New estimates of the magnitude of the sea-level jump during the 8.2 ka event

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ABSTRACT
We analyzed sediment cores from coastal Lake Izabal, Guatemala, to infer Holocene biogeochemical changes in the lake. At ca. 8370 calibrated yr B.P. (cal. yr B.P.), marine waters entered the lake, which presently lies ~38 km from the Caribbean coast. Temporal correlation between Early Holocene drainage of high-latitude Lakes Agassiz and Ojibway (in North America) and marine flooding of Lake Izabal suggests a causal link between the two processes. Our data indicate a relative sea-level jump of 2.60 ± 0.88 m, which is larger than previous estimates of sea-level rise during the 8.2 ka event. The inferred sea-level jump, however, cannot be explained solely by the volume of water released during drainage of Lakes Agassiz and Ojibway. Instead, we propose that previous studies underestimated the magnitude of Lakes Agassiz and Ojibway discharge, or that additional meltwater sources contributed to global sea-level rise at that time.

INTRODUCTION
Rapid delivery of meltwater to the North Atlantic during the Early Holocene was responsible for the 8.2 ka event (Alley et al., 1997). Freshwater input weakened oceanic circulation, which led to colder temperatures in Greenland (Stuiver et al., 1995) and Europe (von Grafenberg et al., 1998) and windier conditions in northern South America (Hughen et al., 1996). The meltwater release caused abrupt sea-level rise (SLR) in coastal areas worldwide, including the Gulf of Mexico and Atlantic regions of the United States (Tornqvist et al., 2004; Cronin et al., 2007), Europe (Hijma and Cohen, 2010), and Asia (Hori and Saito, 2007).

The 8.2 ka event provides insight into how ocean-atmosphere dynamics are influenced by freshwater input to the North Atlantic (LeGrande and Schmidt, 2008). Nevertheless, identification of meltwater sources and constraints on estimates of total freshwater volumes that caused the 8.2 ka event are still debated. One source of meltwater was the catastrophic drainage of Lakes Agassiz and Ojibway (LAO), which released a volume of 163 ± 0.7 m^3 (Teller et al., 2002) at ca. 8470 cal. yr B.P. (B.P. = 1950; 1σ range is 8740–8160; Barber et al., 1999). Bathymetric models of LAO by Leverington et al. (2002) indicate that the volume of freshwater released from LAO would have caused a global SLR of 0.46 m (Hijma and Cohen, 2010), ranging from 0.22 to 0.96 m (Matero et al., 2017). A second source of meltwater was the gradual disintegration of the Laurentide Ice Sheet (LIS), which caused an additional global SLR of 0.44 m around the time of the 8.2 ka event (von Grafenberg et al., 1998). A third source was the rapid melting of ice-sheet saddles, which are estimated to have contributed another 2.5 m to global SLR (Gregoire et al., 2012). Multiple hydrologic sources and different discharge amounts create uncertainty about the total volume of freshwater released and the associated global SLR around the time of the 8.2 ka event, hampering calibration of climate models that could help us better understand changes in oceanic circulation during times of increased delivery of freshwater to the North Atlantic. Additional sea-level data can help further constrain the volume of freshwater released and the potential global SLR at that time.

A distant site proposed to have recorded the sea-level jump during the 8.2 ka event is the Caribbean Sea (Kendall et al., 2008). A compilation of sea-level data from 20 Caribbean sites, however, did not reveal evidence of a distinct sea-level jump at ca. 8200 cal. yr B.P. (Khan et al., 2017). A sea-level jump was documented in the Mississippi Delta region, suggesting a SLR of 1.2 m (Törnqvist et al., 2004) or 1.5 ± 0.7 m (Li et al., 2012), associated with LAO drainage. Evidence of the sea-level jump in the Mississippi Delta, and the apparent lack thereof in the Caribbean, is puzzling because glacio-isostatic adjustment (GIA) models that account for late Pleistocene deglaciation indicate that the Caribbean should have experienced a larger relative SLR as a result of LAO drainage (~60–80% of the LAO sea-level fingerprint) than the Mississippi Delta (~20%; Kendall et al., 2008).

We present evidence of a rapid sea-level rise near the time of the 8.2 ka event in the Caribbean...
region that is inferred from analyses of sediment cores obtained in Lake Izabal, Guatemala (Fig. 1). The lake is fresh and low-lying, with a water surface presently \( \sim 1.5 \) m above mean sea level. The lake has a surface area of 672 km\(^2\), a maximum depth of 15 m, and discharges to the Caribbean Sea via the Dulce River (Brinson and Nordlie, 1975; Obrist-Farner et al., 2019). The sediment record of Lake Izabal enabled us to constrain the timing of Early Holocene marine flooding and provided an estimate of SLR during the 8.2 ka event.

**MATERIALS AND METHODS**

We collected five sediment cores in Lake Izabal (Fig. 1; Table S1 in the Supplemental Material\(^1\)). Our analyses focused on Core 5, which has the best chronology and the most complete record (Table S1). Accelerator mass spectrometry (AMS) radiocarbon dates were obtained on Cores 1, 2, 3, and 5. Dates were calibrated with OxCal 4.4 using IntCal20 (Bronk Ramsey, 2009; Reimer et al., 2020; Tables S2 and S3). We established age-depth relations for Core 5 (Fig. 1) using 11 AMS radiocarbon dates and the Bayesian software Bacon (Blaauw and Christen, 2011; Fig. S1). To identify and determine the timing of the marine incursion in Lake Izabal, we measured sediment magnetic susceptibility (MS) in all cores, and elemental abundances, total organic carbon (TOC), total sulfur (TS), glycerol dialkyl glycerol tetraethers (GDGTs), and the numbers of diatoms and presence of foraminifera in Core 5.

\(^{1}\)Supplemental Material. All sediment core data collected in this study. Please visit https://doi.org/10.1130/GEOL.S.16589951 to access the supplemental material, and contact editing@geosociety.org with any questions. Gold OA

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Figure 1. Bathymetric map of Lake Izabal (Guatemala) and topography of the area. Red circles indicate sites of sediment core collection. Inset map shows Central America and surrounding regions; the location of Lake Izabal in eastern Guatemala is indicated by the red box.

Figure 2. Simplified lithological description and magnetic susceptibility (MS) of the five sediment cores collected in Lake Izabal (Guatemala). Blue box across the figure highlights the interval when MS was low and, in general, when laminations were present. Records from Cores 1 through 4 were shifted downward to correlate all cores using the increase in MS. Radiocarbon dates for Cores 1, 2, and 3 are in calibrated yr B.P. (cal. yr B.P.) and are given with 1σ uncertainties. Dates for Core 5 are modeled age results from R package Bacon (Blaauw and Christen, 2011).
RESULTS AND INTERPRETATIONS

Sediment Cores 3, 4, and 5 contain sediments older than 8200 cal. yr B.P. The three cores contain a traceable contact, i.e., a flooding surface, which separates organic-rich mud from thinly laminated mud in Cores 4 and 5, and gray sandy mud from thinly laminated mud in Core 3 (Fig. 2). In Core 5, the organic-rich mud below the flooding surface spans the interval ca. 9500–8370 cal. yr B.P. (Figs. S1 and S2) and contains the acidophilic diatom *Eunotia*, *Stauroeis*, and *Frustulia* (Fig. 3; Fig. S3; Table S4). Variable log(Fe/Ti) (Kylander et al., 2011) and high log(GDGT-0/crenarchaeol) ratios (Blaga et al., 2009) in that interval indicate episodes of reducing conditions (Fig. 3; Table S5). This is supported by low MS, suggesting dissolution of magnetite under anoxic conditions (Nowaczyk et al., 2007; Fig. 3; Table S5). Variable TS and generally high TOC/TS (Berner and Raiswell, 1984) suggest prevailing freshwater conditions at that time with occasional salinity increases, which is supported by the presence of the mesohaline diatom *Terpsinoë* sp. below the flooding surface (Fig. 3; Table S5). We infer that before 8370 cal. yr B.P., Lake Izabal was shallow and dystrophic, surrounded by low-lying wetlands, and not connected to the Caribbean Sea.

In Core 5, the flooding surface occurs at 8370 cal. yr B.P. (95% range is 8639–8014; Fig. 2; Fig. S1; Table S2). Radiocarbon dates from other cores enabled us to further constrain the age of the flooding surface. A date in Core 3 from below the flooding surface indicates the event occurred after 8375 ± 39 cal. yr B.P. (1σ; Fig. 2). A date in laminated sediment from the base of Core 1 suggests flooding occurred before 7895 ± 45 cal. yr B.P. (1σ; Fig. 2; Table S3).

In addition to the change to laminated mud above the flooding surface in Cores 3, 4, and 5, several biogeochemical changes occur across a 2–3 cm interval in Core 5. TS increases and TOC/TS decreases rapidly (Fig. 3), and diatom taxa shift from predominantly benthic (i.e., shallow-water) and acidophilic to largely planktonic (i.e., deeper-water) and brackish (Fig. S3; Table S4). The diatom *Thalassiosira* sp. and the foraminiferan *Ammonia* sp. appear, and *Terpsinoë* sp. increases in abundance (Fig. 3). Hence, both abiotic and biotic data indicate rapid deepening and a change to brackish conditions in Lake Izabal at ca. 8370 cal. yr B.P.

Upcore, *Thalassiosira* sp. and *Ammonia* sp. disappear, highly dissolved *Terpsinoë* sp. fragments become abundant, TOC/TS decreases, and TS increases, indicating that Lake Izabal was salty and alkaline from 8370 to 4800 cal. yr B.P. (Fig. 3). The presence of sub-millimeter laminations and low MS in all cores (Fig. 2; Table S6) suggest basin-wide, bottom-water anoxia, which is supported by consistently high log(Fe/Ti) and log(GDGT-0/crenarchaeol) ratios in Core 5.

8370 cal. yr B.P. Photo on the right shows the transition from organic-rich mud to sub-millimeter laminated mud after the flooding surface (red dashed line). Photo shows 40 cm of Core 5.
5 (Fig. 3). Lake Izabal sediments deposited during the past 4800 yr are characterized by thin-to-thick-beded mud. An increase in MS (Fig. 2), a decrease in log(Fe/Ti) and log(GDGT-0/crenarchaeol) ratios, low TS content, higher TOC/TS (Fig. 3), and abundant freshwater diatoms (Table S4) provide evidence that Lake Izabal returned to a freshwater status nearly four millennia after the change at 8370 cal. yr B.P.

DISCUSSION AND IMPLICATIONS

Abrupt biogeochemical changes in Lake Izabal sediments at ca. 8370 cal. yr B.P. are best explained by a sudden (2–3 cm; ~20 yr; Fig. 3) change in lake conditions. Two processes can theoretically explain the observations. First, the increased salinity could have been caused by a shift in hydroclimate during the 8.2 kya event. Proxy climate records from the Caribbean region (Peros et al., 2017) and Central America (Lach-niet et al., 2004) suggest lower precipitation and higher evaporation during the 8.2 kya event, which could have led to increased lake water salinity. Our sedimentological and micropaleontological results, however, indicate rapid expansion and deepening of the lake, and other studies found that regional precipitation in the Lake Izabal catchment increased at that time (Winter et al., 2020; Duarte et al., 2021). Second, the climatological changes could have resulted from marine incursion. Bathymetries of Lakes Izabal and El Golfo and the Dulce River, although poorly constrained, indicate that the modern spillway is Lake El Golfete, which currently lies 4 m below sea level (Fig. 1; Fig. S4). Approximately 8400 yr ago, the spillway must have been at 10.70 ± 0.18 m below sea level, assuming a sedimentation rate for Lake El Golfete similar to that estimated from Core 5 (0.80 ± 0.02 mm yr⁻¹). This is reasonable, considering the two lakes are only 10 km apart, share the same catchment, receive similar sediment input, and are connected via the Dulce River. Sea-level data from Belize (Khan et al., 2017) indicate that at 8400 cal. yr B.P., sea level was 13.3 ± 0.7 m lower than at present. This implies the spillway was, at a minimum, ~2.60 ± 0.88 m above sea level prior to the time of inundation. Three processes, which are not mutually exclusive, could have caused marine flooding of the lake.

(1) An abrupt drop in the lake spillway position caused by tectonic movement. Lake Izabal is situated in a pull-apart basin along the North American–Caribbean plate boundary (Bartole et al., 2019; Obst-Farner et al., 2020). It is unlikely, however, that a single or multiple tectonic events could have caused substantial vertical displacement without leaving physical evidence. No fault scarps in the Lake Izabal area display evidence of recent vertical tectonic activity (Lodolo et al., 2009; Obst-Farner et al., 2020). Furthermore, the spillway is currently located on the footwall of the main fault, which further reduces the likelihood of downward displacement, and El Golfete is located in a region of transpression as evidenced by the presence of the Mico Mountains (Fig. 1; Obst-Farner et al., 2020).

(2) A gradual sea-level rise caused by melting of the LIS. Early Holocene sea-level records from Belize suggest that sea level rose to ~10 m below present at ca. 7600 cal. yr B.P. (Khan et al., 2017). This implies that Lake Izabal’s spillway, which was located at ~10.7 m at the time of inundation, would have been breached around 7600 cal. yr B.P. This disagrees with our observations of marine waters entering Lake Izabal 800 yr before at ca. 8400 cal. yr B.P. (Fig. 4).

(3) A rapid rise in sea level at ca. 8400 cal. yr B.P., near the time of LAO drainage (Barber et al., 1999; Fig. 4). Although our inferred sea-level rise of 2.60 ± 0.88 m at 8370 cal. yr B.P. (95% range is 8639–8014) is similar to the relative SLR of 2.11 ± 0.89 m in the Netherlands at 8450 cal. yr B.P. (2σ of 8544–8375; Hijma and Cohen, 2010) and 1.5 ± 0.7 m in the Mississippi Delta region between 8310 cal. yr B.P. and 8180 cal. yr B.P. (Li et al., 2012), it cannot be fully explained by the estimate of freshwater released around the time of LAO drainage (<1 m of global SLR; Leverington et al., 2002). To explain the marine water incursion at Lake Izabal, a much larger volume of freshwater must have been released to the North Atlantic during the 8.2 kya event as suggested by Törnqvist and Hijma (2012). Gregoire et al. (2012) proposed a freshwater volume four times the estimated amount of LAO drainage that was caused by the melting of ice-sheet saddles and accounted for an additional global SLR of 2.5 m. Alternatively, the volume of freshwater released from LAO could be underestimated, as the lakes could have been twice

mean age, and the green histogram at the bottom shows the frequency of age estimates of the flooding event in Lake Izabal.

Figure 4. Records of sea-level rise in the Caribbean region and during the 8.2 kya event. Bottom plot shows a decrease in the Cariaco Basin sediment grain scale (red line) that resulted from windier conditions caused by high-latitude cooling (Hughen et al., 1996) and a decrease in oxygen isotope values in Greenland (black line), which reflect lower temperatures (Stuiver et al., 1995). Upper plot shows the increase in total sulfur (TS; black line) after the flooding event in Lake Izabal (Guatemala) and the sea-level curve (red line) and 1σ uncertainty (light red envelope) from Belize (Khan et al., 2017). Vertical black dashed line and gray box show the age and 1σ uncertainty for the drainage of Lakes Agassiz (in central North America) and Ojibway (in Canada) (Barber et al., 1999). Vertical red dashed line shows the
their assumed size if the ice sheet margins were shifted 1° northward (Leverington et al., 2002). The Lake Izabal data support a SLR of 2.60±0.88 m around the time of the 8.2 ka event (Fig. 4). Climate models that simulate the 8.2 ka event using estimated LAO volumes fail to replicate the duration of the event (Matero et al., 2017). Instead, these models necessitate an ~4.2 m global SLR to accurately simulate the duration of the climate anomaly (Matero et al., 2017). A global SLR of 4.2 m would result in a relative SLR of 2.5–3.3 m in the Caribbean Sea after GIA corrections (Kendall et al., 2008), which is similar to the SLR of 2.60±0.88 m estimated from our data. Our findings support the claim that freshwater volume added to the North Atlantic prior to the 8.2 ka event has been underestimated as suggested by Törnqvist and Hjima (2012). Additional data from other coastal sites can further constrain global SLR during the 8.2 ka event. Such information is needed to calibrate climate models and understand how the climate system will respond to the potential freshwater influx to the oceans under continued global warming.

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