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Geochronology and landscape evolution of the strand-plain of the Usumacinta and Grijalva rivers, southern Mexico

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Abstract

The strand-plain of the Usumacinta and Grijalva rivers is the largest of the Gulf of Mexico as it is characterized by a sequence of well-preserved beach-dune ridges (n > 100) distributed ~150 km along the shoreline. This prominent coastal landform is part of the delta plain of Tabasco and Campeche. We present geochronogical data of the beach-dune ridges sequence of the Usumacinta and Grijalva rivers. Radiocarbon dating failed in providing consistent ages of the ridges in contrast to optically stimulated luminescence (OSL), which yielded coherent and robust dates. The oldest beach-dune ridges were formed ~2.5 ka. The presence of blocked-valley lakes evidences a recent process of sediment aggradation on the delta plain caused by a marine transgression. Using a regression model with the OSL ages and the distance of beach-dune ridges from the shoreline we estimate

that the autoretreat yielded the sediment accumulation ~7 ka. Our estimation agrees with other general models of sea level rising in the Gulf of Mexico that consider a marine stabilization initiated about ~6 to 7 ka. The progradation rates of the beach-dune ridges (4.7 to 8.9 m yr^{-1}) place this strand-plain among those with high sedimentation rates in the Gulf of Mexico and, perhaps, around the world.

Keywords

Strand-plain of Usumacinta and Grijalva rivers, delta plain of Tabasco and Campeche, landscape evolution, OSL, Gulf of Mexico

1. Introduction

Strand-plains are present in all continents but they are more frequent in wave-dominated beaches where there is a large amount of terrigenous sediment in the foreshore that is delivered by rivers (Nordstrom et al., 1991; Otvos, 2000; Tamura, 2012). This type of landform is composed of beach-dune ridges sequences that form in decadal time-scales and prograde toward the sea. In cases where the geochronology of ridges is well constrained the progradational rates are established using the distance of the ridges from inland to the sea. In the Gulf of Mexico, the progradational rates for strand-plains range from 0.08 m yr^{-1}

in the Apalachicola Barrier (Rink and López, 2010) to 1.57 m yr^{-1} for Merrit Island in Florida (Rink and Forrest, 2005). For other strand-plains around the world, low progradational rates have been reported in SW Australia, with 0.57m yr^{-1} in the coast of New South Wales (Thom et al., 1978) and 0.38 m yr–1 in Guichen Bay, south Australia (Murray-Wallace et al., 2002); moderate progradational rates in Phra Thong Island, in Thailand, with 2.7 m yr^{-1} (Brill et al., 2012); and higher rates in Skalligen Spit in Denmank with 30 m yr^{-1} (Aagaard et al., 2007).

We investigate the strand-plain of the Usumacinta and Grijalva rivers (southern Mexico) which forms part of a large delta plain (Fig. 1). The Usumacinta-Grijalva strand-plain is the largest of the Gulf of Mexico as ~150 km wide, that includes part of the coast of Tabasco and Campeche and extends for more than 25 km inland. This landscape preserves more than 100 beach-dune ridges, and constitutes a unique sedimentary record for understanding the sedimentation rates of the coastal plain of Tabasco and Campeche, and denudation rates for the highlands of southern Mexico and northern Guatemala. Moreover, the strand-plain is also direct evidence for the evolution of the Usumacinta and Grijalva rivers, which together form a river system ranked in the 10^{th} position of the largest rivers of

North America with a mean annual discharge of ~2,678 $m^3 s^{-1}$ (Hudson et al., 2005; Benke, 2009).

Despite its extension and geological significance, the region has remained largely understudied (Davis, 2011). Psuty (1965; 1967) and West et al. (1969) conducted the pioneering study of this strand-plain in the 1960s. Based on the projection of the subparallel beach-dune ridges toward the sea, they recognized three progradational phases associated with the relocation of the mouth of the Usumacinta and Grijalva rivers. They, however, did not provide ages of the strand-plain and they only considered the strand-plain as recent fluvial feature of the Quaternary. More recently, Hernández Santana et al., (2007) delineated the translocation of the shoreline of the coasts of Tabasco and Campeche based on the interpretation of aerial photographs.

Our main goal is to provide a robust dating of the beach-dune ridges of this strand-plain to tease out the different phases of its evolution. For this purpose, we use Accelerator Mass Spectrometry (AMS) ^{14}C and Optically Stimulated Luminescence (OSL) analysis. OSL has been proved to provide accurate dates of strand-plain deposits because these tend to be well-reset due to the aeolian redistribution of sediment during the beach-dunes formation

(Rink and Pieper, 2001; Rink, 2003). The role of aeolian processes in the formation of beach-dune ridges among different strand-plains around the world is under debate (Tamura, 2012), however, the studies of Psuty (1965; 1967) and West et al. (1969) indicate that aeolian processes are important in the formation of beach-dune ridges in the coast of Tabasco and Campeche. They observed that the sand transported to the beach by middle intensity waves is redeposited to the top of berms by winds (Psuty, 1965; 1967).

2. Methods

2.1. *Radiocarbon and OSL analysis*

In November 2015, fieldwork was undertaken in Tabasco and Campeche to extract the samples from different beach-dune ridges on the strand-plain for dating. Our sampling strategy consisted of collecting samples from along two transects perpendicular to the coast. We carefully selected only those lands with undisturbed beach-dune ridges and avoided in all cases those sites with evidences of anthropic perturbation. We sampled eight sites with well-preserved crests around the strand-plain of Usumacinta and Grijalva rivers (Figs. 2 and 3).

To extract samples for OSL and AMS ^{14}C dating we excavated a hole in the top of crests. We covered the hole with a black opaque blanket and we took samples at ~0.5 m of depth by inserting a plastic tube of 20 cm long and 5 cm diameter into the deposit. Once the tube was filled with sediment, we extracted and covered it with aluminum foil. The sampled material was used for both luminescence analysis and determination of the environmental dose rates in the laboratory. We removed the sediment adjacent to the place where we extracted the tube and collected ~500 g of material in a bag that was used in the laboratory for the determination of the gamma dose rates. These samples were analyzed at the Scottish Environmental Research Centre (SUERC), in the United Kingdom, using the single aliquot regenerative (SAR) method on grains of quartz. For radiocarbon analysis, we extracted chunks of organic matter, charcoal and organic sediment from inside the same holes from the same ridge where we extracted the OSL samples. Four of the samples were sent to the Beta Analytic Laboratory in USA for their analysis with an AMS.

2.2. Terrain analysis

We used Landsat 8 images and ASTER digital elevation models (DEMs) of 30 m resolution for photointerpretation of major phases of evolution of the Usumacinta and Grijalva strand-plain. Both products were downloaded from the USGS webpage

(https://landsat.usgs.gov). We also analyzed the available high-resolution digital elevation models (HRDEM) of 3 m of resolution from LIDAR datasets offered by the INEGI in their webpage (http://www.inegi.org.mx) which was manipulated in Arc Gis10.1.

3. Results and discussion

3.1 Phases of evolution of the strand-plain of the Usumacinta and Grijalva rivers according to photointerpretation

The three progradational phases of evolution of the strand-plain identified by Psuty (1965; 1967) and West et al. (1969) were confirmed based on photointerpretation of Landsat 8 images and ASTER digital elevation models (DEMs) of 30 m resolution.

During phase I the Usumacinta and Grijalva rivers flowed separately into the Gulf of Mexico. The evidence of this formative period is in the western sector of the strand-plain where the beach-dune ridges are oriented from NW to SE (Fig. 2). The NW-SE orientation indicates that a river inlet flowed ~10 km west from Grijalva River current position. The Grijalva River migrated toward the east in previous episodes to the phase I. This is

confirmed by the presence of palaeo-channels along the coastal plain of Tabasco and the eroded beach-dune ridges found in the river mouth of Tonala and Rio Seco rivers (Fig.1B). During this phase the Usumacinta River probably discharged into the sea, near to Laguna de Terminos (Fig. 1).

During phase II the orientation of the beach-dune ridges indicates that the Usumacinta and Grijalva rivers joined a few kilometers inland and flowed into the sea through the San Pedro-San Pablo (SPSP) River (Fig. 2). Projecting this set of beach-dune ridges toward the sea, we reconstructed a delta lobe that protruded ~6 km seaward. In this phase, a palaeo-channel in the western sector of the strand-plain evolved contemporaneously with the delta lobe at the SPSP River. This palaeo-channel has a distributary channel that was created when the Grijalva River flowed into the sea during phase I and it incises part of the beach-dune ridges built in the phase II.

Phase III initiated with the migration of Usumacinta and Grijalva rivers toward the west where they have remained in their current position (Fig. 2). In this phase these rivers have built the modern delta lobe. In this phase the SPSP River dropped its rate of sediment delivered to the sea and the sea waves started to erode the delta lobe formed during phase II

(see Fig. 4). The precise timing when phase II changed to phase III is when the modern delta lobe grew up and the old delta lobe at SPSP River started to be eroded.

3.2. OSL and Radiocarbon results

Radiocarbon samples resulted in very young ages ranging from 233 ± 236 BP to post 0 BP. The sample extracted close to the shoreline provided post 0 BP, in the middle part of the strand-plain, the closer sample to the coast is of 180 ± 44 BP and the farther inland of 233 ± 236 BP. The sample located in the furthest point inland yield an age of post 0 BP. Three of the four AMS ^{14}C dates contain younger dates toward the shoreline but the sample located farther inland yield a post 0 BP age (see Table 1). All the AMS ^{14}C dates are yielding very recent ages making difficult to constrain the age of strand-plain. We interpreted that the ages are indicative of the colonization of vegetal species on the strand-plain rather than the beach-dune ridges formation.

OSL ages ranged from 560 ± 40 BC (2.57 ± 0.04 ka) in the ridge sampled farther inland to 1880 ± 5 AD (0.14 ± 0.01 ka) for the sample extracted close the shoreline and in the current delta lobe. We observed a strong linear correlation between OSL ages versus their distance from the shoreline ($R^2 = 0.88$; $p<0.01$; $F<0.01$) (Fig. 2 and Table 2). This trend agrees with

178 a simple progradational sequence model of deposits. OSL ages are within historical time,
179 spanning through the Middle and Late Preclassic, and the Classic periods of the Maya
180 chronology (Mascarelli, 2010).
181
182 *3.3. Contrasting OSL results with historical records*
183
184 OSL ages suggest that the strand-plain of the Usumacinta and Grijalva rivers was under
185 formation during the time of the Maya Civilization apogee. The spatial distribution of the
186 Maya archeological sites in Tabasco and Campeche are located outside the strand-plain of
187 the Usumacinta and Grijalva rivers (see Fig. 1). Although this fact does not prove by itself
188 that the strand-plain was under sedimentation during the time of the Maya Civilization, the
189 lack of evidences of human occupation in the strand-plain supports the fact that this
190 landform was in formation during that time.
191
192 The first historical record of the Usumacinta and Grijalva rivers area is from the writings of
193 the Spanish Armada that arrived to the southern coasts of the Gulf of Mexico in 1518 AD
194 [*García-Icazbalceta*, 1972]. These documents described how the ship of Juan de Grijalva
195 navigated the mouth of the Usumacinta and Grijalva rivers. This historical evidence

196 indicates that in 1518 AD the strand-plain was in phase III of evolution. We used the age
197 of samples D6 and D8 to calculate the time of transition between phases II and III,
198 assuming a constant progradational rate. The distance between samples is 5.5 km, and the
199 transition between phase II to III occurred ~4.5 km seaward from sample D8. Using the
200 progradational rate model of ∂8.87 m y^{-1} we calculated that the transition between phase II
201 and III, that is also the starting date of phase III occurred ~1383 AD. This date agrees with
202 the fact that in 1510 AD, when Juan de Grijalva arrived to the coasts of Tabasco and
203 Campeche, the strand-plain was on its phase III of evolution.
204
205 Projecting the orientation of the truncated beach-dune ridges of the delta lobe of the SPSP
206 River (phase II) we estimated the mean erosion rate on this delta lobe, constraining the date
207 for transition between phases II and III at 1405 AD. The mean erosion rate was 10 m yr^{-1}.
208 Hernández Santana et al (2007) calculated a mean erosion rate of 8 m yr^{-1} in this same delta
209 lobe between 1943 to 1995 by using aerial photographs of the coasts of Campeche and
210 Tabasco. In this case, this independent study agrees with our estimation of the erosion rates
211 for the delta lobe of the SPSP River using the OSL ages.
212

3.4.Landscape evolution of the strand-plain of the Usumacinta and Grijalva rivers according to OSL ages

Our regression model demonstrates that there is a linear relationship between distance from the shoreline and age of the sampled sites (Fig. 2). All the ages prograde towards the coast with exception of sample D2 (2.57 ± 0.04 ka) that is in phase II but is older than D1 (Table 2). Because D2 is very close to a paleo-channel (Fig. 2) we suspect that partially bleached grains transported in this fluvial environment were deposited on the top of the ridge at the time the paleo-channel was active. Thus, the OSL age of D2 yields an older age than it should be according to its position in the strand-plain.

Using the OSL ages we propose that phase I of evolution of the strand-plain initiated ~2.5 ka, as the sample located farther inland, D1, yielded 2.37 ± 0.07 ka. To calculate the beginning of Phase II, we considered that the first beach-dune ridge was located at ~1 km inland from D8. Using the same progradational model of ∂8.87 m y^{-1} used to estimate the beginning of Phase III, we calculated that Phase II initiated ~1.25 ka by adding 113 years to the age of D8 (1.14 ± 0.03 ka). As mentioned above, Phase III initiated ~0.63 ka (i.e. 1383 BC).

The progradation rates in the strand-plain variate among the different OSL samples between 4.7 to 8.9 m yr^{-1} and a mean period of bar formation of 13.5 m/yr. These values place the strand-plain of the Usumacinta and Grijalva rivers among those with high sedimentation rates in the Gulf of Mexico and around the world (Fig. 5).

3.5. The strand-plain of the Usumacinta and Grijalva rivers in the delta plain of the Tabasco and Campeche

We recognized two sectors of the delta plain: (1) the western sector, which is composed by abandoned river channels and some remnants of eroded beach-dune ridges sequences located along the shoreline (Fig. 1B) and (2) the eastern sector, which contains the strand-plain of the Usumacinta and Grijalva rivers and where the current channels of these rivers distribute and flow into the sea (Fig. 1B). The western sector has a lower elevation than the eastern sector (Fig. 1), supporting our interpretation that the sedimentation rates in the delta plain are higher in the east.

248 The boundary between the delta plain and the sierra that is marked by an abrupt change in
249 elevation at an average distance from the current shoreline of 90 km, characterized by the
250 presence of blocked-valley lakes, particularly in the eastern sector (Fig. 1). These kinds of
251 lakes indicate that a process of sediment aggradation dammed valleys with insufficient
252 discharge to incise into the coastal plain, like in the case of some tributaries of the Fly River
253 in Papua New Guinea (Lauer et al., 2008). The aggradation process of the delta plain
254 suggests that a marine transgression inundated the surface, more recently in the eastern part
255 of the delta which has a lower elevation, and it was followed by a process of sediment
256 accumulation initiated in the boundary between the delta plain and the sierra and
257 progressively moving towards the sea (Muto and Steel, 1997; Canestrelli et al., 2010).
258 Therefore, the strand-plain of the Usumacinta and Grijalva rivers, that occupies ~25% of
259 the southern sector of the delta plain, correspond to the youngest feature only. To calculate
260 the moment in which the deltaic autoretreat stopped and started the sediment accumulation
261 in the delta, we used a regression model of the OSL ages to distance to the shoreline. For
262 this purpose, we assumed that the sediment delivery from the Usumacinta and Grijalva
263 rivers has remained constant. We obtained that the model of aggradation of the eastern
264 sector delta plain occurred ~7 ka (Fig. 2). Considering that the sea-level rise started to
265 cease about ~6 ka time in the Gulf of Mexico (Balsillie and Donoghue, 2004), our

estimation of the formation of the delta is plausible. Finally, we propose that after the marine transgression, the sediment accommodation in the southern sector of the delta plain must have initiated under shallow waters that inhibited beach-dune ridge formation; as the intensity of waves should have been reduced. When the shoreline moved toward deeper waters, wave energy increased enough to form beach-dune ridges. This explains the lack of beach-dune ridges in the inland part of the delta plain.

4. Conclusions

We introduce a robust geochronological record of the largest strand-plain of the Gulf of Mexico and one of the most important worldwide. Eight OSL ages allow us to constrain the different phases of evolution of the strand-plain of the Usumacinta and Grijalva rivers and to provide progradation rates during it formation. Based on a regression model between OSL ages and distance we propose that aggradation in the coastal plain of Tabasco and Campeche initiated ~7 ka by the onset of sea-level stabilization on the Gulf of Mexico. Results of this study strongly suggests that the strand-plain of the Usumacinta and Grijalva rivers is among the highest denudational rates reported for the Gulf of Mexico and among the world.

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406 **Figure captions**

407

408 **Figure 1**. Location map of the strand-plain of the Usumacinta and Grijalva rivers in the
409 delta plain of Tabasco and Campeche. In A Current position of the Usumacinta and Grijava
410 rivers in the delta plain and location of blocked-valley lakes. Numbers correspond to
411 arqueological sites, 1 = Comacalco; 2 = Palenque; 3 = Balancan and 4 = El Tigre. The
412 topographic data is from ASTER Global DEM of 30 m of resultion, ASTER GDEM is a
413 product of METI and NASA. In B is shown the former delta of Grijalva river at western
414 sector of the delta plain and prior to the formation of the Usumacinta and Grijalva strand-
415 plain (see Fig. 2). Topography extracted from 5m LIDAR DEM produced by INEGI.

416

417 **Figure 2**. Phases of evolution of the strand-plain of the Usumacinta and Grijalva rivers and
418 OSL ages. The inset shows the correlation between OSL ages and the distance of samples
419 from shoreline confirming a markedly progradation of beach-dune ridges from inland
420 towards the sea. The delta plain initiated the aggradation process at ~7 ka evidence by the
421 blocked-valley lakes located 90 km off the shoreline (see Fig. 1A). The satellite images are
422 from Landsat 8 by the NASA) and available in the USGS webpage
423 (https://earthexplorer.usgs.gov).

Figure 3. Well-preserved beach-dune ridges of the strand-plain of the Usumacinta and Grijalva river in Campeche. In this site, crests over the inundated terrain in the swales allowing the identification of these parallel geomorphological forms. The width of ridges is about 2-3 m and difference of elevation between top of crests and bottom of swales is > 1 m.

Figure 4. Erosive shoreline at SPSP River. Notice that a remaining ridge in the front of the picture is partially destroyed by the effect of the waves.

Figure 5. Progradation rate (m yr-1) and period of formation (years per bar) for different reported strand-plains around the world. The Usumacinta-Grijalva is among the highest progradation rates and shortest periods of bar formation. Data of Tagueman Bay and Grand Traverse Bay by Argyilan et al., (2005); Canaveral Peninsula and Merrit Island by Rink and Forrest, (2005); Grinchen Bay by Murray-Wallace et al., (2002); Skallingen Spit by Aagaard et al., (2007); Phra Thong Island by Brill et al., (2012); New South Wales by Thom et al., (1978) and Apalachicola Barrier by Rink and Lopez, (2010).

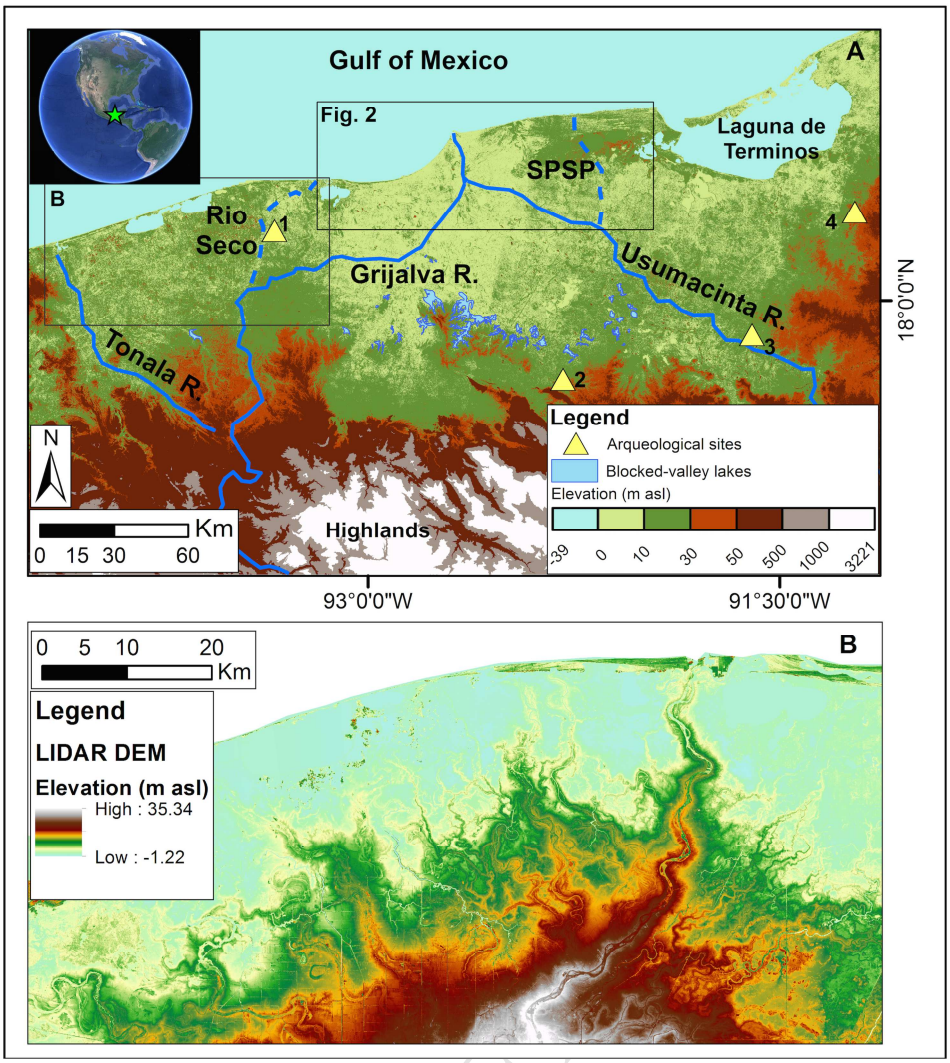
Table 1. List of the age of samples dated for AMS ^{14}C analysis in Beta Analytic Laboratory.

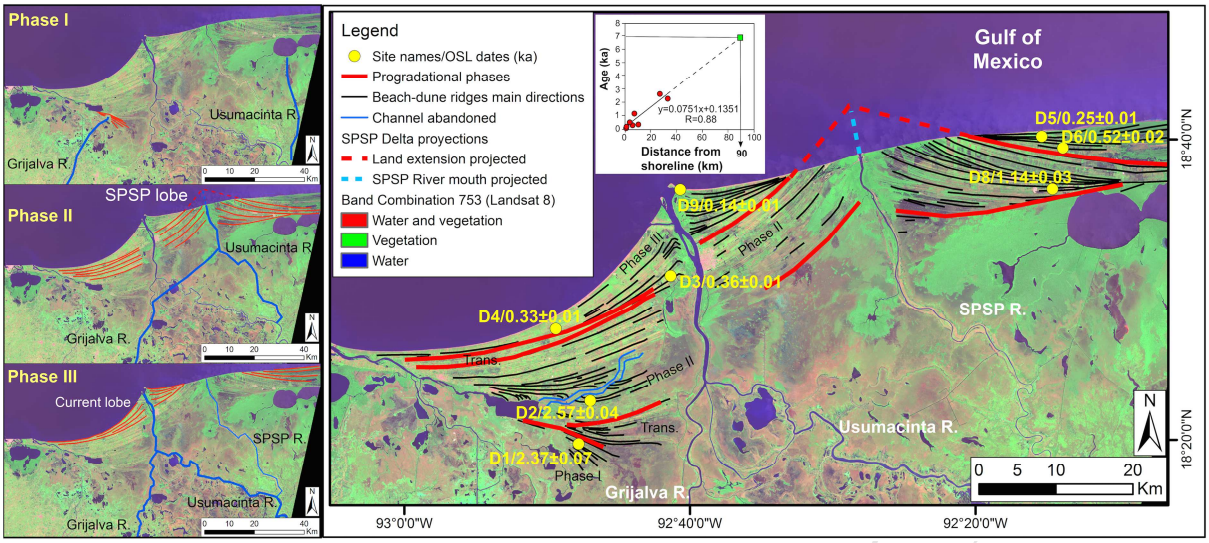
ID	Lab code	Easting	Northing	^{14}C age	Cal. ^{14}C age[a]	Material
D9	Beta - 442567	18°36´40.04395	92°40´40.62489	106.8 +/- 0.3 pMC	Post 0 BP	Plant material
D8	Beta - 442568	18°36´42.32562	92°14´36.39035	210 +/- 130 BP	233 ± 236 BP	Plant material
D3	Beta - 442569	19°30´55.06019	92°41´21.52405	180 +/- 30 BP	180 ± 44 BP	Charred material
D1	Beta - 442570	18°19´44.06024	92°47´48.30420	100.7 +/- 0.3 pMC	Post 0 BP	Organic sediment

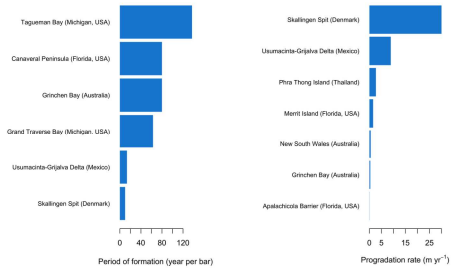
[a]Calibration using IntCal 13.14C (Reimer et al 2013) using the code "CLAM" (Blaawn 2010] written for R (R Development Core Team 2009).

Table 2. Sample names, location and OSL ages obtained for the eight sites around the strand-plain of the Usumacinta and Grijalva rivers. Errors stated are ± standard error (weighted standard deviation). Dose rate was estimated from high-resolution gamma spectrometry (using a EG&G Ortec Gamma-X detector) and a thick source beta counting system (Sanderson, 1988). Effective beta and gamma dose rates followed water corrections with grain size attenuation factors of Mejdahl (1979) for K, U, and Th, and including cosmic dose contribution (Prescott and Hutton, 1994). Equivalent doses were performed in grains of quartz using a Risø DA-15 automatic reader and following a single aliquot regeneration (SAR) protocol (Murray and Wintle, 2000) (For further details on the analytical procedures consult the laboratory report of Kinnaird et al., 2016).

ID	Lab code	Location and Elevation			OSL ages	
Field no.	SUTL no.	Northing	Easting	m asl	Years / ka	Calendar years
D1	2842	18º 19´44.06024	92º 47´48.30420	7	2.37 ± 0.07 (0.38)	-360 ± 70 (380)
D2	2843	18º 22´35.39771	92º 46´59.04204	1.57	2.57 ± 0.04 (0.30)	-560 ± 40 (300)
D3	2844	19º 30´55.06019	92º 41´21.52405	2.88	0.36 ± 0.01 (0.04)	1660 ± 15 (40)
D4	2845	18º 27´23.88197	92º 49´24.17609	0.78	0.33 ± 0.01 (0.04)	1685 ± 10 (40)
D5	2846	18º 40´11.78538	92º 15´21.74478	3.2	0.25 ± 0.01 (0.01)	1770 ± 10 (15)
D6	2847	18º 39´26.48189	92º 13´52.57510	3.5	0.52 ± 0.02 (0.06)	1500 ± 20 (60)
D8	2849	18º 36´42.32562	92º 14´36.39035	0	1.14 ± 0.03 (0.07)	875 ± 30 (70)
D9	2850	18º 36´40.04395	92º 40´40.62489	0	0.14 ± 0.01 (0.06)	1880 ± 5 (60)







- A robust OSL geochronological record for the strand-plain of Tabasco and Campeche
- Different phases of evolution of the strand-plain of Usumacinta and Grijalva rivers
- Aggradation of the coastal plain of Tabasco and Campeche initiated ~7 ka