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Rapid Communication

Holocene and Pleistocene pluvial periods in Yemen, southern Arabia

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ABSTRACT

Arabia is an important potential pathway for the dispersal of *Homo sapiens* ("out of Africa"). Yet, because of its arid to hyper-arid climate humans could only migrate across southern Arabia during pluvial periods when environmental conditions were favorable. However, knowledge on the timing of Arabian pluvial periods prior to the Holocene is mainly based on a single and possibly incomplete speleothem record from Hoti Cave in Northern Oman. Additional terrestrial records from the Arabian Peninsula are needed to confirm the Hoti Cave record. Here we present a new speleothem record from Mukalla Cave in southern Yemen. The Mukalla Cave and Hoti Cave records clearly reveal that speleothems growth occurred solely during peak interglacial periods, corresponding to Marine Isotope Stages (MIS) 1 (early to mid-Holocene), 5.1, 5.3, 5.5 (Eemian), 7.1, 7.5 and 9. Of these humid periods, highest precipitation occurred during MIS 5.5 and lowest during early to middle Holocene.

1. Introduction

The Arabian Peninsula is considered being a key-area for the dispersal of *Homo sapiens* from Africa to the Middle East and beyond as evidenced by the occurrence of numerous paleolithic archaeological sites (Petraglia, 2005) (Fig. 1A). Considering the present arid and hostile environmental conditions in almost all parts of Arabia, humans could only migrate across the Arabian Peninsula when precipitation was considerably higher than today and when environmental conditions were favorable. However, the pattern and nature of pre-Holocene pluvial periods is still poorly known. The most precisely-dated and longest terrestrial climate record from southern Arabia is derived from speleothems from Hoti Cave in Northern Oman (Burns et al., 1998, 2001; Fleitmann et al., 2003a, 2009). Here, intervals of enhanced speleothem deposition occurred exclusively during interglacial periods corresponding to Marine Isotope Stages (MIS) 1, 5.1 (5a), 5.5 (5e), 7.1, and 9. In contrast, glacial periods were characterized by arid to hyper-arid conditions and lack of speleothem deposition (Burns et al., 2001).

In contrast, a stacked marine record of Indian summer monsoon (ISM) wind strength from the Northern Arabian Sea suggests that equally strong ISM winds occurred during periods of peak summer insolation in both glacial and interglacial periods (Clemens and Prell, 2003). Though such a precession-driven pacing of the ISM is consistent with other monsoon records (Wang et al., 2004; Cruz et al., 2005; Weldeab et al., 2007; Cheng et al., 2009), it clearly contrasts to the Hoti Cave record. Several explanations for this discrepancy are conceivable. First, stronger ISM winds might not necessarily coincide with increased monsoon precipitation over Oman (Burns et al., 2001). Second, the monsoon rainfall belt might have been located south of Hoti Cave (23°05′N, 57°21′E) during glacial periods, but still may have reached the areas south of 23°N. Third, speleothem deposition in Hoti Cave may have ceased when total annual precipitation dropped below a certain threshold level. Fourth, glacial stalagmites from Hoti Cave were perhaps simply missing during sample collection. Clearly, additional terrestrial records from the Arabian Peninsula are required to test the

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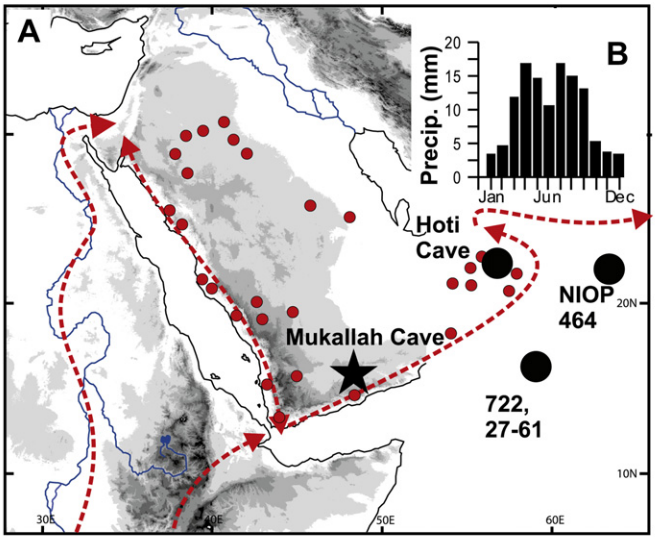

Fig. 1. (A) Map of Arabia showing the location of Hoti Cave (black dot) and Mukalla Cave (black star). Also shown are Paleolithic sites (red dots; Petraglia, 2005), possible human dispersal routes (red dashed lines) and marine sediment records (black labeled dots). (B) Monthly distribution of precipitation around Mukalla Cave (CRU TS 2.1 dataset; Mitchell and Jones, 2005). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

completeness of the composite Hoti Cave record from Northern Oman.

Here we present three new Uranium-series dated (^{230}Th) stalagmites from Mukalla Cave in Southern Yemen (Fig. 1A). The new record confirms the composite stalagmite record from Hoti Cave (Burns et al., 1998, 2001; Fleitmann et al., 2003a) and adds further information on the timing and nature of pluvial periods in Southern Arabia. When combined, both cave records add crucial background information on climate variability along the southern human dispersal route for ex-African migration (Fig. 1A).

2. Environmental setting, material and methods

Mukalla Cave (14°55′02″N; 48°35′24″; ~1500 m asl), approximately 70 km north of Mukalla in Southern Yemen, is a rather shallow and small cave with only one cave entrance. Bedrock thickness is less than 30 m. Vegetation above the cave is almost absent and soil thickness is less than 10 cm. No actively growing stalagmites were found in October 1997 and 1999, when stalagmites were collected.

Recent climate in Southern Yemen follows the monsoon climate pattern and the annual migration of the Intertropical Convergence Zone (ITCZ). The present climate at Mukalla Cave is arid to hyperarid. Total annual precipitation is highly variable both in space and time, but averages ~120 mm yr^{-1} (1971–2005), with maxima in spring and summer (CRU data; Mitchell and Jones, 2005) (Fig. 1B).

Three stalagmites (Y99, Y97-4 and Y97-5) (Fig. 2), were collected from Mukalla Cave. Stalagmite Y99 is a columnar-shaped 3.20 m long stalagmite, which was sampled as an entire column for the upper ~70 cm and by drilling for the lower 250 cm. Stalagmites Y97-4 and Y97-5 (Fig. 2) are considerably smaller and were sampled close to Y99. When cut perpendicular to the growth axis, each stalagmite exhibits distinct changes in color and alternating drip caps (Fig. 2).

A total of 46 ^{230}Th-ages for all stalagmites were measured. ^{230}Th-ages for stalagmite Y99 were performed on a multicollector ICP mass spectrometer (Nu-Instruments; Supplementary information Table A1) at the Institute of Geological Sciences, University of Bern. ^{230}Th-ages for stalagmites Y97-4 and -5 were determined with a Thermal Ionization Mass spectrometer at the Heidelberg Academy of Sciences (Supplementary information Table A2). Detailed information on chemical separation and purification of uranium and thorium as well as on instrumental set up is provided by Burns et al., 2001 and Fleitmann et al., 2007, 2009.

A total of 545 oxygen isotope (δ^{18}O) measurements were performed with an online, automated, carbonate preparation system linked to a VG Prism ratio mass spectrometer and Finnigan Delta V

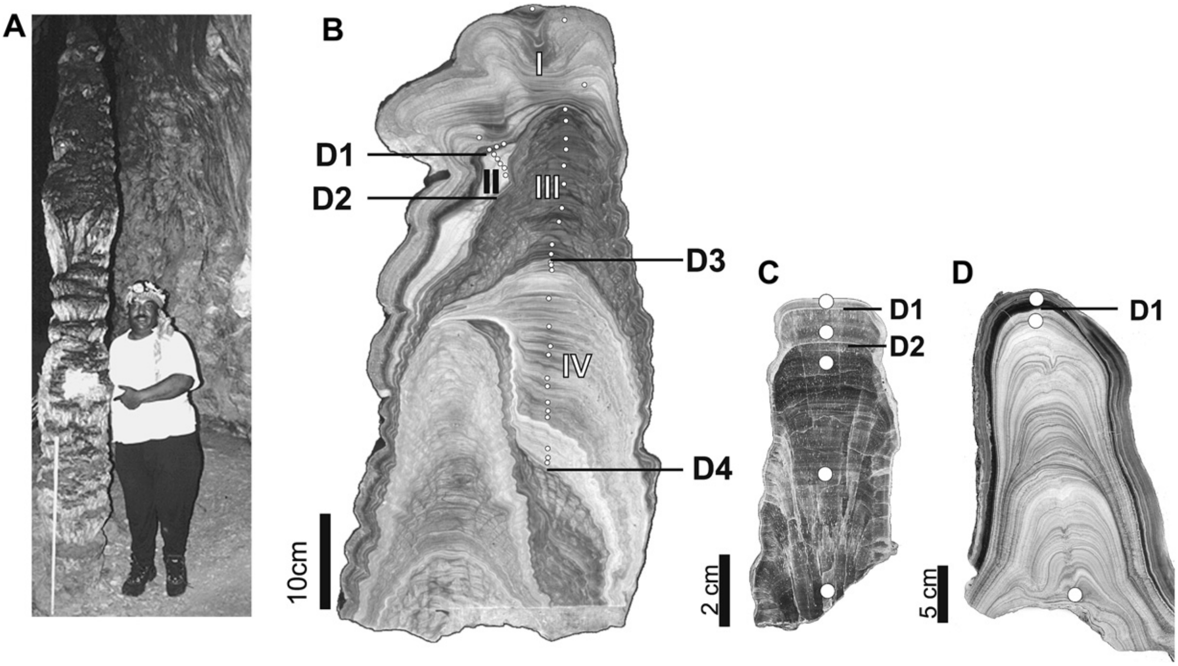

Fig. 2. (A) Image of stalagmite Y99 from Mukalla Cave. (B) Top of stalagmite Y99. D1-4 and I–VI mark discontinuities and growth intervals respectively. (C) Stalagmites Y99-4 and (D) Y99-5. White dots mark location of ^{230}Th-dates.

Advantage mass spectrometer equipped with an automated carbonate preparation system (Gas Bench II) at the Institute of Geological Sciences, University of Bern. Precision of $\delta^{18}O$ measurements is <0.8‰ (1σ-error) (Fleitmann et al., 2007, 2009). Results are shown as the per mil difference between sample and the VPDB standard in delta notation. Oxygen isotope data can be downloaded from the NOAA National Climatic Data Center (NOAA Paleoclimatology; http://www.ncdc.noaa.gov/paleo/).

3. Results

^{230}Th-ages reveal at least five discrete intervals of stalagmite growth in Mukalla Cave which occur from ∼6–10 (early to middle Holocene), ∼100–105; 123–130, ∼195–209, ∼230–245 and ∼300–330 ka BP (Fig. 3). Each of these growth intervals is visibly recognizable in our stalagmites separated by hiatuses marked by lateral displacements in the growth axis or by distinct changes in calcite texture and color. Precise estimates for the onset and termination of all growth intervals are difficult to make due to age uncertainties and limited number of ^{230}Th-ages for the Holocene sections of stalagmites Y99-4 and -5.

$\delta^{18}O$ values of Mukalla Cave stalagmites range very broadly from −12.3‰ to −2.8‰. For the early to middle Holocene, $\delta^{18}O$ values vary between −6.5‰ and −2.8‰ and are on average less negative than those of the preceding interglacial periods (Fig. 3). The most negative $\delta^{18}O$ values are observed during the MIS 5.5 (Eemian), with values ranging between −12.3‰ and −5.4‰. The Box–Whisker plot shows a comparison of the range in $\delta^{18}O$ for the different growth intervals (Fig. 4).

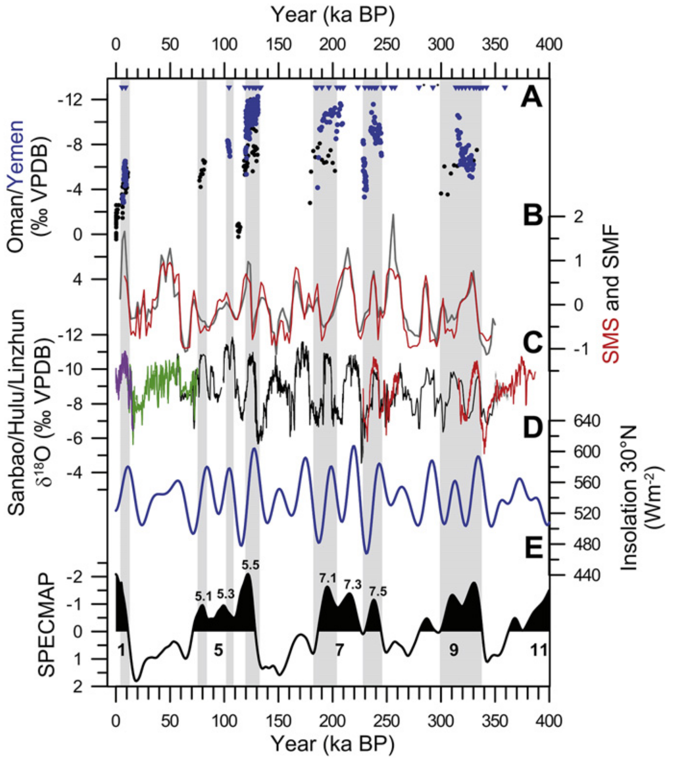

Fig. 3. (A) $\delta^{18}O$ records of stalagmites from Mukalla Cave (blue dots) and Hoti Cave (black dots). Blue triangles mark ^{230}Th-ages of stalagmites from Mukalla Cave. The gray shaded areas mark intervals of speleothem growth. Two triangles marked with a black start denote ^{230}Th-ages which are affected by post depositional alteration. (B) Comparison between a stacked record of monsoon wind strength (Clemens and Prell, 2003) expressed as SMS (summer monsoon stack) and SMF (summer monsoon factor). (C) Shanbao/Hulu/Linzhun $\delta^{18}O$ time series from China (Cheng et al., 2009). Colors denote different stalagmites and caves respectively. (D) Summer insolation for 30°N (Berger and Loutre, 1991). (E) Also shown are the SPECMAP curve and Marine Isotope Stage numbers (Imbrie et al., 1990). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

4. Discussion

4.1. Timing of speleothem deposition in Yemen

Speleothem deposition in Mukalla Cave is restricted to peak interglacial periods corresponding to MIS 1 (Holocene), 5.3, 5.5 (Eemian), 7.1, 7.5 and 9, with no evidence for speleothem growth during any of the intervening glacial periods (Fig. 3). This pattern of speleothem growth is remarkably consistent with that in Hoti Cave in Northern Oman (Burns et al., 2001; Fleitmann et al., 2003a). Negative $\delta^{18}O$ calcite values of between approximately −4‰ and −12.3‰ are characteristic for calcite deposited under monsoonal precipitation (Neff et al., 2001; Fleitmann et al., 2003b; Lézine et al., 2007) and indicate that the ITCZ and the ISM rainfall belt reached Southern Arabia during MIS 1 (early to middle Holocene), 5.1, 5.3, 5.5, 7.1, 7.5 and 9. Because Mukalla Cave is located at 14.5°N and close (<100 km) to the Arabian Sea coast, the lack of stalagmite growth during glacial periods is strong evidence that the ISM rainfall belt did not reach Southern Arabia or that precipitation was too low to recharge the karst aquifer above Mukalla Cave. A key question is therefore, how much precipitation is required to trigger speleothem deposition in Southern Arabia?

Under present-day climate conditions, with precipitation averaging ∼120 mm yr^{-1} (CRU TS 2.1 dataset; Mitchell and Jones, 2005), no drip sites with active speleothems were found in Mukalla Cave. In Hoti Cave, where total annual rainfall is only slightly higher at ∼170 mm yr^{-1} (station Al-Hamra; 1977–1997), very few sites with dripping water and only small actively growing stalagmites have been found (Burns et al., 2001). Thus, precipitation

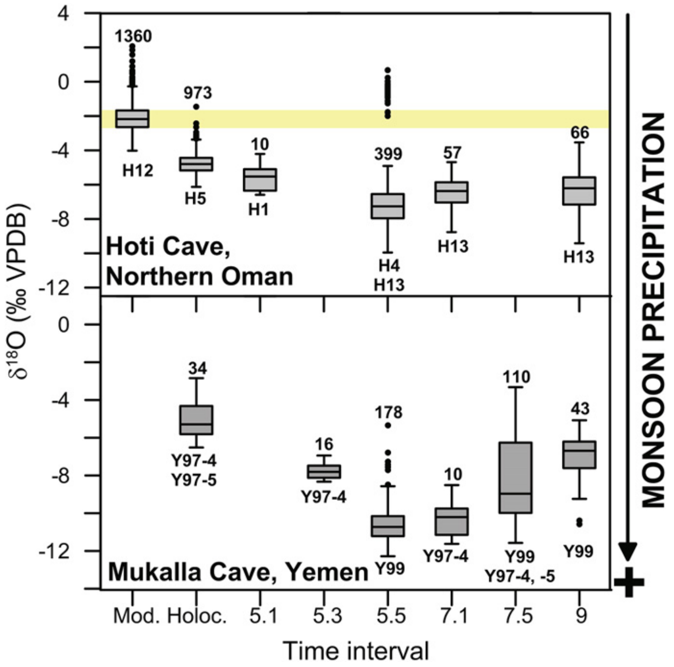

Fig. 4. Box–Whisker plot of $\delta^{18}O$ values for Hoti Cave, Northern Oman, and Mukalla Cave, Yemen. The gray shaded box marks the lower and upper quartiles, and the line in the center of the box is the median. The yellow box marks the modern range in $\delta^{18}O$. Outliers are marked by black dots. Numbers denote the number of stable isotope analyses and labels stalagmites. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

between ~120 and ~170 mm yr^{-1} at both cave sites is not sufficient for recharging the karst aquifer to such an extent that large stalagmites can grow. This is in good agreement with observations in the Negev desert in Israel, where the ~300–350 mm isohyet marks the limit of modern speleothem deposition (Vaks et al., 2010). Based on this study, a two- to three-fold increase of total annual precipitation from around ~120–170 mm yr^{-1} to >300–350 mm yr^{-1} is required for triggering the growth of speleothems. Because two of the studied stalagmites (stalagmites Y99 from Mukalla Cave and H-13 from Hoti Cave) have a large diameter and are taller than 3 m (Fig. 2A), precipitation must have been even significantly higher than 300 mm yr^{-1} as formation of such tall and large diameter stalagmites requires rather high and constant drip rates.

4.2. Comparison between pluvial periods in Yemen and Oman

Previous studies performed on stalagmites from Oman and Yemen reveal that $\delta^{18}O$ values are a proxy for the amount of precipitation (Burns et al., 1998, 2001; Fleitmann et al., 2003a,b, 2004, 2007, 2009), with more negative $\delta^{18}O$ values indicating higher monsoon precipitation (the so-called "amount effect"). This relationship allows us to compare the different interglacial periods with respect to the amount of precipitation. The Box–Whisker plots show clear differences in $\delta^{18}O$ among the pluvial periods (Fig. 4), which are very similar in Mukalla and Hoti Cave. Surprisingly, the least negative mean $\delta^{18}O$ values and thus lowest monsoonal rainfall of all interglacials are observed for the early to middle Holocene. Highest monsoon precipitation indicated by the most negative $\delta^{18}O$ values is observed during the MIS 5.5 (Eemian) at both cave sites. This observation is consistent with climate model simulations, which demonstrate that precipitation during the early- to mid-Holocene was considerably lower than during MIS 5.5 (Braconnot et al., 2008; Fischer and Jungclaus, 2010). $\delta^{18}O$ values of the other pluvial periods corresponding to MIS 5.1, 5.3, 7.1, 7.5 and 9 plot somewhere between the Eemian and middle Holocene; whereas MIS 7.1 seems to have been the second wettest of all pluvial periods in southern Arabia.

4.3. Comparison with other Indian summer monsoon records

A key question is how the Mukalla and Hoti Cave records compare to other Indian summer monsoon (ISM) records. The longest time series of ISM wind strength covers the last 350 ka continuously and is based on three marine sediment cores from the Arabian Sea (cores 722, 27–61 and NIOP 464; Fig. 1A), just offshore of Southern Arabia (Clemens and Prell, 2003). The stacked record is based on lithogenic grain size, carbon mass-accumulation rates, and relative percentages of foraminifers, which are all considered being proxies for ISM wind intensity. This record suggests that for periods of high summer insolation, controlled by precession, equally strong ISM winds occurred during glacial and interglacial periods (Clemens and Prell, 2003) (Fig. 3), a monsoonal pacing that is in stark contrast to our speleothem records from southern Arabia. Thus, ISM precipitation and wind strength over Southern Arabia and the Arabian Sea appear to be decoupled during glacial periods. The combined Hulu/Shanbao/Linzhu Cave record (Fig. 3), shows also clear evidence for heavy Asian monsoon precipitation during glacial periods and clearly follows a precessional rhythm (Cheng et al., 2009). For instance, the Hulu/Shanbao/Linzhu Cave record indicates high monsoon precipitation during MIS 6 when precipitation was even higher than during MIS 5.5 (Eemian). Clearly, periods of continental wetness in southern Arabia with precipitation higher than 300 mm yr^{-1} do not simply follow precession-driven changes in monsoon intensity and the northward movement of the ITCZ into the Arabian Peninsula seems to be impeded during glacial periods.

4.4. Pluvial periods and human dispersal along the southern dispersal route

Though our data cannot deliver any direct evidence for phases of human migration in southern Arabia, they help to define so-called "windows of opportunity" for early humans to migrate along the southern dispersal route (Fig. 1A). There is now mounting evidence that the main phase of human dispersal took place sometime between 130 ka and 65 ka BP (Walter et al., 2000). For this time interval at least three pluvial phases at 130–123 (MIS 5.5), ~100 (MIS 5.3) and 80–78 (MIS 5.1) ka BP are now firmly established by our stalagmite records from Southern Arabia. Thus, there were three "windows of opportunity" or favorable "climatic windows" (Vaks et al., 2007) when humans could migrate along the southern dispersal route or move across large parts of the Arabian Peninsula. Furthermore, the lack of speleothem growth between MIS 5.1 and the MIS 1 (early Holocene) is indicative of rather arid climate conditions with precipitation of less than 300 mm yr^{-1} in southern Arabia. Thus, climatic and environmental conditions between M5.1 and MIS 1 along the southern dispersal route were rather hostile and not favorable for modern humans.

5. Conclusions

Speleothem growth in Yemen and Oman occurred only during peak interglacial periods corresponding to the early to middle Holocene, MIS 5.1, 5.3, 5.5, 7.1, 7.5 and 9. Of these pluvial periods, the early to middle Holocene was the driest and MIS 5.5 (Eemian) the wettest one. Speleothem deposition ceased in Yemen and Oman during glacial periods. For the time interval between 130 and 65 ka BP, the proposed main period for human dispersal from Africa, three pluvial periods at 130–123, 105–100 and 80–78 ka BP can be firmly established. Thus there were at least three time slots for modern humans to use the southern dispersal route (Fig. 1).

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Appendix. Supplementary information

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.quascirev.2011.01.004.

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