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Bahamian speleothem reveals temperature decrease associated with Heinrich stadials

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A B S T R A C T

Temperature reconstructions across Heinrich stadials 1–3 are presented from an absolute-dated speleothem from Abaco Island in the Bahamas to understand the nature of climate change across these intervals in the subtropical Atlantic. The stalagmite carbonate record, dated by the U–Th geochronometry technique, includes higher $\delta^{18}O$ and $\delta^{13}C$ values within Heinrich stadials 1, 2, and 3 followed by rapid declines at the end of the stadials. To aid in the interpretation of these results, the $\delta^{18}O$ of fluid inclusions associated with the Heinrich stadials were also analyzed. These measurements, which allowed for the relative influence of temperature and $\delta^{18}O$ of precipitation to be distinguished, demonstrate minimal changes in the $\delta^{18}O$ of fluid inclusions, suggesting that changes in the $\delta^{18}O$ values of the speleothem carbonate associated with Heinrich stadials 1–3 are principally driven by an average ∼4 °C temperature decrease, rather than a change in the $\delta^{18}O$ of the rainfall (hence rainfall amount). These findings support previous work in the North Atlantic and are consistent with the climate response to a weakening of the Atlantic meridional overturning circulation.

1. Introduction

Ice core and deep sea sediment records of the last 65 000 years show 18 periods of millennial scale climate events known as the Dansgaard/Oeschger (D/O) cycles and 6 Heinrich stadials (Dansgaard et al., 1984). Dansgaard/Oeschger events in Greenland are millennial scale alternations between warm (interstadial) and cold (stadial) periods (Bond et al., 1997). Heinrich events are characterized in the North Atlantic by cold periods, and are recognized in the sedimentary record as eroded terrigenous materials (Ice Rafted Debris, IRD) deposited in the North Atlantic by icebergs upon melting (Bond et al., 1997; Heinrich, 1988). Heinrich stadials are associated with a slowdown of the Atlantic meridional overturning circulation (AMOC) and an inter-hemispheric climate response (Wolff et al., 2010; McManus et al., 2004). Observations and models (Zhang and Delworth, 2005) support reduction in sea surface temperatures (SSTs) associated with Heinrich stadials, thought to be caused by reduced northward heat transport, driven by the slowdown of the AMOC (Clement and Peterson, 2008) or the increase in sea/land ice (Chiang and Bitz, 2005). Reduced Northern Hemisphere SSTs led to the southward shift in the intertropical convergence zone (ITCZ) and drier conditions in the tropical Northern Hemisphere (Chiang and Bitz, 2005; Stager et al., 2011). Recent studies have also demonstrated the impact of varying height of the Laurentide ice sheet as a climate forcing during Heinrich stadial events (Roberts et al., 2014). During interstadial periods (i.e. D/O interstadial events), the inverse occurs with a poleward shift of the Northern Hemisphere summer ITCZ and the jet streams (Asmerom et al., 2010). However, the exact mechanisms driving these events are still not well understood (Clement and Peterson, 2008).

Various types of paleoclimate data support the global response to North Atlantic Heinrich stadials, as well as the abrupt nature of the events. Paleoclimate records suggest that the global signature of Heinrich stadials includes: a drier Europe (Genty et al., 2003), weaker Asian monsoon (Wang et al., 2001), wetter

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southwestern North America (Asmerom et al., 2010; McGee et al., 2012), drier northern South America (Peterson et al., 2000), wetter southern South America (Kanner et al., 2012), an overall drier tropical Asia and Africa (Stager et al., 2011), and a gradually warming Antarctica (Wolff et al., 2010) (for a review of paleoclimate data across Heinrich stadials see Clement and Peterson, 2008). While a comprehensive picture of climate across North Atlantic Heinrich stadials is emerging from records in both hemispheres, very few studies have been conducted in the subtropical western Atlantic (Grimm et al., 2006; Lachniet et al., 2013; Sachs and Lehman, 1999), which may be an important area for detecting the global propagation of these events and constraining climate models. In this study, geochemical data obtained from a speleothem spanning Heinrich stadials 1–3 are presented from a cave in Abaco Island, Bahamas. Each Heinrich stadial event exhibited unique characteristics, supporting other studies showing Heinrich stadial 1 to be the strongest event (Stager et al., 2011), with almost complete shutdown in AMOC (McManus et al., 2004).

1.1. Speleothems as paleoclimate archives

Speleothems have proven to be valuable archives for paleoclimate reconstructions, particularly for the study of climate variability on millennial timescales (Asmerom et al., 2010; Wang et al., 2001). Stable isotope ratios of oxygen and carbon ($\delta^{18}O$ and $\delta^{13}C$) of the carbonate are the most common geochemical proxies analyzed within speleothems. There are several climate factors that can lead to changes in the $\delta^{18}O$ values of the carbonate record. In the case of tropical speleothems, the $\delta^{18}O$ of the carbonate is typically interpreted to be driven primarily by the $\delta^{18}O$ of the rainfall and/or the temperature of the cave (Kanner et al., 2012; van Breukelen et al., 2008), and studies have shown that cave drip water has $\delta^{18}O$ values similar to local precipitation (Tremaine et al., 2011; van Breukelen et al., 2008). In the Bahamas and throughout the Caribbean and south Florida, there is an inverse relationship between the amount of rainfall and the $\delta^{18}O$ of the rainwater (Baldini et al., 2007; van Breukelen et al., 2008), and therefore the amount of rainfall (the amount effect) is considered to exert the main control on the $\delta^{18}O$ composition of the rainfall precipitation (Dansgaard, 1964). However, distinguishing the competing influences of temperature and $\delta^{18}O$ of the rainwater is inherently complex when interpreting the carbonate $\delta^{18}O$ results. One approach to address the confounding influences of temperature and water $\delta^{18}O$ is through the $\delta^{18}O$ analysis of fluid inclusions. These inclusions are microscopic water filled cavities located within the speleothem calcite mineral structure which contain drip water trapped at the time the stalagmite formed. As suggested above, the drip water is thought to directly represent precipitation, and therefore the isotopic analysis of the trapped water provides a direct measure of the temporal changes in the $\delta^{18}O$ of rainfall (hence rainfall amount). Determining the $\delta^{18}O$ value of both the trapped fluid and that of the accompanying mineral allows the temperature at the time of speleothem formation to be calculated (van Breukelen et al., 2008).

In contrast, the $\delta^{13}C$ of the carbonate is a function of the type and amount of vegetation above the cave, root respiration, organic material decomposition, the amount of water/rock interactions and prior calcite precipitation (Fairchild et al., 2006). Variation in the biogenic CO_2 component of the carbon is in turn influenced by precipitation amount and temperature (Genty et al., 2003). Generally the partial pressure of CO_2 (pCO_2) is expected to show an inverse correlation with $\delta^{13}C$ values in the soil horizon. Changes in the amount of rainfall or temperature could also alter the ratio of C_3 and C_4 plants, causing further isotopic changes, particularly over longer timescales (Fairchild et al., 2006). Cave ventilation may also exert control over the $\delta^{13}C$ of the CO_2 in the cave and therefore ultimately the $\delta^{13}C$ in the cave fluids (Tremaine et al., 2011). Through the combination of both $\delta^{18}O$ and $\delta^{13}C$ of the carbonate as well as $\delta^{18}O$ of the fluid inclusions, variations in the temperature and amount of rainfall can be estimated over the sample time period.

1.2. Previous work on Bahamian speleothems

Several studies have been conducted on the formation, growth, age, and geochemistry of Bahamian speleothems, with most of the work carried out on samples from caves currently submerged in seawater (Richards et al., 1994 and references therein). These speleothems formed during previous sea level low-stands and stopped forming when rising sea level flooded the caves, making the speleothems potential archives of paleo-sea level. However, it has also been shown in some instances that the speleothems ceased forming prior to seawater flooding, presumably as a result of drier conditions (Richards et al., 1994). Richards et al. (1994) also found no geochemical evidence of alteration in samples from submerged caves. Stalagmites from the Bahamas have been additionally utilized as recorders of past atmospheric $\Delta^{14}C$ concentration for radiocarbon calibrations (Hoffmann et al., 2010; Beck et al., 2001).

The aim of this work is to determine the paleoclimatic changes associated with Heinrich stadials over the last ∼32 000 years by applying multiple geochemical tools. This study represents the first high resolution paleoclimate reconstruction utilizing a Bahamian speleothem and the first multi-collector ICP-MS dated speleothem from this region. Additionally, the combination of both stable isotope analyses of the carbonate and fluid inclusions is unique and the resolution of the fluid inclusion analyses for a stalagmite record from this time period is unprecedented. Finally, considering that relatively few studies have been conducted in the subtropical western Atlantic (Escobar et al., 2012; Grimm et al., 2006; Hagen and Keigwin, 2002; Hodell et al., 2012; Keigwin and Jones, 1994; Sachs and Lehman, 1999), and even fewer studies are from terrestrial records, this study offers the opportunity to better understand abrupt climate change at this location during the Pleistocene and its relationship to the climate of the North Atlantic.

2. Sample locality and methods

2.1. Regional setting

The modern climate of the Bahamas is primarily controlled by the easterly trade winds and winds from the west are limited to frontal passages (Baldini et al., 2007). The annual variation in air temperature ranges from 22 to 28 °C (Baldini et al., 2007). There are distinct wet and dry seasons with the wetter period between April to December driven by the Bermuda high.

The stalagmite (sample AB-DC-09) was collected from a currently submerged cave located in the middle of southern Abaco Island, Bahamas (N26°14, W77°10) in July of 2007 from a depth of 16.5 m below current sea level (Fig. 1). The cave is accessed through a collapsed sinkhole and consists of three laterally extensive levels at ∼22, 33.5 and 45 m below sea level. The overlying bedrock of the cave is composed of Pleistocene limestone aeolianites and marine limestones (Walker et al., 2008). After collection, the speleothem was sectioned along the main growth axis (Fig. 2a) and sampled in the central region for U–Th geochronometry, stable C and O isotopes ($\delta^{13}C_c$ and $\delta^{18}O_c$), and $\delta^{18}O_w$ of fluid inclusions. Sample AB-DC-09 has a total length of 23 cm and is comprised of dense milky white calcite with no evidence of post-depositional diagenesis (Fig. 2a).