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Hydrological and climatological controls on radiocarbon concentrations in a tropical stalagmite

Franziska A. Lechleitner [a,b,*], James U.L. Baldini [b], Sebastian F.M. Breitenbach [c,1], Jens Fohlmeister [d,e], Cameron McIntyre [a,f,g], Bedartha Goswami [h,i], Robert A. Jamieson [b], Tessa S. van der Voort [a], Keith Prufer [j], Norbert Marwan [h], Brendan J. Culleton [k], Douglas J. Kennett [k], Yemane Asmerom [l], Victor Polyak [l], Timothy I. Eglinton [a]

[a] Department of Earth Sciences, ETH Zurich, Sonneggstrasse 5, 8092 Zurich, Switzerland
[b] Department of Earth Sciences, Durham University, Durham DH1 3LE, UK
[c] Department of Earth Sciences, Cambridge University, Downing Street, Cambridge CB2 3EQ, UK
[d] Institute of Environmental Physics, University of Heidelberg, Im Neuenheimer Feld 229, 69129 Heidelberg, Germany
[e] Institute of Earth and Environmental Science, University of Potsdam, Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany
[f] Department of Physics, Laboratory of Ion Beam Physics, ETH Zurich, 8093 Zurich, Switzerland
[g] Scottish Universities Environmental Research Centre (SUERC), East Kilbride, UK
[h] Potsdam-Institute for Climate Impact Research,Transdisciplinary Concepts & Methods, Telegraphenberg A 31, 14473 Potsdam, Germany
[i] Department of Physics,Universität Potsdam, Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany
[j] Dept. of Anthropology, University of New Mexico, Albuquerque, NM 87106, USA
[k] Dept. of Anthropology, Institute for Energy and the Environment, The Pennsylvania State University, PA 16802, USA
[l] Dept. of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, USA

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Abstract

Precisely-dated stalagmites are increasingly important archives for the reconstruction of terrestrial paleoclimate at very high temporal resolution. In-depth understanding of local conditions at the cave site and of the processes driving stalagmite deposition is of paramount importance for interpreting proxy signals incorporated in stalagmite carbonate. Here we present a sub-decadally resolved dead carbon fraction (DCF) record for a stalagmite from Yok Balum Cave (southern Belize). The record is coupled to parallel stable carbon isotope ($\delta^{13}C$) and U/Ca measurements, as well as radiocarbon (^{14}C) measurements from soils overlying the cave system. Using a karst carbon cycle model we disentangle the importance of soil and karst processes on stalagmite DCF incorporation, revealing a dominant host rock dissolution control on total DCF. Covariation between DCF, $\delta^{13}C$, and U/Ca indicates that karst processes are a common driver of all three parameters, suggesting possible use of $\delta^{13}C$ and trace element ratios to independently quantify DCF variability. A statistically significant multi-decadal lag of variable length exists between DCF and reconstructed solar activity, suggesting that solar activity influenced regional precipitation in Mesoamerica over the past 1500 years, but that the relationship was non-static. Although the precise nature of the observed lag is unclear, solar-induced changes in North Atlantic oceanic and atmospheric dynamics may play a role.

Keywords: Stalagmite; Tropics; Radiocarbon; Trace elements; Hydroclimate

* Corresponding author at: Department of Earth Sciences, ETH Zurich, Sonneggstrasse 5, 8092 Zurich, Switzerland.
E-mail address: franziska.lechleitner@erdw.ethz.ch (F.A. Lechleitner).
[1] Now at Institute for Geology, Mineralogy & Geophysics, Ruhr-Universität Bochum, Universitätsstr. 150, 44801 Bochum, Germany.

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1. INTRODUCTION

Stalagmites are critical archives for the reconstruction of terrestrial paleoclimate. They are dateable with exceptional precision, and provide high-resolution time series data that reflect past climatic and environmental conditions (e.g., Vaks et al., 2013; Ridley et al., 2015a). However, because local conditions that influence proxy signals can vary between cave sites, careful interpretation of stalagmite paleoclimate records is necessary. A robust interpretation of stalagmite paleoclimate proxies therefore requires detailed knowledge of surface and cave conditions, including cave monitoring studies (Breitenbach et al., 2015), and assessments of hydrological and carbon cycle processes within the karst system (Frisia et al., 2011; Rudzka-Phillips et al., 2013; Noronha et al., 2015).

Combined analyses of stable carbon isotopes and ^{14}C in stalagmite carbonate can be particularly informative because the two proxies reflect carbon inputs from different surface environment sources (atmosphere, soil and vegetation), and from the host rock (Hendy, 1971; Genty et al., 2001; Oster et al., 2010). Meteoric water encounters high CO_2 levels in the soil, epikarst, and bedrock atmosphere (Baldini, 2010; Breecker et al., 2012; Noronha et al., 2015). Due to the biological nature of the processes involved in the production of soil CO_2 (microbial decomposition of soil organic matter (SOM) and root respiration), the $\delta^{13}C$ is strongly depleted (around −26‰ for areas dominated by C_3-type plants), whereas ^{14}C is often slightly to moderately depleted compared to the contemporaneous atmosphere through the decomposition of older residual SOM (Suppl. Fig. 1) (Genty and Massault, 1999). Dissolution of the ancient (i.e., ^{14}C-free) carbonate host rock by the acidic aqueous solution results in higher $\delta^{13}C$ values but a further reduction in ^{14}C contents in the water solution (Suppl. Fig. 1) (Genty et al., 2001). Carbonate speleothems form when dripwater saturated with respect to $CaCO_3$ enters a cave, where CO_2 levels are generally much lower than in the dripwater solution (McDermott, 2004). CO_2 degassing leads to supersaturation in the solution with respect to $CaCO_3$ and subsequent carbonate precipitation. Rapid degassing, for example in well-ventilated caves or under slow drip rates, promotes kinetic isotopic fractionation effects, leading to substantially higher $\delta^{13}C$ values (Frisia et al., 2011; Breitenbach et al., 2015).

Early studies attempting to date groundwater using ^{14}C concluded that the composite origin of groundwater carbon leads to large age offsets compared to the contemporaneous atmosphere (Wigley, 1975; Fontes and Garnier, 1979), which is then transferred to stalagmite carbonate. The difference between the stalagmite and the contemporaneous atmosphere ^{14}C content at the time of carbonate deposition is called the 'dead carbon fraction' (DCF), and can be highly variable depending on karst and soil conditions, such as the thickness of bedrock overlying the cave and SOM age spectrum (Genty et al., 2001; Rudzka et al., 2011; Griffiths et al., 2012; Noronha et al., 2014). Detailed understanding of carbon cycle controls is therefore paramount for understanding specific karst systems and for the correct interpretation of stalagmite proxy records.

Well-dated stalagmite ^{14}C time series have extended the IntCal calibration curve, taking into account DCF as a constant offset between stalagmite ^{14}C measurements and IntCal (Hoffmann et al., 2010; Southon et al., 2012). These studies led to significant improvements in our ability to date natural and archaeological samples in the absence of direct atmospheric ^{14}C records such as tree rings (i.e., beyond 13.9 kyr BP) (Reimer et al., 2013). However, DCF variations beyond the tree-ring based interval of the calibration curve are difficult to account for and to distinguish from variations in atmospheric ^{14}C activity, requiring a method independent from the calibration curve for the detection of DCF variations in stalagmites. Although DCF may be relatively constant in a cave environment over long periods of time (e.g., in stalagmite H-82 from Hulu Cave; Southon et al., 2012), significant short-term variations can occur (Griffiths et al., 2012; Noronha et al., 2014), especially during climatic extremes (e.g., the last deglaciation; Oster et al., 2010; Rudzka et al., 2011). Understanding the factors driving DCF variations would not only be important for calibration purposes, but might also open the door to ^{14}C dating of stalagmites using conventional calibration approaches.

Here we present a sub-decadally resolved stalagmite ^{14}C record from the tropical Yok Balum Cave, Belize. The exceptional resolution and chronological precision of our ^{14}C record allows direct comparison to atmospheric ^{14}C activity over the past 1500 years, and provides valuable insights into how hydrology and the karst pathways respond to climatic changes at the site. We use $\delta^{13}C$ and U/Ca to infer the importance of kinetic fractionation and prior calcite precipitation (PCP) and/or prior aragonite precipitation (PAP) occurring at the site. Carbon cycle modeling and the analysis of soil samples from above the cave help disentangle the main processes influencing ^{14}C and $\delta^{13}C$ at our site and strengthen the proxy interpretation. We compare our high-resolution ^{14}C record to atmospheric ^{14}C from IntCal13 (Reimer et al., 2013) and solar activity proxies to detect similarities and infer driving mechanisms.

2. CAVE SETTING AND CLIMATE

Yok Balum Cave is located in southern Belize in the district of Toledo (16°12′30.780″ N, 89°4′24.420″ W, 366 m above sea level) (Fig. 1). The cave developed in a steep and remote hill in a SW-NE trending karst ridge composed of limestone of Cretaceous age of the Campur Formation (Miller, 1996; Kennett et al., 2012). The vegetation above the cave consists of dense subtropical forest, composed primarily of C3 plants. Soil thickness above Yok Balum Cave varies considerably; it is generally very thin (<30 cm) but occasionally forms deeper (up to 60 cm) pockets in the strongly karstified limestone. The soil is a leptosol (WRB, 2006) and has poorly developed horizons. Due to the generally inaccessible location of the hilltop above Yok Balum Cave, it is unlikely that the vegetation and cave hydrology was ever disturbed by farming activities in the past, although the area has been populated for millennia (Kennett et al., 2012; Walsh et al., 2014).