A.D., Islebe, G., Hillesheim, M.B., Grzesikc, D.A., Anselmetti, F.S., Ariztegui, D., Brenner, M., Curtis, J.H., Hodell, D.A., & Venzc, K.A. (2009). Climatic drying and associated forest decline in the lowlands of northern Guatemala during the Late Holocene. Quaternary Research, 71, 133–141.

Mueller, R.G., Joyce, A.A., & Borejsza, A. (2012). Alluvial archives of the Nochixtlan valley, Oaxaca, Mexico: Age and significance for reconstructions of environmental change. Palaeogeography, Palaeoclimatology, Palaeoecology, 321–322, 121–136.

Ochoa-Salas, L. (1978). Estudios preliminares sobre los mayas de las Tierras Bajas noroccidentales. México: IIF-CEM, UNAM.

Ortiz-Perez, M.A., Siebe, C., & Cram, S. (2005). Diferenciación ecogeográfica de Tabasco. Cap. 14: 305–322. In J. Bueno, F. Álvarez, & S. Santiago (Eds.), Biodiversidad del Estado de Tabasco (p. 386). Mexico: Instituto de Biología, UNAM- CONABIO.

Padilla, R., & Sánchez, R.J. (2007). Evolución geológica del sureste mexicano desde el Mesozoico al presente en el contexto regional del Golfo de México. Boletín de la Sociedad Geológica Mexicana, LIX, 1, 19–42.

Polk, J.S., van Beynen, P.E., & Reeder, P.P. (2007). Late Holocene environmental reconstruction using cave sediments from Belize. Quaternary Research, 68, 53–63.

Pope, K.D., & Dahlin B.H. (1989). Ancient Maya wetland agriculture: New insights from ecological and remote sensing. Journal of Field Archaeology, 16, 87–106.

Pope, K.D., & Dahlin B.H. (1993) Radar detection and ecology of ancient Maya canal system. Journal of Field Archaeology, 20, 379–383.

Pope, K.O., Pohl, M.E.D., Jones, J.C., Lentz, D.L., Von Nagy, C., Vega, F.J., & Quitmyer, I.R. (2001). Origin and environmental setting of ancient agriculture in the lowlands of Mesoamerica. Science, 292, 1370–1373.

Rands, R.L. (1977). The rise of Classic Maya civilizations in the Northwestern zone: Isolation and integration. In R.E.W. Adams (Ed.), The origins of Maya civilization (pp. 159–180). Albuquerque: University of New Mexico Press.

Rands, R.L. (1987). Ceramic patterns and traditions in the Palenque area. In P.M. Rice, & R. Sharer (Eds.), Maya Ceramics: Papers of the 1985 Maya Ceramic Conference. Vol I (pp. 203–238). Oxford: BAR International Series 345. British Archaeological Reports.

Retallack, G.J. (1990). Soils of the past: An introduction to paleopedology. United Kingdom: Blackwell Science. 404 p.

Ritchie, J.C., Eyles, C.H., & Haynes, C.V. (1985). Sediment and pollen evidence for an early to mid-Holocene humid period in the eastern Sahara. Nature, 314, 352–355.

Rivas, J., Ortega, B., Sedov, S., Solleiro-Rebolledo, E., & Sycheva, S. (2006). Rock magnetism and pedogenic processes in the Luvisol profiles: Examples from central Russian and central Mexico. Quaternary Internacional, 156–157, 212–223.

Rosenmeier, M.F., Hodell, D.A., Brenner, M., & Curtis, J.H. (2002). A 4000-year lacustrine record of environmental change in the Southern Maya Lowlands, Petén, Guatemala. Quaternary Research, 57, 183–190.

Rzedowski, J. (2006). Vegetación de México. 1ra. edición digital. México: Comisión Nacional para el Conocimiento y el Uso de la Biodiversidad.

Sedov, S., Solleiro-Rebolledo E., Fedick S.L., Gama-Castro J., Palacios-Mayorga S., & Vallejo Gómez E. (2007). Soil genesis in relation to landscape evolution and ancient sustainable land use in the northeastern Yucatan Peninsula, Mexico. Atti della Societa Toscana di Scienze Naturali. Memorie, Serie A, 112, 115–126.

Sofer, Z. (1980). Preparation of carbon dioxide for stable carbon isotope analysis of petroleum fractions. Analytical Chemistry, 52, 1389–1391.

Targulian, V.O., & Goriachkin, S.V. (2004). Soil memory: Types of records, carriers, hierarchy and diversity. Revista Mexicana de Ciencias Geológicas, 21, 1–8.

Turner, B.L., II. (1974). Prehistoric intensive agriculture in the Mayan Lowlands. Science, 185, 118–24.

USDA. (2009). Soil Survey Field and Laboratory Methods Manual. Soil Survey Investigations Report No. 51. Lincoln Nebraska: United States Department of Agriculture, 405 p.

Velez, M.I., Curtis, J.H., Brenner, M., Escobar, J., Leyden, B.W., & Popenoe de Hatch, M. (2011). Environmental and cultural changes in highland Guatemala inferred from Lake Amatitlán sediments. Geoarchaeology, 26, 346–364.

Voorheis, B., & Metcalfe, S.E. (2007). Culture and climate in Mesoamerica during the Middle Holocene. In D.G. Anderson, K.A. Maasch, & D.H. Sandweiss (Eds.), Climate change and cultural dynamics: A global perspective on mid-Holocene climate transitions (pp. 157–187). United Kingdom: Academic Press London.

Webster, J.W., Brook, G.A., Railsback, L.B., Cheng, H., Edwards, L., Alexander, C., & Reeder, P.P. (2007). Stalagmite evidence from Belize indicating significant droughts at the time of Preclassic abandonment, the Maya hiatus, and the Classic Maya collapse. Palaeogeography, Palaeoclimatology, Palaeoecology, 250, 1–17.

West, R.C., Psuty, N.P., & Thom, B.G. (1969). The Tabasco lowlands of Southern Mexico. Lousiana: Louisiana State University Press, 88 p.

Whitmore, T.J., Brenner M., Curtis, J.H., Dahlin, B.H., & Leyden, B.W. (1996). Holocene climatic and human influences on lakes of the Yucatán Peninsula, Mexico: an interdisciplinary, palaeolimnological approach. The Holocene, 6, 273–287.

4. DISCUSIÓN

4.1 Historia fluvial del Río Usumacinta Medio

La historia de la planicie aluvial del río Usumacinta inicia en el Plio-Pleistoceno. West (1976) y Psuty (1966) han establecido que las terrazas aluviales se formaron por la sedimentación del río durante el último interglacial, entre 100 y 115 ka (Goñi et al., 2005; Khondri et al., 2005). En estás terrazas aluviales, los suelos desarrollados se encuentran expuestos por la incisión actual del río, y por ello ha sido posible caracterizarlos en la parte baja de la secuencia de Tierra Blanca, los denominados Gleysoles con fuertes rasgos de intemperismo. Las edades obtenidas en los sedimentos en la base de la secuencia 65 y 126 ky y de 9 ky en su parte superior, muestran una fase prolongada, de más de 55 ky de estabilidad del sistema fluvial durante el Pleistoceno. Esta estabilidad se ve interrumpida a inicios del Holoceno, en una etapa en donde los procesos de erosión/sedimentación dominan. El sedimento limo-arcilloso de color claro demuestra la activación de la terraza. El tipo de pedogénesis que se observa marca la presencia de la planicie de inundación. Estos Gleysoles de Tierra Blanca tienen gran similitud con los registrados en Balancán; mientras que en las terrazas más elevadas del Pleistoceno TP3 y TP2 se desarrollan Luvisoles crómicos (Ortiz et al., 2005). Todos estos suelos (Gleysoles, Plintosoles y Luvisoles) evidencian condiciones más cálidas y húmedas que en la actualidad.

En el Holoceno, la historia fluvial se modifica debido a la activación de los procesos de sedimentación de baja energía en la planicie de inundación. Como se ha mencionado, la presencia del sedimento limoso laminado y que además tiene estratificación cruzada, en la terraza TH2, evidencia fuertemente la fase de inestabilidad geomórfica. Se puede considerar que este sedimento limoso se ha depositado sobre la planicie de inundación de la terraza TP1, poco después de que el río cortara y diera origen a la terraza TH2. Otro cambio importante en las condiciones ambientales se registra en las secuencias aluviales en el Holoceno medio, marcado por la presencia de carbonatos pedogenéticos cuya edad es de 5450-5380 años cal. AP, que indican condiciones más secas durante este periodo en las Tierras Bajas Noroccidentales. Es interesante que esta tendencia a condiciones más secas, también ha sido registrada en los sedimentos lacustres del Petén (Rosenmeier et al., 2002). Se presume que el río cuenta con una menor descarga del cauce y, por lo tanto, abandona la planicie de inundación, permitiendo una mayor estabilidad en el paisaje, en el que se desarrollan suelos con buen drenaje. Esta situación puede favorecer la distribución de los asentamientos del Formativo y por lo mismo, éstos sean numerosos sobre la terraza TH2.

En el Formativo, la estabilidad de paisaje permite el desarrollo de suelos, Vertisoles, con características distintivas: los rasgos vérticos, los cuales se relacionan con climas estacionales, en donde se presenta un periodo seco de varios meses al año, y uno de lluvia de menor duración. Los carbonatos fechados en 5,500 años se asocian también a estos Vertisoles, reforzando la idea de climas más secos que en la actualidad. Los paleosuelos Formativos tienen una distribución amplia, es decir, no sólo se han reconocido en el área del Usumacinta, sino que, aparentemente, conforman una superficie continúa (Solís-Castillo et al. 2013a). La estabilidad del paisaje se interrumpe nuevamente, promoviendo procesos de erosión/sedimentación, hace 1900 años. Durante este tiempo se depositaron nuevos sedimentos aluviales sobre la terraza TH2, más arenosos, lo que indica una mayor carga en el cauce del río. Esta nueva fase de actividad origina la terraza del Holoceno más reciente TH1; es importante hacer notar que aún no se sabe si esta inestabilidad es provocada por el cambio en las condiciones ambientales o es resultado de una mayor erosión producto de la actividad humana en la región durante el Formativo. Es a partir de estos nuevos sedimentos que se desarrollan los suelos asociados con el periodo Clásico, tanto las edades como los materiales arqueológicos registrados en el suelo establecen su temporalidad. Finalmente, es a partir de Clásico tardío-Posclásico que los periodos de inestabilidad en el paisaje se presentan con mayor frecuencia debido a la actividad del sistema fluvial, que puede ser relacionado directamente con una mayor densidad de asentamientos, así como mayor explotación de los recursos naturales.

4.2 Paleoambiente y actividad humana en el Noroeste de las Tierras Bajas Mayas

El amplio desarrollo cultural del área Maya corresponde con la parte media-final del Holoceno donde se registra gran variabilidad climática (de los 5,000 años al presente); el periodo que abarca de 1200 a 1000 años coincide con el colapso a gran escala de la civilización en el área, por lo cual, los estudios sobre la reconstrucción paleoambiental se enfocan en el impacto del hombre al medio, dando énfasis a los efectos de la actividad agrícola, como la degradación, erosión y sedimentación (Beach et al., 2011; 2009; Brenner et al., 1990). Es importante señalar que la mayoría de estos estudios, como se ha mencionado en los apartados anteriores, se han realizado en Belice, Guatemala y Honduras, y en menor cantidad en la Península de Yucatán y la Planicie Costera del Golfo (Dahlin, Chambers, y Foss, 1980; Dunning et al., 2002; Beach et al., 2003; Fernández et al., 2005; Dunning et al., 2006; Cabadas et al., 2010), siendo esta última el área con el registro más temprano de la agricultura (Pope et al., 2001). No obstante, Ortiz-Pérez et al. (2005) menciona que las diferencias en las geoformas del paisaje de las Tierras Mayas, producen una alta variabilidad en los ecosistemas modernos, por ende, suponemos que esta diferencia también se presentan en los ambientes del Holoceno y, en consecuencia, las reconstrucciones paleoambientales con base en los diferentes registros no reflejen las condiciones climáticas de toda la región.

Es así que los estudios locales se hacen necesarios para comprender la dinámica regional. Particularmente, hemos llevado a cabo estos estudios locales en paleosuelos, debido a su amplia distribución espacial. La fuerte dependencia del suelo con los factores ambientales, hacen que el registro paleopedológico muestre las variaciones locales y permita reconstruir el mosaico de microambientes en la región. Los paleosuelos aluviales en la cuenca media del río Usumacinta reflejan tanto la tendencia natural de cambio en las condiciones ambientales del Holoceno como las modificaciones de origen antrópico, particularmente sobre la cubierta vegetal debido a la intensa actividad agrícola.

Ya hemos comentado sobre las condiciones ambientales que hemos reconstruido durante el Pleistoceno tardío y el Holoceno, por medio de los paleosuelos. Para enfatizar, se tiene que el Pleistoceno tardío es húmedo, evidenciado por la presencia de Gleysoles arcillosos, formados en el periodo entre 110 y 9 ka. El inicio del Holoceno muestra cambios importantes en las condiciones climáticas de la región, aumentando las tasas de sedimentación debido posiblemente a las condiciones más húmedas reportadas para el Noreste de Guatemala por Islebe et al., (1996) y Mueller et al., (2009) en el Lago de Petén Itzá durante el Holoceno temprano; que también son documentados en otros registros lacustres como en Salpetén y Quexil al norte de Guatemala (Leyden, 1984, 1987, 2002; Islebe et al., 1996); Cobá (Whitmore qt al., 1996), y Chichancanab (Hodell et al., 2001; Hodel, Brenner y Curtis, 2007).

En el Holoceno medio se tiene una tendencia hacia condiciones más secas, que se indican por la precipitación de carbonatos secundarios. Durante este periodo se desarrollan Vertisoles, que marcan climas estacionales, los cuales representan la cubierta edáfica durante el periodo Formativo; la combinación de los carbonatos secundarios y los rasgos vérticos representan una transición hacia climas más secos con una marcada estacionalidad que está relaciona con una tendencia regional que ha sido registrada en Mesoamérica. Metcalfe et al., (2000) documentan un periodo más seco con fuertes oscilaciones entre los 6,000 y 5,000 años cal. A. P., en tanto que Islebe et al., (1996) reportan una disminución del polen tropical en el lago de Petén Itza alrededor de los 5600 años cal A.P. que se asocia con climas más secos; en Guatemala a los 4500 (Mueller et al., 2009) y en Yucatán (Carillo Bastos et al., 2010) también se observa una tendencia hacia climas más secos en el Holoceno medio. A escala global se conoce una disminución de la humedad atmosférica entre los 6500 y 4500 años cal. A.P. (Ritchie, Eyles y Haynes, 1985) que coincide con estos patrones.

5. CONSIDERACIONES FINALES

La arquitectura fluvial y la distribución espacial de los asentamientos humanos

En la Tierras Bajas Mayas Noroccidentales, la historia fluvial evidencia una clara relación entre la morfología aluvial y los asentamientos humanos en la región. Los sitios arqueológicos del Formativo preferentemente se localizan en la terraza más baja del río, TH2, en donde la planicie se inunda ocasionalmente. Aunque estos asentamientos son de menor escala que los registrados para el Clásico, son numerosos y se han asociado con aldeas agrícolas cercanas al cauce para un mejor aprovechamiento del medio (Liendo et al., 2013). En contraste, los asentamientos del Clásico como los grandes sitios urbanos de Palenque, Piedras Negras Yaxchilán, Pomoná , Santa Elena , Reforma Moral y Chinikihá se encuentran situados en las terrazas más antiguas (TP3 y TP2) y alejados del cauce actual del río, en donde la estabilidad del paisaje permitió la construcción de estructuras monumentales, así como proporcionar condiciones de defensa.

6. REFERENCIAS BILBIOGRÁFICAS

Beach, T., Luzzadder-Beach, S., Dunning, N., Scarborough, V. (2003). Depression soils in the lowland tropics of northwestern Belize. In A. Go´mez-Pompa, M. Allen, S.L. Fedick, & J.J. Jim´enez-Osornio (Eds.), Lowland Maya area: Three millennia at the human–wildland interface (pp.139–173). Binghamton, NY: Haworth Press.

Blum M. D., Törnqvist T., (2000). Fluvial responses to climate and sea-level change: a review and look forward: Sedimentology 47 (1), 2-48

Brenner, M., Rosenmeier, M.F., Hodell, D.A., y Curtis, J. (2002). Paleolimnology of the Maya Lowlands. Ancient Mesoamerica, 13, 41–157.

Bridgland D. R., Westaway R., (2008). Climatically controlled river terrace staircases: A worldwide Quaternary phenomenon: Geomorphology 98: 285-315.

Brown, A.G., (1997). Alluvial geoarchaeology: floodplain archaeology and environmental change: Cambridge, University Press, 377 p.

Cabadas, H., Solleiro, E., Sedov, S., Pi Puig, T., Gama-Castro, J., (2010). Pedosediments of karstic sinkholes in the eolianites of NE Yucatán: a record of Late Quaternary soil development, geomorphic processes and landscape stability. Geomorphology 122, 323–337pp

Correa-Metrio, A., Bush, M.B., Cabrera, K.R., Sully, S., Brenner, M., Hodell, D.A., Escobar, J., Guilderson, T. (2012). Rapid climate change and no-analog vegetation in lowland Central America during the last 86,000 years. Quaternary Science Reviews, 38, 63–75.

Dahlin, B.H., Chambers, M.E. & Foss, J.E. (1980). Project Acalches: Reconstructing the natural and cultural history of a seasonal swamp at El Mirador, Guatemala; preliminary results. In R. Matheny (Ed.), El Mirador, Peten, Guatemala: An interim report, Publication 45 (pp. 37–58). Provo, Utah: New World Archaeological Foundation.

Dunning N.P., Luzzadder-Beach, S.L., Beach, T., Jones, J.G., Scarborough, V. Culbert, T.P. (2002): Arising from the Bajos: The Evolution of a Neotropical Landscape and the Rise of Maya Civilization. – Annals of the Association of American Geographers, 92: 267–283.

Dunning, N., Beach, T., Luzzadder-Beach, S., (2006). Environmental variability among *bajos* in the southern Maya Lowlands and its implications for ancient Maya civilization and archaeology. In: University of Arizona Press, Lucero, L., Fash, B. (Eds.), Pre-Columbian Water Management, 111-133pp.

Dunning, N.P., Beach, T. (2010). Farms and forests: Spatial and temporal perspectives on ancient Maya landscapes. In I.P. Martini, & W. Chesworth (Eds.), Landscapes and societies (pp. 369–389). Springer Science Business Media B.V. New York.

Dunning, N.P, Luzzadder-Beach, S., Beach, T., Jones, J.G., Scarborough, V., Culbert, T.P., (2012). Arising from the Bajos: The Evolution of a Neotropical Landscape and the Rise of Maya Civilization: Annals of Association of American Geographers, 92, 267-283.

Fernández, F., Johnson, K., Terry, R., Nelson, S., Webster, D. (2005). Soil resources of the Ancient Maya at Piedras Negras, Guatemala. Soil Science Society of America Journal, 69, 2020–2032.

Gill, R.B. (2000). The great Maya droughts. Albuquerque: University of New Mexico Press.

Gregory, K.J., Benito, G., Dikau, R., Golosov, V., A.J.J. Jones, A.J.J., Macklin, M.G., Parsons, A.J., Passmore, D.G., Poesen, J., Starkel, L., D.E. Walling, D.E. (2006). Past hydrological events related to understanding global change: En: ICSU Research Project. In: Gregory, K.J., Macklin, M.G., Walling, D.E. (Eds.) 2006, Past hydrological events related to understanding global change. Catena 66, 2–13.

Haug, G., Gunther, D., Peterson, L., Sigman, D., Hughen, K., Aeshlimman, B. (2003). Climate and collapse of Maya civilization. Science, 299, 1731–1735.

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

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

Hodell D.A., Anselmetti, F.S. Ariztegui, D. (2008). An 85 ka record of climate change in lowland Central America. Quaternary Science Reviews, 27:1152–1165.

INEGI (1986). Síntesis geográfica y anexo cartográfico del Estado de Tabasco, México D. F., pp. 118

Leyden, B.W. (1984). Guatemalan forest synthesis after Pleistocene aridity. Proceedings of the National Academy of Sciences, USA, 81, 4856–4859.

Liendo S. R., Solleiro R. E., Solís-Castillo B., Segey S., Ortiz P. M. A. (2013). Prehispanic Population Dynamics in the western Maya Lowlands: Evaluating resilence and vulnerability in ancient landscape. En: Resilence and vulnerability ancient landscape . Transforming Maya Archeology IHOPE. Antropological papers of the American Antropological Asociation. Editores: Aelen Chase y Vernon Scarborough. Willey Backwell, Hoboken, NJ. (in press)

López, S. (2012). Indicadores de la paleovegetación en las secuencias edafosedimentarias holocénicas del Río Usumacinta. Tesis profesional, Facultad de Ciencias, UNAM, 148 pp. (inédita).

Lounejeva-Baturina, E., Morales-Puente, P., Cabadas-Báez, H.V., Cienfuegos-Alvarado, E., Sedov, S., Vallejo-Gómez, E., Solleiro-Rebolledo, E. (2006). Late Pleistocene to Holocene environmental changes from $\delta^{13}C$ determinations in soils at Teotihuacan, Mexico: Geofísica Internacional, 45, 85-98pp.

Mayewski-A., Rohling-E., E., Stager-Curt, J., Karlén, W., Maasch-A., K., Meeker, D.L., Meyerson-A., E., Gasse, F., Kreveld-Van, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schineider-R., R., Steig-J., E. (2004). Holocene climate variability: Quaternary Research, 62, 243-255pp.

Mueller, A.D., Islebe, G., Hillesheim, M.B., Grzesikc, D.A., Anselmetti, F.S., Ariztegui, D., Brenner, M., Curtis, J.H., Hodell, D.A., & Venzc, K.A. (2009). Climatic drying and associated forest decline in the lowlands of northern Guatemala during the Late Holocene. Quaternary Research, 71, 133–141.

Ortiz M. A., Siebe C., Cram S. (2005). Diferenciación ecogeográfica de Tabasco: En: Bueno J., Álvarez F., Santiago S. (Eds) Biodiversidad del Estado de Tabasco, pp. 336. Instituto de Biología, UNAM-CONABIO, México.

Palma D. J., Cisneros J., Trujillo A., Granados N., Serrano J., Argueta J. (1985). Caracterización de los suelos de Tabasco, uso actual y potencial y taxonomía: SECUR, Gobierno del Estado de Tabasco, 42pp.

Mayewski-A., Rohling-E., E., Stager-Curt, J., Karlén, W., Maasch-A., K., Meeker, D.L., Meyerson-A., E., Gasse, F., Kreveld-Van, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schineider-R., R., Steig-J., E. (2004). Holocene climate variability: Quaternary Research, 62, 243-255pp.

Solís-Castillo, Berenice (a), Solleiro-Rebolledo, E., Sedov, S., Liendo, R., López-Rivera, S. and Ortiz-Pérez, M.A. (2013). Paleoenvironment and human occupation in the Maya lowlands of the Usumacinta River, Mexico: Geoarchaeology 28: 268–288.

Solís-Castillo Berenice (b), Christine Thiel, Héctor Cabadas, Elizabeth Solleiro, Sergey Sedov, Birgit Terhorst, Bodo Damm, Manfred Frechen and Sumiko Tsukamoto. (2013) Holocene sequences in the Mayan Lowlands: a provenance study using heavy mineral distributions: Eiszeitalter und Gegenwart. Quaternary Science Journal (in press)

Turner,B.L., Miksicek,C.H. (1984). Economic plant species associated with pre-historic agriculture in the Maya Lowlands: Economic Botany, 38, 179-193.

Vandenberghe J. (1995). Timescales, climate and river development: Quaternary Science Review 14, 631-638

Walker, I.J., Desloges, J.R., Crawford, G.W., Smith, D.G. (1997). Department of Anthropology, Erindale College, Floodplain Formation Processes and Archaeological Implications at the Grand Banks Site, Lower Grand River, Southern, Ontario Geoarchaeology: An International Journal, Vol. 12, No. 8, 865–887.

Webster, D. (2002). The Fall of the Ancient Maya: London, Thamesand HudsonLtd.

West R. C., Psuty P., Thom B. (1976). Las Tierras Bajas de Tabasco en el Sureste de México: Gobierno del Estado de Tabasco, México, pp. 409.

Wiesbeck, C. (2012). The influence of Mayan land use on soils and pedosediments in carstic depressions in Yucatan, Mexico. Diplomarbeit zur Erlangung des akademischen Grades einer Diplom-Geographin. Julius-Maximilians-Universität Würzburg, Institut für Geographie, 143 pp.