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Notes

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ABSTRACT

An annual laminated stalagmite from northern Spain recorded two outstanding oxygen isotope ($\delta^{18}O$) pulses during the 8.2 ka event. Most of the oxygen isotope record variability is related to the amount of rainfall, although other factors affect the signal. The lamina thickness record, which is also related to amount of rainfall, does not show any significant anomaly at the time of oxygen isotope spikes. Considering the factors affecting the isotope signal, the two prominent falls in $\delta^{18}O$ during the event are interpreted to be caused by the release of large amounts of fresh waters into the North Atlantic. Thus, ^{18}O-depleted ocean surface waters shifted the rainfall $\delta^{18}O$ composition for Europe and Greenland. Our precise chronology provides the timing of the outbursts that caused the $\delta^{18}O$ anomalies at 8350–8340 and 8221–8211 ± 34 yr B.P., most probably generated by the drainage of proglacial lakes Agassiz and Ojibway. Therefore, in the North Atlantic region $\delta^{18}O$ records during the 8.2 ka event trace important hydrological modifications in the ocean, not just local climate. As a consequence, paleoclimate reconstructions from Europe and Greenland using the $\delta^{18}O$ proxy that does not take this into account would be overestimating the magnitude of the anomalies during the 8.2 ka event.

INTRODUCTION

The largest depletion in ^{18}O recorded in Greenland ice cores during the Holocene occurred ~8200 years ago during the so-called 8.2 ka event (Alley et al., 1997). Its age and duration have been dated by lamina counting, recording an anomaly lasting <200 years (Thomas et al., 2007; Kobashi et al., 2007). Although climate changes have been broadly described for the Northern Hemisphere around the 8.2 ka event (Alley et al., 1997; Alley and Ágústsdóttir, 2005; Rohling and Pälike, 2005; Wiersma and Renssen, 2006), anomalies differ in duration and age (Morril and Jacobson, 2005). The duration of the event is within uncertainties of conventional dating methods. Precise correlations are also impeded because the structure of the event is not well defined; some records show two major episodes instead of one (Nesje and Dhal, 2001; Lachniet et al., 2004; Ellison et al., 2006; Hald and Korsum, 2008). In addition, different proxy parameters record different responses to the event, and anomaly duration frequently differs within the same record (Ellison et al., 2006; Prasad et al., 2006; Flesche Kleiven et al., 2008). Therefore, in order to put the event in a North Atlantic context and to advance in the knowledge of the structure of the event, it is necessary to have high-resolution records based on well-resolved chronologies and with proxy parameters with similar responses to the event.

MATERIAL AND METHODS

Here we present a stalagmite record from Kaite Cave (43°2′N, 3°39′W, 860 m above sea level) in northern Spain, only 50 km from the Atlantic Ocean (Fig. 1; Fig. DR1 in the GSA Data Repository[1]). The climate in the region is humid and temperate with >1000 mm of annual precipitation and a mean annual temperature of ~12 °C (Domínguez-Villar et al., 2008). The stalagmite LV5 is 1 m long and covers most of the Holocene, with three major hiatuses recognized from U-Th dating (Fig. DR2). The age model for the 8.2 ka event uses a chronology based on annual laminae with a counting error <1%. The floating chronology was anchored to U-Th dates using a minima quadratic error fitting (Fig. 2). The standard error of the age model is ±34 years on the absolute age, which takes into account the difference between U-Th dates and model chronology as well as the lamina counting uncertainties. This provides a high-quality chronology to the event with which, in the North Atlantic area, only other annually resolved chronologies using $\delta^{18}O$ as a proxy can be compared (Veski et al., 2004; Thomas et al., 2007).

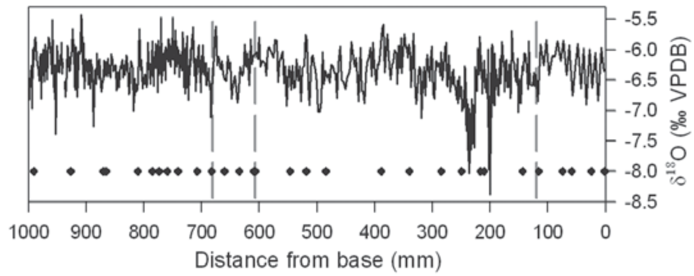

Figure 1. $\delta^{18}O$ composition of LV5 stalagmite. U-Th dates shown as diamonds. Gray vertical dashed lines represent major hiatuses. $\delta^{18}O$ data were corrected for ice volume using –0.1‰/10 m of sea-level rise (after Bard et al., 1996). VPDB—Vienna Peedee belemnite.

RESULTS

The oxygen isotope record presents a flat profile during the Holocene (Fig. 1), the most outstanding feature being the existence of two sharp depletions in $\delta^{18}O$ that are more than 2σ away from the running

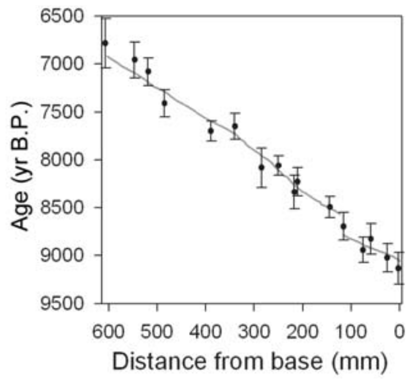

Figure 2. Age model for early Holocene in LV5 stalagmite based on lamina counting linked to U-Th dates. Gray line represents the age model based on lamina counting. U-Th dates are reported with their errors (2σ).

[1]GSA Data Repository item 2009271, Figures DR1 (LV5 stalagmite pictures), DR2 (LV5 growth rate), DR3 (significance of $\delta^{18}O$, $\delta^{13}C$, and lamina thickness anomalies), and DR4 (sampling resolution and filtered series for the 8.2 ka event), is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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mean of the Holocene record (Fig. DR3). A record of lamina thickness has been obtained from the laminated portion of LV5 from the early Holocene (Fig. DR3). Growth rates were reduced shortly after the first oxygen isotope anomaly, and recovered by ca. 8 kyr B.P. Reduced growth rates are outside the 2σ range of the laminated portion of the stalagmite for only a few decades. In addition, although there is a clear long-term decrease in lamina thickness associated with the occurrence of the isotope anomalies, the growth rate is not smaller than for other periods in the Holocene (Fig. DR2). Therefore, the two anomalies recorded in the δ^{18}O signal represent the only outstanding spikes for this proxy, whereas the amplitude of synchronous anomalies in growth rate is not different from other oscillations during the Holocene.

STALAGMITE PROXY INTERPRETATIONS

Variability of δ^{18}O in late Holocene Kaite Cave stalagmites has been interpreted in terms of the δ^{18}O values in local rainwater, since the precipitation occurs close to isotopic equilibrium and no significant fractionation has been reported prior to the drip (Domínguez-Villar et al., 2008). The fractionation during calcite precipitation is temperature dependent (O'Neil et al., 1969). However, in the Iberian Peninsula modern-day correlations of δ^{18}O in rainfall with temperature show gradients of the same magnitude but different sign (Plata, 1994). Even if the gradient could have changed through time, plausible variations are too small, and temperature effects recorded in the stalagmite are considered to be of minor importance. The amount of rainfall is responsible for much of the δ^{18}O variability in rainwater; lower δ^{18}O values are found with increased rainfall in northern Spain (Domínguez-Villar et al., 2008). However, rainwater isotope composition is also dependent on changes in the source of moisture, modifications in the seasonality, and changes in ocean isotope composition. As a consequence, the interpretation of δ^{18}O in rainwater recorded in the stalagmite results from the combination of all these controls (Domínguez-Villar et al., 2008). The diameter of LV5 stalagmite during the early Holocene is stable at ~2 cm, which is in good agreement with the minimum diameter for stalagmites. Minimum-diameter stalagmites are only formed below very slow drips (Curl. 1973), and in these cases changes in drip rates, and hence variations in amount of rainfall, are the dominant factor affecting the growth rate (Kaufmann, 2003). So, we interpret periods of lower growth rates in LV5 within the interval ca. 8.5–7.0 kyr B.P. as a decrease in rainfall at the site.

An anticorrelation is observed between lamina thickness and δ^{18}O values within the events (r = 0.48 and r = 0.49, respectively), suggesting that the amount of rainfall increases caused some of the large drops found during both isotope anomalies (Fig. 3). Similar correlations are observed for periods outside the events when short time scales are analyzed, although correlations become insignificant over long time periods. Thus, the anomalously low isotope values are not restricted to periods of higher growth rates; conversely, most of the low δ^{18}O values within both events are found with regular and even low growth rates. One might presume that a factor other than rainfall amount was causing the major shift toward lighter isotope values. During the events the mean δ^{18}O values dropped by ~0.7‰ and 1.0‰, respectively, in relation to the Holocene average (Fig. DR4). Signal variability was investigated within each event. Unfortunately, the first event is too short (only 11 data points) to obtain a reliable analysis. However, the second event (n = 30) provides a standard deviation of 0.32, which is equivalent to that obtained during the Holocene (0.31). The comparison of δ^{18}O and lamina thickness records as well as the analysis of the δ^{18}O variability suggests that factors such as changes in the rainfall amount continued during the events, causing a mostly similar mode of oscillation, although during such periods the average signal was depleted by an additional factor, which was that responsible for the anomalous values recorded in relation to the entire Holocene.

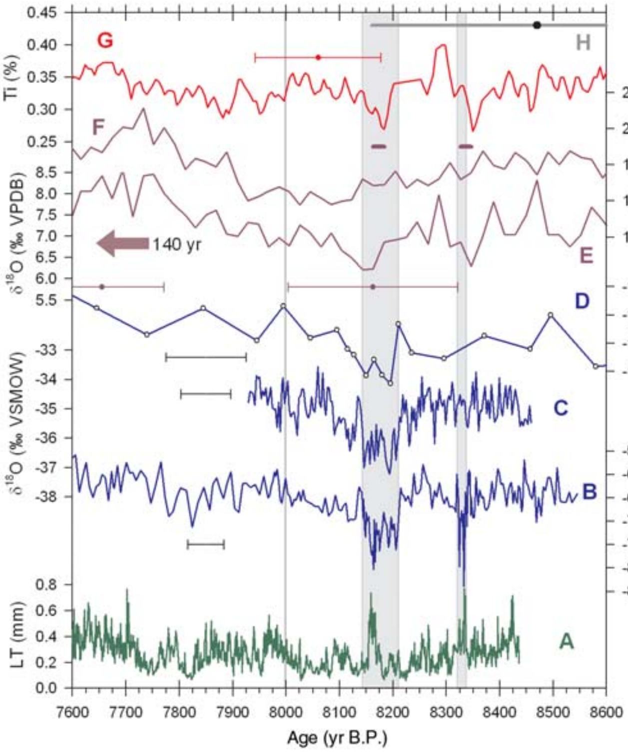

Figure 3. Comparison of records for the 8.2 ka event. A: Lamina thicknesses (LT) in LV5. B: δ^{18}O in LV5. C: δ^{18}O normalized from Greenland ice cores (Thomas et al., 2007). D: δ^{18}O in Lake Rõuge, Estonia (Veski et al., 2004). E: Sea-surface temperature (SST) in North Atlantic. F: Grain size (SS) as indicator of Atlantic Meridional Overturning Circulation strength in North Atlantic Ocean at core MD99–2251 (Ellison et al., 2006). These time series have been displaced 140 years toward younger ages to match two peaks of depleted δ^{18}O in seawater recorded in this core (bold purple bars at top of plots) to both δ^{18}O spikes in LV5. Age displacement is in agreement with specific date corrections for ocean reservoir in the North Atlantic during the event (Flesche Kleiven et al., 2008). G: Titanium content of ocean core in Cariaco Basin, Venezuela (Haug et al., 2001). H: Reported age and uncertainties (1σ) for final outburst of proglacial lakes Agassiz and Ojibway (Barber et al., 1999). Uncertainties in age models accompany each record as single error bar for annually resolved chronologies, or with singular dates and their errors (2σ). Vertical gray bars along graph indicate location of both δ^{18}O falls in LV5, and vertical gray line indicates recovery in growth rate ca. 8 kyr B.P. VPDB—Vienna Peedee belemnite; VSMOW—Vienna standard mean ocean water.

Modifications in the source of moisture, the effects of seasonality, or changes in ocean isotope composition are additional factors that may play a significant role in the δ^{18}O signal recorded in the stalagmite. Moisture to our cave site comes from the North Atlantic (Zorita et al., 1992), and slight modifications in its source location during the event cannot reproduce such a large response in δ^{18}O (LeGrande et al., 2006; Schmidt et al., 2007; LeGrande and Schmidt, 2008). Insolation changes related to orbital parameters caused major shifts in seasonality during the Holocene (Schmidt et al., 2007), but the flat signal of the δ^{18}O record in LV5 implies that changing seasonality cannot be a significant factor for δ^{18}O. Thus, we propose that drastic changes that occurred in surface ocean isotope composition, transferred to precipitation via moisture uptake from the ocean, were the most likely cause for the two events with anomalous δ^{18}O depleted values recorded in LV5 stalagmite. Thus, changes in source δ^{18}O composition account for a consistent shift toward more negative δ^{18}O values, whereas rainfall amount is only responsible for high-frequency variability within the events.

DISCUSSION

The final outburst of proglacial lakes Agassiz and Ojibway took place between 8160 and 8740 yr B.P. (Barber et al., 1999). The occurrence of the $\delta^{18}O$ anomalies in LV5 is within this age range (Fig. 3). Moreover, the continental and ocean archives record the existence of two major pulses in lake drainage (Teller et al., 2002; Hillaire-Marcel et al., 2007; Lajeunesse and St.-Onge, 2008), and two events of depleted seawater in $\delta^{18}O$ values have been reported in the North Atlantic (Ellison et al., 2006; Hald and Korsum, 2008). In addition, two prominent Ti anomalies are recorded in the Cariaco Basin; these are interpreted as dry events caused by cooler conditions at higher latitudes in the North Atlantic (Haug et al., 2001). This Cariaco record is thought to be one of the most robust series for the 8.2 ka event (Morril and Jacobson, 2005), and is synchronous with $\delta^{18}O$ anomalies in LV5. These records support the interpretation that the LV5 speleothem $\delta^{18}O$ signal is tracing the occurrence of the two pulses of freshwater releases in the North Atlantic and their incorporation in the hydrological cycle. The average amplitude of the $\delta^{18}O$ anomalies in both spikes at LV5 (≤1‰) and their duration are in agreement with predictions that model the effect on rainwater anomalies in western Europe as a consequence of the final drainage of the proglacial lakes to the North Atlantic (LeGrande et al., 2006). The duration of both $\delta^{18}O$ anomalies in precipitation should be linked to the period in which the fresh waters remained in the surface of the North Atlantic Ocean. The first pulse from the final drainage of the proglacial lakes Agassiz and Ojibway has been argued to be the larger outburst (Teller et al., 2002). However, reduction in the Atlantic Meridional Overturning Circulation (AMOC) has been predicted by models as a consequence of the outburst of the lakes (Renssen et al., 2002; Alley and Ágústsdóttir, 2005; Wiersma et al., 2006; Wiersma and Renssen, 2006; LeGrande et al., 2006; LeGrande and Schmidt, 2008), and recognized in ocean cores along the North Atlantic (Risebrobakken et al., 2003; Ellison et al., 2006; Flesche Kleiven et al., 2008). The models suggest that the durations of $\delta^{18}O$ anomalies are dependent on the strength of the AMOC (LeGrande et al., 2006). Hence, model outputs reproduce a surface $\delta^{18}O$ anomaly lasting for a few decades with no disturbance to the strength of the AMOC, whereas the situation with a reduced AMOC, which was already effective during the second pulse (Ellison et al., 2006), indicates longer lasting anomalies because of weaker ocean sinking, allowing depleted isotope waters at the ocean surface to remain for additional decades (LeGrande et al., 2006). In addition, the amplitude of the $\delta^{18}O$ anomaly reported here is in agreement with other European locations recording $\delta^{18}O$ of rainwaters, showing a reduction of the amplitude of the anomaly depending on their distance from the Atlantic Ocean (Von Grafenstein et al., 1998; Marshall et al., 2007; Zanchetta et al., 2007).

The well-resolved age model of our record demonstrates a duration of <20 years for the first $\delta^{18}O$ anomaly and ~70 years for the second. A duration for the later pulse of ~70 years is in broad agreement with the main event in other records (Risebrobakken et al., 2003; Thomas et al., 2007; Kobashi et al., 2007; Ellison et al., 2006), whereas not all records agree in the duration or even the existence of a significant prior anomaly. However, there are several sites recording a first event with a duration similar to that reported in LV5 (Haug et al., 2001; Lachniet et al., 2004; Flesche Kleiven et al., 2008). Due to the short duration of the first pulse, records that do not achieve subdecadal sampling resolution do not resolve this anomaly, as in Lake Rõuge, Estonia (Veski et al., 2004). However, high-resolution Greenland ice cores are clearly missing this first pulse. Taking into account that the first event presents a smaller rainfall $\delta^{18}O$ amplitude anomaly (Fig. DR4), a possible cause to explain its omission in Greenland is that the observed increase of sea ice at high latitudes (Risebrobakken et al., 2003; Wiersma and Renssen, 2006; Hald and Korsum, 2008) could counteract the $\delta^{18}O$ freshwater anomaly in those regions. When we consider the signal following the $\delta^{18}O$ spikes, the AMOC anomaly continued, having a longer lasting effect on sea-surface temperatures (SST) as recorded in MD99–2251 site (Ellison et al., 2006). SST correlates with rainfall amount in the Iberian Peninsula (Zorita et al., 1992), and hence the longer lasting anomaly in lamina thickness.

CONCLUSIONS

We have interpreted the large ^{18}O depletion in LV5 to trace a significant modification in ocean surface waters. The stalagmite most likely records two major pulses of freshwater into the North Atlantic, the most plausible cause being the final outburst of the proglacial lakes Agassiz and Ojibway. As the lag time between outburst and rainfall-depleted values is thought to be <10 years (LeGrande et al., 2006), we are reporting precise and accurate ages for both lake outbursts, recorded in LV5 $\delta^{18}O$ at 8350–8340 and 8221–8211 ± 34 yr B.P. In addition, a change of ocean isotope water composition has been considered the dominant factor causing two major drops in $\delta^{18}O$ in our continental record during the 8.2 ka event. In consequence, interpretations of $\delta^{18}O$ records under the influence of the North Atlantic that do not take this into consideration could be overestimating climate anomalies. This could be the case for the estimates of temperature drops in Greenland based on ice $\delta^{18}O$ records (Alley et al., 1997) that are double the reported values obtained using $\delta^{15}N$ in air bubbles (Kobashi et al., 2007).

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