Quantification of soil erosion rates related to ancient Maya deforestation

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ABSTRACT

We used seismic and sediment core data to quantify soil erosion rates for the past ~6000 yr in the closed catchment of Lake Salpetén, in the tropical lowlands of northern Guatemala. The region was affected by ancient Maya land use from before ca. 1000 B.C. to A.D. 900. This period of human impact coincided with deposition in the lake of a detrital unit (Maya Clay) as much as 7 m thick that contrasts sharply with the relatively organic-rich gyttja deposited both before and after Maya occupation of the watershed. The greatest soil loss, with mean sustained values of ~1000 t/km^{2}yr^{-1}, occurred in the Middle and Late Preclassic Periods (700 B.C. to A.D. 250), associated with relatively low Maya population densities. Soil erosion slowed during the period of maximum population density in the Late Classic Period (A.D. 550–830), indicating a decoupling between human population density and soil erosion rate. The most rapid soil loss occurred early during initial land clearance, suggesting that even low numbers of people can have profound impacts on lowland tropical karst landscapes.

Keywords: soil erosion, lake sediments, land use, Maya, seismic stratigraphy, human impact.

INTRODUCTION

The impact of the ancient Maya civilization on lowland tropical karst landscapes has been cited as an example of long-term, human-induced environmental degradation (Beach, 1998; Binford et al., 1987; Redman, 1999). Previous studies in the central Petén region of northern Guatemala indicated that Maya-induced deforestation and intensified agricultural activity led to accelerated topsoil erosion, increased lacustrine sedimentation, rapid soil nutrient depletion, and declining crop yields (Deevey et al., 1979; Olson, 1981; Rice and Rice, 1990). It was even suggested that human-induced environmental degradation contributed to the collapse of the Maya civilization in the ninth and tenth centuries A.D. (Redman, 1999).

Here we quantify changes in soil erosion rates in a closed drainage basin by combining seismic and sediment core investigations of the lacustrine sediments in Lake Salpetén. The Salpetén catchment is a simple source-to-sink system where lake deposits reflect erosional and runoff processes in the catchment. Temporal patterns of soil loss were compared to estimates of ancient Maya population densities (Rice et al., 1985; Rice and Rice, 1990) and with vegetation changes inferred from pollen analysis (Leyden, 1987).

Previous studies investigated prehistoric human impacts on soil erosion in Central America (Fisher, 2005; Fisher et al., 2003; O'Hara et al., 1993) and identified periods of relatively higher and lower erosion (Beach et al., 2006; Deevey et al., 1979; Dunning et al., 1998, 2002). Our approach enabled us to both identify the timing of erosion rate changes and estimate quantitatively the amount of soil downwasting, which we related to changes in human population density and land clearance through time.

APPROACH

The amount of sediment accumulated in lake basins has been used to quantify sediment yield and denudation rates in various catchments (De Vente and Poesen, 2005; Einsele and Hinderer, 1997; McIntyre, 1993). We applied a limnogeological approach to the Lake Salpetén catchment in northern Guatemala (Fig. 1) to quantify soil erosion history in relation to ancient Maya occupation in the watershed. Lake Salpetén is a small water body (2.55 km^2) with a surrounding catchment of 3.81 km^2 (Brezonik and Fox, 1974). It has a maximum depth of 34 m and is at 104 m above sea level. The lake has no permanent inflows and receives surface runoff only during strong precipitation events. It has no surface outflows, making the lake an effective sediment trap. The small catchment size, in combination with a lack of significant sediment storage capacity, implies rapid transport of eroded particles from the catchment (i.e., source) to the lake (i.e., sink). Scale dependency of the erosion rate, as observed in large catchments and for longer time scales (De Vente and Poesen, 2005), is thus minimal.

Sediments in Lake Salpetén were imaged geophysically with a 3.5 kHz seismic reflection survey (Fig. 2). Multiple transects provided a quasi-three-dimensional (3D) image of the sediment architecture, and

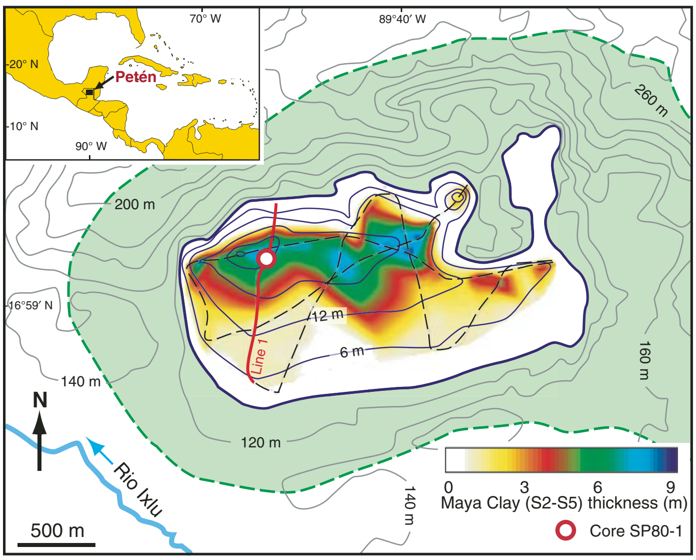

Figure 1. Bathymetry and catchment area of Lake Salpetén. Green area indicates lake catchment. Contour lines on land (gray) are plotted every 20 m. Bathymetric contour lines (blue) are 6 m intervals. Colored areas in lake indicate thickness of Maya Clay unit. Positions of seismic section (red line) displayed in Figure 2 and drill hole SP80-1 are also indicated. Inset shows lake location in Petén district of northern Guatemala. TOC—total organic carbon.

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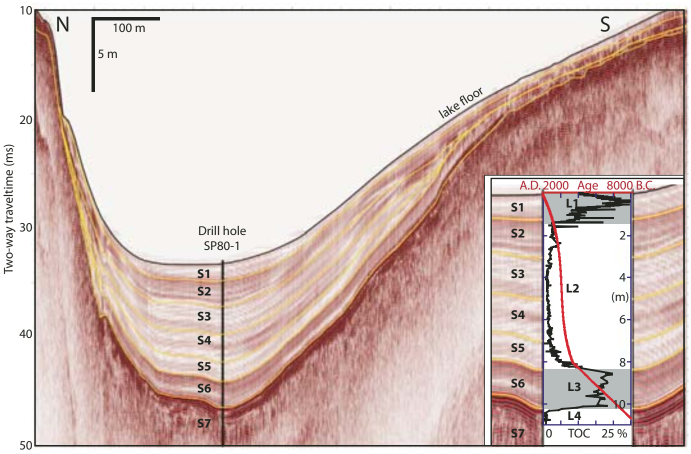

Figure 2. Seismic line 1 crossing the lake from north (left) to south (right) and location of drill hole SP80-1. Depth is given in two-way traveltime (ms). Seismic sequences S1–S7 are indicated by yellow lines (vertical exaggeration = 20×). Inset shows seismic to core correlation with coinciding lithologic units L1–L4 (L4—evaporites and/or clay; L3—Lower Gyttja, L2—Maya Clay; L1—Upper Gyttja). ^{14}C age data (in calendar k.y.; red dots) provide age model (red line) (Rosenmeier et al., 2002a, 2002b; Fig. DR1 [see footnote 1]). Total organic carbon curve (TOC, black line) indicates relatively sharp boundaries between lithologic units.

sediment volumes were quantified throughout the basin. Previous studies in Petén lakes that used single or even multiple sediment cores were unable to quantify basin-wide deposition because of sediment focusing and spatial variability in sediment thickness. Furthermore, chronological control in cores was poor because radiocarbon dates on bulk sediment were unreliable as a consequence of hard-water-lake error (Deevey and Stuiver, 1964). In this study, we combined information from seismic data with accelerator mass spectrometry (AMS) ^{14}C radiocarbon dates on lake sediment cores. We dated only terrestrial organic matter, enabling us to obtain a reliable sediment chronology (Rosenmeier et al., 2002a, 2002b; see GSA Data Repository Fig. DR1[1]).

SEDIMENT CORES

Lithologic and chronologic control was provided by an ~14 m core (SP80-1) that was recovered in Lake Salpetén in 1980 (Deevey et al., 1983) (Figs. 1 and 2). Because the uppermost 1.6 m of sediment were not recovered in SP80-1, a composite section was developed using two additional sediment cores collected in 1999 (Rosenmeier et al., 2002a; Table DR1, and the Composite Core and Age-Depth Model Construction in the Data Repository). All presented depths refer to this composite depth scale. Four main lithologic units were defined (L1–L4) on the basis of changes in sediment composition and chemistry (Rosenmeier et al., 2002b). Lithologic units were recognized by sharply contrasting organic matter content, as expressed by total organic carbon (TOC) concentrations (Fig. 2). Lowermost unit L4 (below 10.0 m) is composed of organic-poor, gypsum-rich lacustrine sediments. Units L3 (10.0–8.1 m) and L1 (1.5–0 m) are composed of dark-colored, organic-rich sediments (gyttja) with TOC values of ~20%. Between these two gyttja units is a thick, mostly inorganic deposit (L2; 8.1–1.5 m) that has been referred to as Maya Clay (Binford et al., 1987; Brenner, 1994; Deevey et al., 1979). L2 sediments consist mostly of fine-grained, partly laminated clays with variable amounts of carbonate and less organic matter (TOC value ~2%). This 6.5-m-thick package of clay-rich deposits is derived mostly from eroded soil that is interpreted to be a consequence of human deforestation of the watershed coupled with intense sediment focusing into deeper water (Brenner, 1994).

SEISMIC DATA AND SEDIMENT VOLUMES

Seismic profiles indicate a sediment geometry in the deep basin consisting of an ~10-m-thick package of regularly layered sediments that overlies a distinct high-amplitude reflection (lowermost yellow horizon in Fig. 2). Seismic stratigraphic analysis subdivides this sediment succession into seven seismic units (S1–S7) that are separated by traceable reflections (Fig. 2). The correlation of the seismic section to the core was achieved using the highest-amplitude reflection as a marker horizon (S6-S7) that coincides with the pronounced lithologic change at 10.22 m (L3-L4 boundary) and its sharp contrast in physical properties. The resulting acoustic velocity of 1560 m/s is a reasonable value for clay-rich lacustrine sediments at ~25 °C and was applied to the entire section. Using this core to seismic correlation, L1 corresponds to S1, L2 coincides with S2–S5, and L3 is equivalent to S6 (Fig. 2). In this study, the Maya Clay was subdivided into four seismic units (S5–S2) that are separated by reflections that can be traced with confidence throughout the basin.

To estimate the volume of deposits within seismic units S6–S1, sediment thicknesses for each unit were interpolated between the measured values along seismic lines and extrapolated to the edges of the basin (Table DR1). Sediment volumes were converted to dry sediment mass using a grain density of 2.5 g/cm^3 and average porosities of 90% and 70% for gyttja and clay, respectively, on the basis of empirical measurements in several Salpetén cores (Rosenmeier et al., 2002b). Using the seismic to core correlation and AMS ^{14}C age model (Rosenmeier et al., 2002a, 2002b; Fig. 2; Table DR2 and Fig. DR1), dates were assigned to the boundaries between units S6–S1, permitting the calculation of the mean annual mass sedimentation rate for each unit. We assumed that organic matter was of lacustrine origin and that inorganic components (carbonate and clays) were detrital. As a consequence, we did not include the average organic matter content in clay units (10%) or gyttja units (40%) to calculate detrital inorganic sediment yield (Table DR1). Erosion rates for the carbonate-poor, pre- and post-Maya gyttjas may be slightly overestimated, because much carbonate in these deposits is probably biogenic. However, the majority of the carbonate in the Maya Clay is detrital (Brenner, 1994). Unlike previous studies, for which site-specific changes in sedimentation rate were calculated from single, or even multiple cores, our 3D approach enabled us to estimate the total lake-wide sediment mass that was transported to this closed basin during various times that correspond to archaeologically defined periods of Maya occupation. Because the catchment size is known (Brezonik and Fox, 1974), we were able to use the annually deposited sediment mass to compute the average annual erosion rate of mineral soil (t/km^2 yr^{-1}) and the vertical soil loss (in centimeters) in the watershed for the specified time intervals.

EROSION RATES

Our approach provides a sediment budget with a quantitative record of erosion rates in the Lake Salpetén catchment in six discrete steps from the pre-Maya period to modern time (Fig. 3; Table DR1). Average basin-wide erosion rates were low (16.3 t/km^2 yr^{-1}) prior to ca. 2200 B.C., during the deposition of the pre-Maya gyttja. After ca. 2200 B.C., erosion rates increased consistently from 134 to 988 t/km^2 yr^{-1}, representing high annual soil loss values that provided a substantial and sustained input of sediment to the lake basin. This intense phase of soil erosion began in the early Preclassic (2000–700 B.C.) and culminated in the late Preclassic Period

[1]GSA Data Repository item 2007226, Table DR1 (data of seismic units S1–S6 with resulting soil erosion and vertical soil loss values); Description of composite core and age-depth model construction; Table DR2 (list of AMS ^{14}C samples); and Figure DR1 (ages of terrestrial organic matter versus composite depth), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

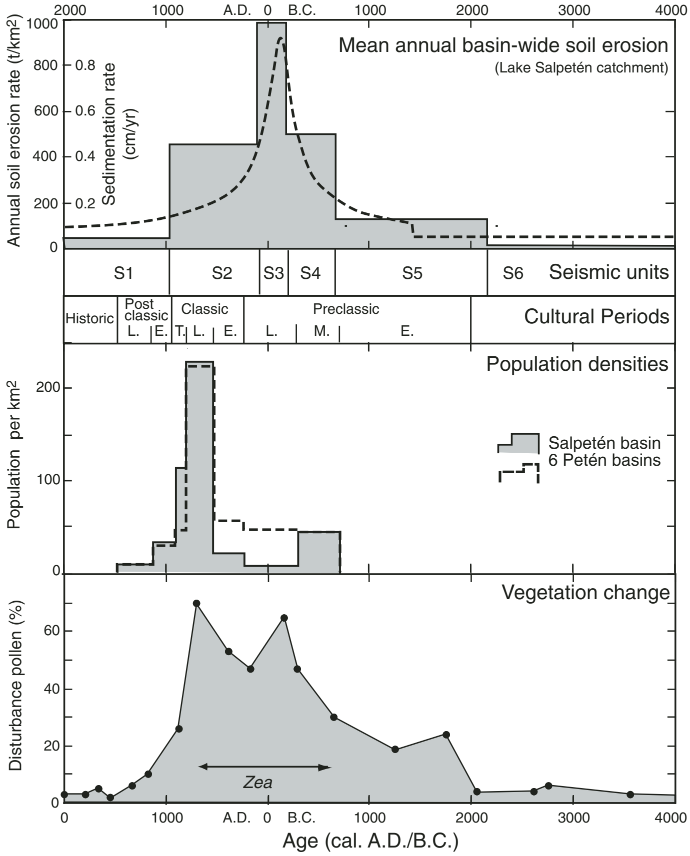

Figure 3. Salpetén basin variables plotted versus time for past 6000 yr (from top to bottom). Annual soil erosion rates are averaged over entire catchment (gray area). Black dashed line indicates lacustrine sedimentation rate at the coring site based on the applied age model (Rosenmeier et al., 2002a, 2002b; Fig. DR1 [see footnote 1]). Also shown are seismic units S6–S1; Maya cultural periods (E—Early; M—Middle; L—Late; T—Terminal) (Rice and Rice, 1990); population densities of Salpetén basin alone (gray area) and combined with five other Petén basins (black dashed line) (Rice and Rice, 1990); and disturbance pollen percentage (e.g., grass, weeds) from analysis of drill core SP80-1 in Lake Salpetén (Leyden, 1987) (black line and dots), indicating replacement of regular high-forest taxa. Occurrence of *Zea* (corn; black arrow) indicates nearshore anthropogenic land use.

(250 B.C.–A.D. 250). In the subsequent Classic Period (A.D. 250–950), the soil erosion rate dropped to 457 $t/km^2 yr^{-1}$, but nevertheless remained high relative to pre-Maya levels. After ca. A.D. 1000, i.e., following the Classic Maya collapse, soil erosion rates declined to 49 $t/km^2 yr^{-1}$. If the Maya Clay is treated as a single unit, the calculated mean anthropogenic erosion rate, sustained over a period of ~3100 yr, is 359 $t/km^2 yr^{-1}$, or ~22 times the pre-Maya baseline rate. Estimates of basin-wide soil erosion rate for the six discrete periods were compared to the coring-site–specific, age-model–based curve of sedimentation rate (dashed line in Fig. 3). Similar to the trend for soil erosion in the catchment, sediment accumulation in core SP80-1, taken in the depocenter of Lake Salpetén, also displayed a maximum in the late Preclassic.

DISCUSSION

The Salpetén basin is characterized mostly by mollisols, fertile mineral soils that possess a thin organic surface layer (Olson, 1981) and have a typical bulk density of ~1.4 g/cm^3 (Simmons et al., 1959). Taking a simple approach, we used this bulk density value to convert mass downwasting in $t/km^2 yr^{-1}$ to soil loss in centimeters (Table DR1), without accounting for possible density variations within soil profiles or in different areas of the catchment. If Maya Clay units S5–S2 are combined, the resulting total soil loss amounts to ~80 cm averaged over the entire catchment. The northern shore likely underwent higher than average soil loss because of its steepness. About 71% of total soil loss, or ~56 cm of the soil profile, was removed prior to the Classic Period. Averaged over the entire catchment, a large fraction of available soil had been removed in an early phase of erosion, and almost all the soil above bedrock had been transported into Lake Salpetén by the end of the Classic Maya period. After the decline of the Classic Maya culture, soil recovered partially in the catchment; modern soil thickness is an average of 40 cm (Brenner et al., 2002), indicating higher soil formation rates than the ~7 cm/k.y. reported from some areas in northern Petén (Beach, 1998).

Calculated soil erosion rates were compared with pollen-inferred changes in vegetation from Salpetén core SP80-1 (Fig. 3) (Leyden, 1987), in which plant taxa were grouped into high forest and disturbance (e.g., grasses, weeds) categories. Coincident increases in disturbance taxa and soil erosion rates suggest a causal link between vegetation removal and soil loss. Maximum erosion rates during the Late Preclassic coincided with a peak in disturbance taxa (65%). Even though erosion rates decreased in the Classic Period, percentages of disturbance pollen taxa remained high, indicating continued regional land clearance. Both disturbance taxa and erosion rates decreased ca. A.D. 1000, when human populations declined and agricultural activities were curtailed.

These shifts in vegetation cover may have also been influenced to some degree by climate change. Geochemical climate proxies from lake sites on the northern Yucatan Peninsula reveal a series of dry events in Maya prehistory that might have affected initial forest decline, influenced human land-use practices, and even contributed to cultural demise in the ninth century A.D. (Hodell et al., 1995, 2005; Curtis et al., 1996). The dramatic 20–50× increase in soil erosion during the period of Maya occupation, however, cannot be explained by Holocene drying alone, and can only be accounted for by intense land use. To evaluate how human numbers affected soil removal, erosion rates were compared to estimated population densities that were reconstructed from dated house mounds along archaeological transects around Lake Salpetén and in other Petén catchments (Fig. 3) (Rice and Rice, 1990). Contrary to the previously hypothesized direct relationship between population numbers and soil erosion (Rice et al., 1985), our results from Salpetén indicate that greatest erosion occurred early, during the Preclassic Period when population in the basin was relatively low (Fig. 3). When population peaked in the Classic Period, soil erosion had already diminished. A large part of the soil profile was removed prior to the period of highest population density. Lake Salpetén has a relatively small watershed, and similar studies on quantified soil erosion have not yet been done in other Petén basins. Nevertheless, site-specific sedimentation rates derived from cores in other Petén lakes, such as Lake Petén Itzá, also indicate that an early pulse of sedimentation preceded maximum population densities in the Classic Maya Period (Fig. 3) (Hillesheim et al., 2005; Rice and Rice, 1990). Soil erosion pulses from other Petén basins (Beach et al., 2006; Dunning et al., 2002) and from the Patzcuaro Basin in the Mexican Altiplano (Fisher et al., 2003; O'Hara et al., 1993) also indicate substantial environmental impact during initial settlement. Estimated soil loss for the Salpetén catchment, however, is more than two orders of magnitude greater than values inferred for the Patzcuaro Basin (O'Hara et al., 1993), reflecting the high erodibility of Petén soils and the enormous pressure on riparian soils during the period of lowland Maya occupation.

CONCLUSION

This sediment study from the Lake Salpetén basin in the lowlands of northern Guatemala provides a 6000 yr record of quantified soil loss for the periods before, during, and after Maya occupation in the watershed. Early, rapid soil loss associated with initial land clearance probably made farming increasingly difficult during the subsequent centuries. Decoupling of population density and soil erosion through time in the Salpetén basin is explained by a pulse of intense erosion during initial land clearance in the Preclassic Period, when highly erodible soils were first exposed (Beach et al., 2006). After this rapid soil loss, erosion rate declined despite a growing human population, because erodibility deeper in the soil profile decreased. Soil erosion may have been recognized as an early environmental challenge and may have influenced ancient Maya agricultural practices. Declining erosion rates in the Classic Period may reflect not only decreased soil erodibility through time, but a change in agricultural strategies, from extensive slash and burn cultivation in the Preclassic Period, to more intensive practices that incorporated soil conservation techniques (Beach, 1998; Beach et al., 2006; Fisher et al., 2003). In any case, the ancient Maya had to contend with severe soil erosion long before their populations attained high densities in the Late Classic Period (A.D. 550–830) and then ultimately declined during the Terminal Classic Period (A.D. 830–950). Erosion rates decreased, and soils and forests recovered partially during the following Postclassic and Historic Periods when human disturbance declined substantially, contradicting the concept that abandonment leads to massive degradation of once-cultivated landscapes (Fisher, 2005). The ongoing population increase in Petén that began after the 1950s has once again increased deforestation (Schwartz, 1990), and presumably erosion rates, in the region.

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DATA REPOSITORY ITEMS (Anselmetti et al.)

Table DR1: Sedimentologic, volumetric and chronostratigraphic data of seismic units S1-S6 with resulting soil erosion and vertical soil loss values

Seismic units	Depth of base (ms/m)	Age of base (AD/BC)	Sediment volume (10^3 m^3)	Average porosity (%)	Dry sediment mass (t/yr)	LOI* (%)	Basin-wide erosion rate (t/km^2yr)	Basin-wide vertical soil loss† (cm)
S1	1.5/1.17	975AD	1262	90	308.0	40	48.5	4
S2	3.9/3.04	108AD	2235	70	1932.8	10	456.6	28
S3	6.4/4.99	177BC	1589	70	4181.3	10	987.7	20
S4	8.9/6.94	665BC	1383	70	2125.5	10	502.1	17
S5	10.7/8.35	2151BC	1124	70	567.0	10	133.9	14
S6	13.1/10.22	6815BC	1934	90	103.5	40	16.3	5

Note: Seismic-to-core correlation was achieved with an acoustic velocity of 1560 m/s. Unit age boundaries were calculated using an age model based on AMS ^{14}C dates on terrestrial material from core SP80–1 and two short gravity cores (Rosenmeier et al., 2002a, 2002b).

*LOI (loss on ignition) is an estimate of mean weight percent organic matter.

†Vertical soil loss was calculated assuming a soil density of 1.4 g/cm^3.

Composite Core and Age-Depth Model Construction:

In May 1980, a 14 m sediment core (here designated SP80-1) was obtained from the deep basin of Lake Salpetén in 26.1 m of water using a standard split-spoon sampler. Topmost sediments were not recovered. In August 1999, two additional sediment cores were recovered from Lake Salpetén in water depths of 16.3 and 23.2 m (designated SP2-19-VIII-99 and SP1-17-VIII-99, respectively). Surface sediments were collected with a sediment-water interface corer and deeper sections were taken in one meter segments with a square-rod piston corer. Interface cores were sectioned in the field at 1-cm intervals. Square-rod core sections were extruded and sampled at 1-cm intervals in the laboratory. Archived core sections from SP80-1 were reexamined in May 2000 and sampled at 5-cm intervals.

Lake Salpetén sediment cores were correlated using numerous tie points in the total organic carbon records. These points included major stratigraphic boundaries such as the base of the 'Maya-Clay' and the lower boundary of the post-Maya, organic-rich sediments. The high degree of stratigraphic correlation between cores allowed construction of a composite depth series (based on core SP80-1) consisting of twenty accelerator mass spectrometry (AMS) ^{14}C dates (Table DR2). Calibrated ages (AD/BC) were calculated using the INTCAL04 tree-ring calibration data set (Reimer et al. 2004). Age-depth values for the last ~4000 calendar years were fit by a fourth-order polynomial (Fig. DR1):

$Yr = 1999 - (10.644 \times d) + (0.0164 \times d^2) - (3.071\text{E-}6 \times d^3) - (9.183\text{E-}9 \times d^4)$ ($R^2 = 0.96$)

where Yr is the calibrated age (AD/BC) and d is the composite depth in centimeters. Age-depth values in earlier deposits were determined by linear interpolation using the equation

$Yr = 18697.969 - (24.964 \times d)$ ($R^2 = 0.98$).

Table DR2: AMS ^{14}C DATES FOR SAMPLES FOR LAKE SALPETEN.

Accession number (CAMS)	Composite core depth (cm)	AMS ^{14}C age (years BP)	Two sigma (2σ) age range (AD/BC)	Relative probability (1.000)	Median age (AD/BC)
62943	0033.6 [a]	0180 ± 050	1720 AD – 1890 AD	0.609	1810 AD
			1650 AD – 1710 AD	0.217	1680 AD
			1910 AD – 1950 AD	0.173	1930 AD
62939	0082.7 [b]	0400 ± 040	1430 AD – 1530 AD	0.698	1480 AD
			1560 AD – 1630 AD	0.302	1600 AD
64858	0151.4 [b]	1370 ± 040	0580 AD – 0730 AD	0.903	0660 AD
			0740 AD – 0770 AD	0.097	0760 AD
65387	0157.0 [c]	1820 ± 190	0210 BC – 0610 AD	0.990	0200 AD
			0350 BC – 0320 BC	0.010	0340 BC
64859	0167.0 [b]	1380 ± 140	0400 AD – 0970 AD	1.000	0690 AD
60079	0215.0 [a]	1320 ± 040	0650 AD – 0770 AD	1.000	0710 AD
64860	0237.0 [b]	1690 ± 140	0060 AD – 0640 AD	1.000	0350 AD
62940	0350.7 [b]	1850 ± 050	0050 AD – 0260 AD	0.969	0160 AD
			0300 AD – 0320 AD	0.031	0310 AD
65388	0395.0 [c]	2200 ± 070	0400 BC – 0090 BC	0.990	0250 BC
			0070 BC – 0060 BC	0.010	0070 BC
65389	0503.0 [c]	2200 ± 060	0390 BC – 0110 BC	1.000	0250 BC
60749	0535.3 [b]	2090 ± 040	0200 BC – 0000 AD	0.993	0100 BC
			0340 BC – 0330 BC	0.007	0340 BC
62941	0549.0 [b]	2200 ± 050	0390 BC – 0160 BC	0.980	0280 BC
			0130 BC – 0120 BC	0.020	0130 BC
64861	0646.0 [c]	2430 ± 050	0600 BC – 0400 BC	0.658	0500 BC
			0760 BC – 0680 BC	0.211	0720 BC
			0670 BC – 0610 BC	0.131	0640 BC
65390	0707.0 [c]	2500 ± 060	0790 BC – 0480 BC	0.916	0640 BC
			0470 BC – 0420 BC	0.084	0450 BC
60078	0749.0 [b]	2820 ± 040	1120 BC – 0900 BC	0.984	1010 BC
			0870 BC – 0850 BC	0.016	0860 BC
64978	0774.0 [c]	2990 ± 190	1640 BC – 0800 BC	0.997	1220 BC
			1660 BC – 1650 BC	0.003	1660 BC
65797	0813.0 [c]	3160 ± 080	1620 BC – 1260 BC	0.987	1440 BC
			1240 BC – 1220 BC	0.013	1230 BC
62942	0815.5 [b]	3240 ± 040	1610 BC – 1430 BC	1.000	1520 BC
65391	0960.0 [c]	6990 ± 050	5980 BC – 5760 BC	1.000	5870 BC
65798	1012.0 [c]	7235 ± 050	6220 BC – 6020 BC	1.000	6120 BC

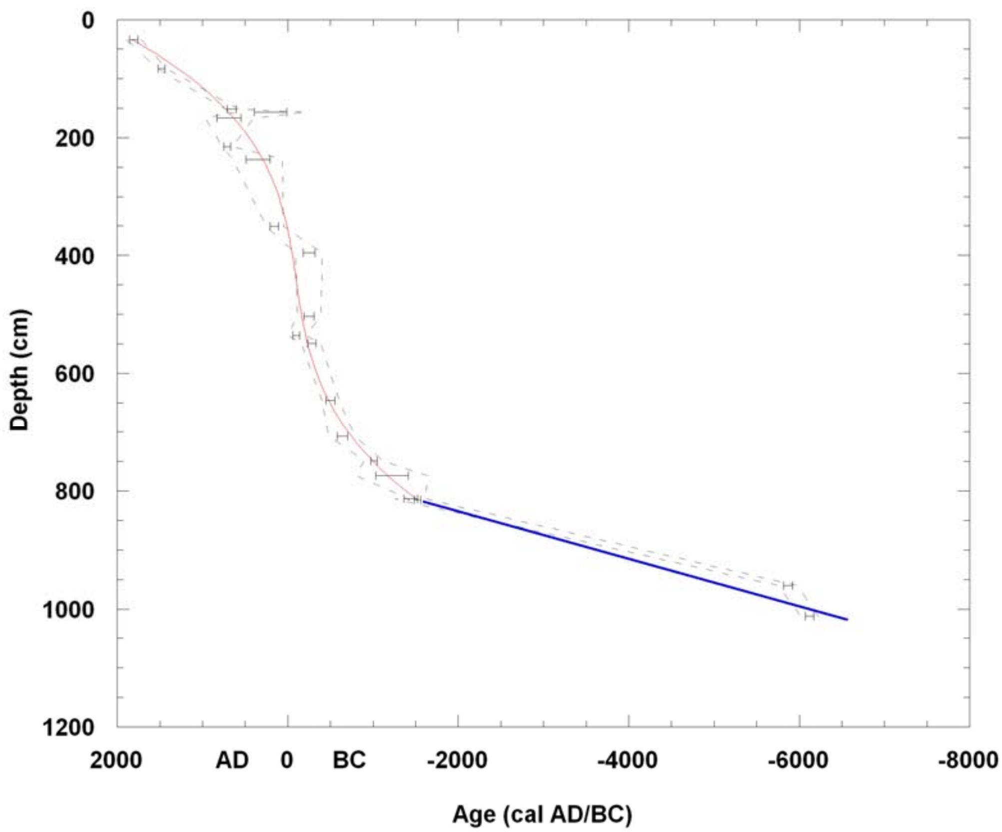
Note: Sediment ages from Lake Salpetén were determined by accelerator mass spectrometry of ^{14}C in terrestrial organic matter (wood, seeds, and charcoal) at the Lawrence Livermore National Laboratories Center for Accelerator Mass Spectrometry (CAMS). All calibrated ages were rounded to the nearest ten years. Median ages calculated from the 2σ range with the highest relative area under the probability distribution were used in construction of the age-depth model.

[a] denotes core SP1-99

[b] denotes core SP2-99

[c] denotes core SP80-1

Fig. DR1: Ages of terrestrial organic matter versus composite depth in cores from Lake Salpetén. Age-depth values for the last ~3500 years were fit by a fourth-order polynomial (red line). Basal ages were determined by linear interpolation (blue line). Error bars delineate the analytical error assigned to the median ages used in the curve fits. Dashed gray lines indicate the upper and lower bounds of the calibrated age range at two standard deviations.



Anselmetti et al., Fig DR1

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