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Speleothem evidence for the greening of the Sahara and its implications for the early human dispersal out of sub-Saharan Africa

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Although there is a consensus that there were wet periods (greening events) in the Sahara in the past, the spatial extent and the timing of these greening events are still in dispute, yet critical to our understanding of the early human dispersal out of Africa. Our U-series dates of speleothems from the Northeastern Sahara (Wadi Sannur cave, Egypt) reveal that the periods of speleothem growth were brief and restricted to the interglacial Marine Isotope Stages MIS 5.5, MIS 7.3, and the early MIS 9 with a remarkable absence of the Holocene deposition of speleothems. These growth periods of Wadi Sannur cave speleothems correspond to periods of high rainfall and spread of vegetation (green Sahara). Distinct low $\delta^{18}O$ values of speleothems indicate a distal moisture source that we interpret to be the Atlantic Ocean. These two lines of evidence from the Wadi Sannur speleothems thus suggest that maximal northward shifts in the West African monsoon system occurred during the growth periods of the speleothems, leading to greening of the Sahara, facilitating human migration into Eurasia. The periods of speleothem growth at Wadi Sannur cave are contemporaneous with important archeological events: (1) the earliest occurrence of the Middle Stone Age assemblages and *Homo sapiens* in North Africa (Jebel Irhoud), suggesting wide spread of greening conditions over the East–West transect of the Sahara, (2) the sharp technological break between the Acheulo-Yabrudian and the Mousterian industries, and (3) the arrival of *Homo sapiens* in Levant, indicating a key role of the Sahara route in early human dispersal out of Africa.

1. Introduction

The Sahara desert is one of the warmest and driest places on Earth today. However, a wealth of marine and surface continental archives suggests that the Sahara had been periodically transformed to a green landscape (greening of the Sahara) in the past (e.g., Castañeda et al., 2009; Kuper and Kröpelin, 2006; Larrasoana et al., 2003). At present, the southern border of the Sahara desert is located at 17°N to the north of the Savanna (green landscape) which includes three main vegetation belts (woodland, wooded grassland and grassland). These vegetation belts lie between the following isohyet ranges: 1800–1225, 1225–265 and 265–100 mm/year, respectively (Larrasoaña et al., 2013). Cerling et al. (2011) have inferred from carbon isotope compositions of paleosols in east Africa that the latter two vegetation belts contained the majority of hominin sites (70%) over the last 6 million years. While a dry Sahara (<100 mm/year) would have been a human migration barrier, a green Sahara (≥100 mm/year) could have been habitable, facilitating the migration of early humans out of Africa (Drake et al., 2011; Scerri et al., 2014). Palynological investigation of marine sediments offshore from northwestern Africa showed that the spatial extension of the greening events in the Sahara was restricted to north of latitude 23°N in the last 250 ka (Hooghiemstra et al., 2006), while lacustrine sediments from northeast Africa indicate the existence of paleolakes at 25°N within the same period (Kieniewicz and Smith, 2009; Schwarcz and Morawska, 1993). Paleolakes imply an uninterrupted humid corridor which extended

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between latitudes 21°N to 30°N in the central Sahara during MIS 5 (Osborne et al., 2008). Although lacustrine remnants provide excellent records of wetter periods in the past, their records in most cases are partly or entirely lost as a result of erosional processes (deMenocal, 2013). Consequently, our understanding of the past climate of the Sahara through climate models (e.g., Kutzbach and Liu, 1997; Herold and Lohmann, 2009) is hampered by the lack of evidence on the ground to test these models.

Speleothems are cave carbonate deposits, isolated from surface weathering and alteration. The formation of dripstone and flowstone speleothems, such as stalagmites, is a function of water and vegetation availability. Rainfall water is a carrier for soluble calcium carbonate which is leached from the host rock and made available primarily by the CO_2 respiration of plants in soils (Ford and Williams, 2007). In arid regions, such as the Sahara, the absence of vegetation in the presence of water would terminate speleothem growth because of the insufficient pCO_2 gradient between the drip water and cave atmosphere (Vaks et al., 2010; White, 1976). Therefore, speleothem growth in the Sahara is a powerful proxy for the greening of the Sahara and consequently its human accessibility. Abundant archeological evidence exists for the presence of humans in the Sahara during the Early, Middle and Later Stone Age (Wendorf et al., 1976, 1993; McBrearty and Brooks, 2000), implying that there were multiple greening events over the last million years. The periods of speleothem growth have potential to be dated by the U-Th method back to 500,000 years (Cheng et al., 2016; Vaks et al., 2013). Moreover, the oxygen isotope composition of speleothem carbonates is an invaluable geochemical tracer for their moisture source (Asmerom et al., 2010).

In this work, we studied a double stalagmite, sample WS-5d, from the Wadi Sannur cave in Egypt in the Northeast Sahara (Fig. 1). This cave is well suited for the assessment of greening of the Sahara and its implication for early human migration out of sub-Saharan Africa and into Eurasia. The cave is potentially located in the path of two different climate systems, the Atlantic–Mediterranean westerlies and the West African Monsoon. Today's climate of the region is driven by Mediterranean westerlies, and the cave has no active dripping sites (Fig. 1a). Growth of stalagmite WS-5d must have occurred only when the climate was wetter than at present and when vegetation existed above the cave. Therefore, timing of growth periods and determination of oxygen isotope composition in the WS-5d stalagmite can help us to delineate the timing and causes of the greening of the Sahara in the past. This will also allow us to put time constraints on likely periods of human migration across the currently hyper arid Sahara. The Wadi Sannur cave region of the Sahara is at the gateway to a potential land-based migration into Eurasia, hindering (during arid intervals) or facilitating (during wet periods) human migration out of Africa. Moreover, Wadi Sannur is intermediately situated between two proposed routes for early human migration out of Africa; the Nile River route (Van Peer, 1998) and the Red Sea route (Walter et al., 2000) (Fig. 1a), thus significant greening in the region would make it a potential corridor for each route.

2. Wadi Sannur cave

The Wadi Sannur cave is located 200 km southeast of Cairo, east of the Nile River, in the Beni Suef governorate, Egypt at N28° 37' and E31° 17' (Fig. 1). It was a completely closed cave until 1991 AD when a narrow opening was discovered beneath an alabaster quarry. This opening is 200 m.a.s.l (i.e., 50 m below ground surface) and currently used as a lone entrance to the cave. The cave chamber has a crescent shape of 275 m length that is divided into left and right corridors (Günay et al., 1997). The latter corridor is more decorated with various types of speleothems (flowstone, helicities, stalactities, soda straws and stalagmites) than the other. The cave developed in the middle Eocene limestone of the Sannur formation by dissolution and precipitation mechanisms (Philip et al., 1991). The floor of the Wadi Sannur cave is 40 m above the modern water table. Modern climate in the cave area is arid with annual precipitation of 7 mm/year limiting the local vegetation to only rare C4 grasses. The cave lies in the Wadi Sannur basin which has extensive drainage network, NW-SE structural lineaments system and large surface area (5412 km^2, Fig. 1b and c). The drainage network of the Wadi Sannur drains into the Nile and is fed by rains received on the uplands in the eastern part of the basin (e.g., El Galala mountains: 1200 m.a.s.l). The Red Sea mountains to the southeast of the Wadi Sannur basin could have acted as an orogenic barrier by directing rains toward the Wadi Sannur basin in the past (Fig. 1b and c). A paleo-karst surface in the Wadi Sannur basin and residues of terra-rossa soil found in fractures above the cave indicate previous intensive paleorainfall and paleovegetation in the area (Philip et al., 1991). These field observations along with the drainage pattern and the high topography to the east support the possibility of the Wadi Sannur basin serving as a paleorainfall gauge for the northeastern Sahara.

A double stalagmite of 36 cm length, sample WS-5d (Fig. 2), was collected from the right corridor of the cave in May of 2012. There is no water dripping inside the cave today. The mean annual temperature inside the cave is 23 °C. A longitudinal cross section of WS-5d shows elongated columnar crystals with no visible signs of hiatuses (Fig. S3a). These elongated crystal fabrics suggest that the stalagmite WS-5d formed at near chemical equilibrium conditions (i.e., low $CaCO_3$ supersaturation) and grew through a spiral growth mechanism under a constant flow rate. Therefore, its stable isotope composition could be used as a reliable proxy to infer paleoclimate information (Frisia, 1996; Frisia et al., 2000).

3. Analytical methods

U-series isotope measurements were made at the Radiogenic Isotope Laboratory, University of New Mexico. Subsample powders (90–160 mg) were milled out and completely dissolved in concentrated nitric acid and spiked with a mixed ^{229}Th-^{233}U-^{236}U spike. U and Th were separated using conventional anion-exchange chromatography. Isotope ratio measurements were made with a Thermo Neptune Plus multicollector inductively coupled plasma mass spectrometer (MC-ICPMS). The MC-ICPMS measurements were run in static mode using a mix of 10^{10}, 10^{11} and 10^{12} Ω resistors in conjunction with Faraday cup detectors and an ion-counting secondary electron multiplier detector. NBL-112A U isotope standard was measured with the samples, obtaining the published $\delta^{234}U$ value of −38.0 (Cheng et al., 2013). The $\delta^{234}U$ is the permil variation of a sample's $^{234}U/^{238}U$ atomic ratio relative to the ratio at secular equilibrium equal to one. The analytical uncertainties are given as 2σ of the mean. The corrected age uncertainties include analytical errors and uncertainties in the initial $^{230}Th/^{232}Th$ ratio of a possible detrital contaminant. An initial $^{230}Th/^{232}Th$ atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$ was used in the age calculations. ^{234}U and ^{230}Th decay constants were taken from Cheng et al. (2013). The oxygen isotope analyses were conducted by the McMaster Research Group for Stable Isotopologues (MRSI) at McMaster University. The WS-5d stalagmite was sampled at 5 mm interval along the growth axis of the large stalagmite. The collected carbonate samples were analyzed with an automated carbonate device at 90 °C for their $\delta^{18}O$ values using an OPTIMA gas source stable isotope ratio mass spectrometer. Reported $\delta^{18}O$ values were normalized to the recommended values for two isotopic reference materials NBS 18 and NBS 19. Long-term internal precision of these reference materials is better than 0.08‰. All oxygen isotope compositions are reported in