Explosive eruption of El Chichón volcano (Mexico) disrupted 6 th century Maya civilization and contributed to global cooling

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ABSTRACT

A remarkably long period of Northern Hemispheric cooling in the 6th century CE, which disrupted human societies across large parts of the globe, has been attributed to volcanic forcing of climate. A major tropical eruption in 540 CE is thought to have played a key role, but there is no consensus about the source volcano to date. Here, we present evidence for El Chichón in southern Mexico as the most likely candidate, based on a refined reconstruction of the volcano's eruption history. A new chronological framework, derived from distal tephra deposits and the world's largest Holocene beach ridge plain along the Gulf of Mexico, enabled us to positively link a major explosive event to a prominent volcanic sulfur spike in bipolar ice core records, dated at 540 CE. We speculate that voluminous tephra fall from the eruption had a severe environmental impact on Maya societies, leading to temporary cultural decline, site abandonment, and migration within the core area of Maya civilization.

INTRODUCTION

The onset of an exceptionally long period of Northern Hemispheric cooling in the mid–6th century CE has been attributed to explosive volcanic activity (Sigl et al., 2015; Büntgen et al., 2016), but its exact cause and impact are highly debated and remain largely obscure. A single volcanic eruption in 536 CE was long held responsible for the "event", based on historical evidence for a dust veil or "dry fog" over Europe in that year (Stothers and Rampino, 1983). However, recent advances in the reconstruction of past explosive volcanic events from polar ice-core records (Sigl et al., 2015) indicate that multiple eruptions must have occurred within less than a decade. Prominent sulfate peaks in ice cores from Greenland point to one or more high-latitude Northern Hemispheric eruptions in 536 CE, whereas a large sulfate peak in ice cores from both Greenland and Antarctica records a tropical eruption in 540 CE (Sigl et al., 2015). Strong partitioning of volcanic sulfate toward the Northern Hemisphere, indicated by a factor of two higher deposition flux over Greenland compared to Antarctica (Sigl et al., 2015), suggests that the tropical source was located north of the equator. Volcanoes proposed as the source include Rabaul (Papua New Guinea; Stothers and Rampino, 1983), El Chichón (Mexico; Gill, 2000; Nooren et al., 2009), and Ilopango (El Salvador; Oppenheimer, 2011), although Rabaul has recently been discarded (McKee et al., 2015). Here, we present evidence for El Chichón (17.36°N, 93.23°W) in southern Mexico (Fig. 1) as the most likely candidate.

El Chichón has had multiple explosive eruptions during the Holocene, some of them probably several times larger than the well-known 1982 CE eruption (Tilling et al., 1984; Espíndola et al., 2000). The 1982 eruption created the worst volcanic disaster in modern Mexican history. It destroyed nearby villages via pyroclastic flows and lahars, covered ~45,000 km² with

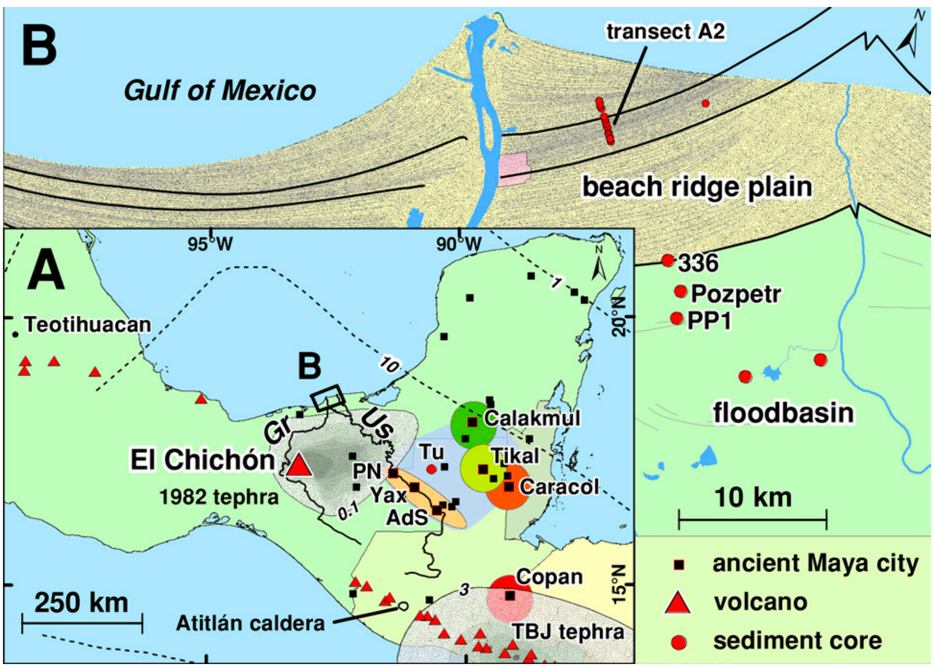

Figure 1. A: Major Maya cities during Classic Period and five subregions (encircled cities) in and near Central Maya Lowlands (blue) with relatively abundant dateable monuments dedicated during this period. Tephra-fall isopachs (in cm) are indicated for El Chichón's (Mexico) 1982 CE eruption (Varekamp et al., 1984), Ilopango's (El Salvador) Tierra Blanca Joven (TBJ) tephra (Kutterolf et al., 2008), and Atitlán's (Guatemala) Los Chocoyos tephra (dashed lines; Drexler et al., 1980). Us—Usumacinta River; Gr—Grijalva River; Tu—Lake Tuspan; PN—Piedras Negras; Yax—Yaxchilan; AdS—Altar de Sacrificios. B: Core locations and paleo-shorelines.

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volcanic ash (Fig. 1) (Varekamp et al., 1984), and injected ~7.5 Tg SO_2 into the stratosphere (Krueger et al., 2008). The stratospheric cloud spread globally (Robock and Matson, 1983), and subsequent deposition of aerosol particles was traced as sulfate anomalies in snow pits and ice cores from Greenland (Zielinski et al., 1997) and Antarctica (Traufetter et al., 2004). The extremely high sulfur content of El Chichón's 1982 magma (Luhr et al., 1984) and older pyroclastic deposits (Rose et al., 1984) makes it likely that earlier explosive eruptions ejected large quantities of SO_2 as well.

Dated pyroclastic flow deposits near the volcano point to an eruption in the mid–6th century CE (Tilling et al., 1984; Espíndola et al., 2000), but age constraints are inadequate to correlate this event with a particular sulfate spike in the ice-core records. Even the most reliable sample from carbonized tree branches, dated to 1520 ± 75 ^{14}C yr B.P. (Espíndola et al., 2000), yielded a calibrated age range that overlaps with at least five volcanic sulfate spikes in the ice-core records (Fig. 2A).

AGE CONSTRAINTS FROM DISTAL TEPHRA-FALL DEPOSITS

We significantly reduced this uncertainty in the timing of the eruption through radiocarbon dating of distal tephra deposited ~140 km northeast of El Chichón volcano. The late Holocene organic flood-basin sediments of the Usumacinta-Grijalva delta (Fig. 1B) contain two distinct tephra layers (Fig. 3), both derived from past eruptions of El Chichón as we could confirm by chemical fingerprinting of volcanic glass particles (Fig. 3). We also found small pumice fragments with a major-element composition comparable to that of the Los Chocoyos tephra from the caldera-forming Atitlán (Guatemala) eruption that occurred ~84,000 yr ago (Drexler et al., 1980). Because those pumice fragments are present throughout the sediment cores, they probably represent reworked material incorporated into the sediment after large floods. None of the analyzed glass shards had a major-element composition comparable to that of the Tierra Blanca Joven tephra from a large 5th–6th century CE eruption of Ilopango in El Salvador (Dull et al., 2001), indicating the unlikelihood that volcanic ash from this eruption reached the flood basin.

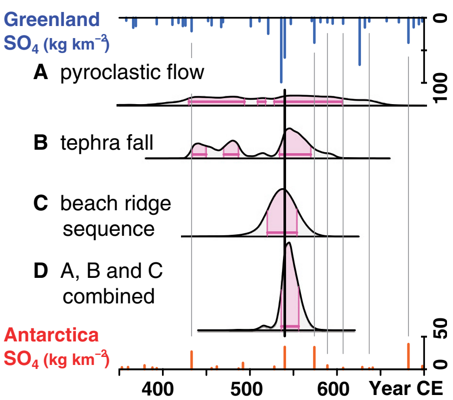

Figure 2. Probability distribution for age of mid–6th century CE eruption, El Chichón (Mexico). A: Individual sample of carbonized tree branches from pyroclastic flow deposit near volcano (Espíndola et al., 2000). B: Average of four carbonized fragments from distinct tephra layer in Pozpetr (Nooren et al., 2009) and PP1 cores. C: Modeled age of initial magnetite enrichment in beach ridge sequence. D: Equal weighted mean of A, B, and C (see GSA Data Repository[1] for complete list of ages in ^{14}C yr B.P.). Bipolar volcanic sulfate spikes (vertical black lines) and yearly volcanic sulfate deposition at Greenland (blue) and Antarctica (red) are derived from North Greenland Eemian project NEEM-2011-S1 ice core and WAIS (West Antarctic Ice Sheet) Divide WDC06A ice core (Sigl et al., 2015).

We dated six terrestrial macro-remains samples isolated from the organic sediments around the lowermost of the two distinct tephra layers in our PP1 core using accelerator mass spectrometry (AMS) ^{14}C analysis. Samples were pretreated by standard acid-alkali-acid and dated at the Groningen University AMS facility. The ^{14}C ages are reported in years before present (before 1950 CE; yr B.P.) and calibrated with the software package OxCal 4.2 (Bronk Ramsey, 2009) using the recommended IntCal13 calibration curve (Reimer et al., 2013). Three dated samples showed random shifts and are regarded as outliers. The other three samples yielded consistent ages of 1515 ± 75, 1530 ± 35, and 1535 ± 40 ^{14}C yr B.P., which are in accordance with a 1535 ± 44 ^{14}C yr B.P. age obtained for the tephra layer at the same stratigraphic position in the nearby Pozpetr core (Nooren et al., 2009). Although the calibrated age range for the average of these four ^{14}C ages overlaps with four bipolar volcanic sulfate spikes, the 540 CE date has the highest probability (Fig. 2B).

AGE CONSTRAINTS FROM THE BEACH RIDGE SEQUENCE

Additional evidence that the eruption occurred ca. 540 CE comes from the dating of a volcanic interval within a sequence of beach ridges along the Gulf of Mexico. Ample sediment supply, including transport of volcaniclastic components from El Chichón toward the coast, has produced the world's largest Holocene beach ridge plain (Fig. 1). Exceptionally high progradation rates (2–6 m/yr) enable precise dating of individual ridges and volcanic-derived intervals.

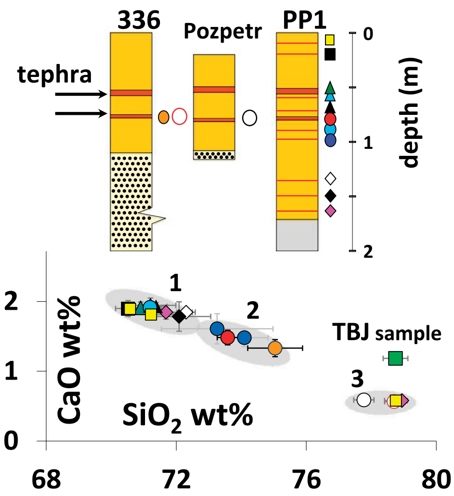

Figure 3. SiO_2-CaO diagram for analyzed volcanic glass shards retrieved from flood-basin cores Pozpetr (Nooren et al., 2009), PP1, and 336 (Mexico) and from a sample of Ilopango's (El Salvador) Tierra Blanca Joven (TBJ) tephra. Clusters 1 and 2 relate to El Chichón, whereas cluster 3 corresponds to Los Chocoyos tephra of Atitlán caldera (Guatemala) (see Data Repository [see footnote 1] for complete set of major-element results).

Considering that volcaniclastics from El Chichón contain titanomagnetite (Luhr et al., 1984), a strong increase in the supply of titanomagnetite following an eruption can be traced as elevated magnetic susceptibility values of the accumulating beach ridge sands. We took sediment cores along transect A2 (Fig. 1B), including 6th-century CE deposits, and far from (former) river mouths to avoid unwanted effects from dynamic shore progradation or erosion. Cores were taken with a Van der Staay suction corer to 4–11 m depth, and magnetic susceptibility was measured with a ZH Instruments SM 30 on sand samples collected at 20–50 cm depth intervals. Leaf fragments isolated from organic debris layers were AMS ^{14}C dated following the same procedure as described above. An age-distance model was constructed using a depositional P-sequence model ($k = 0.05$) of the Oxcal 4.2 calibration program (Bronk Ramsey, 2009) using the IntCal13 calibration curve (Reimer et al., 2013) and an estimated shoreface slope of 4°. Beach ridge sands near the former mean sea level had the highest magnetic susceptibility values (Fig. 4), consistent with accumulation of heavy minerals mainly taking place within the swash zone (Komar, 2007). The onset of enhanced supply of volcanic-derived magnetite to the beach ridges occurred in 537 ± 17 CE (at 1σ confidence level) (Figs. 2C and 4).

The combined results from proximal pyroclastic flow deposits, distal tephra-fall deposits

[1]GSA Data Repository item 2017047, detailed description of methods, complete set of major element results, and list of ^{14}C dated samples, is available online at http://www.geosociety.org/pubs/ft2017.htm or on request from editing@geosociety.org.

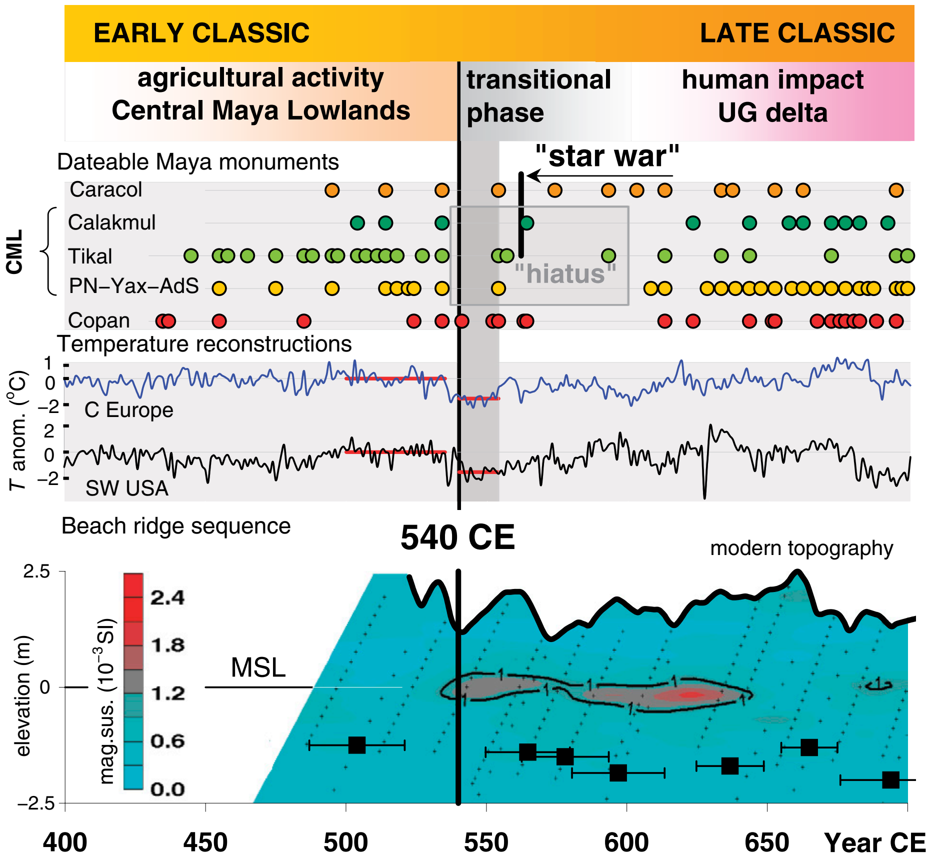

Figure 4. El Chichón (Mexico) 540 CE eruption, registered in beach ridge sequence as sudden increase in magnetic susceptibility, was followed by prolonged period of Northern Hemispheric summer cooling (June, July, August) temperature anomaly (after Büntgen et al., 2016; Salzer et al., 2014), reduction in dedication of monuments in Central Maya Lowlands (CML) (after Kennett et al., 2012), reduced agricultural activity near Lake Tuspan (Galop et al., 2004), and increased human activity in Usumacinta-Grijalva (UG) delta a few decades after eruption (Nooren et al., 2009). Beach ridge sequence has been transferred to a time scale and interpolated magnetic susceptibility values of analyzed sand samples (crosses) and modeled ages of accelerator mass spectrometry ^{14}C dated samples with 1σ uncertainty bars (squares) are indicated. PN-Yax-AdS—Piedras Negras–Yaxchilan–Altar de Sacrificios; T anom.—temperature anomaly; C Europe—Central Europe; SW USA—southwestern USA; mag.sus.—magnetic susceptibility; MSL—mean sea level.

in the Usumacinta-Grijalva delta, and magnetite enrichment in the beach ridge sequence yield an eruption date of 546 ± 10 CE (at 1σ) (Fig. 2D), which matches only with the 540 CE sulfur spike in the bipolar ice-core data.

IMPACT

The inferred age of the eruption coincides with a sudden episode of stagnation, decline, and increased warfare in what was at that time the densely populated Central Maya Lowlands (CML) (e.g., Dahlin and Chase, 2014). The period is also known as the "Early-Late Classic hiatus" because of a lack in the production and erection of carved monuments during this transitional phase (Morley, 1938) (Fig. 4). Although many theories have been postulated to explain this "dark age" in Maya history, the proximity of El Chichón to the CML makes a major eruption a likely catalyst. The spread of tephra fall from the 540 CE eruption is unknown, but main dispersal axes of ash plumes from El Chichón's last two eruptions were both directed toward the CML (Varekamp et al., 1984; Macías et al., 2003).

The most detrimental consequences for local Maya societies were probably the direct impact of tephra fall and associated hydrological changes in the watershed of the Usumacinta River, in line with evidence that the region was repeatedly affected by ash fall from explosive volcanic events (Tankersley et al., 2016). Denudation of large areas in the upper parts of the watershed probably resulted in increasing surface runoff and the generation of extensive floods in lower parts, as indicated by the deposition of a smectite-rich turbidite layer in Lake Tuspan (Fig. 1A) ca. 540 CE (Galop et al., 2004; Fleury et al., 2014). Smectite can form after post-depositional alteration of rhyolitic tephra (e.g., Poppe et al., 1985) and can also be a constituent of El Chichón's primary volcanic ash (Macías et al., 1997). A high sulfur content of 3.0 wt% of Lake Tuspan's 540 CE turbidite (determined by inductively coupled plasma–optical emission spectrometry after carbonate removal) and a high magnetic susceptibility (Galop et al., 2004) are also consistent with a volcanic admixture.

The pollen record from Lake Tuspan (Galop et al., 2004) shows evidence for a sudden reduction in agricultural activity and probably an abandonment of the area following the deposition of the turbidite. A demographic shift toward the Usumacinta-Grijalva delta has been suggested (Nooren et al., 2009), and increased human impact on the flood-basin vegetation a few decades after the eruption is concurrent with recovering and growing populations within the CML during the Late Classic period (Fig. 4). Probably not all Maya polities within the CML were equally affected by the eruption. Caracol does not show clear evidence for any decline (Dahlin and Chase, 2014), whereas Tikal was more severely impacted and weakened and may have been conquered later by an alliance of Caracol and Calakmul in the so-called "star war" of 562 CE. Societies were able to rebound from this "dark age" in Maya history, and culture flourished again in the Late Classic Period.

Although the eruption's magnitude and the local impact of large volcanic eruptions on societal-environmental conditions in the Maya Lowlands at large require further exploration (Sheets, 2001), an atmospheric effect of the eruption can confidently be associated with a prolonged period of summer cooling in the Northern Hemisphere. Evidence for growth reduction in tree-ring records of southwestern USA and Central Europe (Salzer et al., 2014; Büntgen et al., 2016) indicates a mean summer temperature reduction of 1.5 °C for the period 540–554 CE compared to the 500–535 CE period prior to the eruption (Fig. 4). It is likely that the El Chichón eruption reinforced a climatic cooling that had already been initiated by a single or multiple preceding high-latitude Northern Hemispheric volcanic eruptions in 536 CE (Sigl et al., 2015). Any volcanogenic climate effect on Maya civilization within the CML was probably subordinate to the various direct environmental impacts from the eruption itself.

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