The history of the monsoon in southern Arabia: results based on stable isotopes and U/Th dating of speleothems

S. J. Burns
A. Matter
Geological Institute, University of Bern, Baltzerstrasse 1, Bern, Switzerland CH-3012

A. Mangini
Heidelberg Academy of Sciences, Im Neuenheimer Feld 266, Heidelberg, Germany D-69120

M. Mudelsee
Institute of Mathematics and Statistics, University of Kent at Canterbury, Canterbury, Kent CT2 7NF, UK

Studies of marine sediments have shown that the intensity of the Indian Ocean monsoon system has varied greatly over the past several glacial-interglacial cycles in response to changes in Northern Hemisphere insolation in the precession band and/or to glacial boundary conditions (e.g. Sirocko *et al.*, 1993; Overpeck *et al.*, 1996). Less well known is how marine indicators of increased monsoon intensity relate to climate variation of continental areas around the Indian Ocean, particularly the Arabian Peninsula. Here we present a palaeoclimate record extending back to 125 ka from northern Oman based on U-Th dating and stable isotope analyses of speleothems. The aims of this study are to provide further information on the timing and intensity of monsoonal rainfall on the Arabian Peninsula, to extend the palaeoclimate record further back in time, and to investigate how continental climate variation compares to marine records of monsoon variation from the nearby Arabian Sea.

Sample descriptions and methods

Samples used in this study were collected from Hoti Cave in northern Oman (57 21′E, 23 05′N, 800 m above sea level). The overall morphology of the cave deposits is as follows. The stratigraphically lowest deposit in the cave is a large flowstone, ~2.3 m thick and several 100s of metres long, which forms the floor of part of the cave. The flowstone is by far the largest carbonate deposit in the cave. On top of the flowstone, several generations of stalagmites were deposited, the largest of which are 1–1.5 m high. All larger stalagmites are inactive. Several different large stalagmites were sampled, either by collecting entire, previously-broken specimens or by drilling. Small, growing stalagmites and samples of cave drip waters were also sampled.

General climate evolution

Figure 1 shows the overall results of stable isotopic and TIMS U/Th age determinations for the flowstone and overlying stalagmites. The flowstone was deposited between ca. 120 and 125 ka. Results of 164 stable isotope analyses show that the $\delta^{18}O$ values for the lower 220 cm fall into a fairly narrow range, from −9‰ to −12‰. In the upper 10 cm of the flowstone, $\delta^{18}O$ values increase slightly to between −7‰ and −9‰. The flowstone is overlain by at least two generations of large (>30 cm) stalagmites. Sample H-4 grew directly on top of the flowstone. The uppermost 4 cm of the stalagmite is composed of brown, very finely laminated, the lower 80 cm of the stalagmite is composed of white sparry calcite. A sample from 0.5–1.5 cm, within the brown laminated calcite, yields a U-Th age of 112.9±2.7 ka. Samples from, 4–4.5, 34–36, 56–58 and at 82.5–84 cm, all within the white sparry calcite, yield U-Th ages of 121.6 ±5.2, 116.9±2.6, 117.6±2.6 and 119.0±4.4 ka, respectively. $\delta^{18}O$ values for the lower 80 cm of the stalagmite (the white, sparry portion) vary from −6‰ to −10‰. The transition from sparry to laminated calcite is accompanied by a large shift in $\delta^{18}O$ to values ranging from −2‰ to 0‰. A second generation of stalagmites was also deposited on the flowstone. Sample H-5 grew on top of a partly eroded portion of the flowstone. Due to drilling equipment failure, only the upper 34 cm of the stalagmite could be sampled. The entire core is composed of white to brown, finely laminated calcite. Six U-Th measurements date deposition to between 6.22 ± 0.18 and 9.70 ± 0.05 ka . For the lower 33.6 cm, $\delta^{18}O$ values vary between −4‰ and −6‰ . In the upper 40 mm of the core, $\delta^{18}O$ values increase to −1.4‰ in the topmost sample.

The general climate evolution of the Hoti Cave

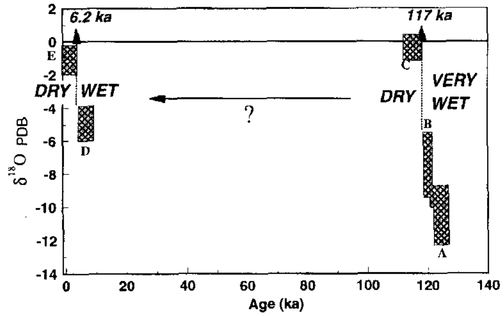

FIG. 1. $\delta^{18}O$ values for speleothems from Hoti Cave *vs* age. Capital letters identify sample data. A: flowstone, B: lower part of stalagmite H-4, C: upper part of stalagmite H-4, D: stalagmite H-5, E: modern stalagmites.

area is shown in Fig. 1. The flowstone is indicative of very heavy, monsoon-type rainfall during the period from 125 ± 3 to 120 ± 2 ka. At *c*. 120 ka there was a change in both the style and isotopic composition of speleothems being deposited in Hoti Cave: flowstone deposition ceased and was followed by deposition of stalagmites with slightly higher $\delta^{18}O$ values. These changes indicate a slight reduction in precipitation. Stalagmite deposition continued for perhaps several thousand years, until *c*. 117 ± 3 ka, when monsoon conditions ended with a transition to a much more arid climate, similar to the present (Fig. 1). None of the samples date from the period between 112.9 ± 2.7 ka and 9.07 ± 0.05 ka, probably indicating continued aridity. Sometime prior to 9.70 ± 0.05 ka a second period of monsoonal rainfall began, though rainfall was not as intense as during the 117–125 ka period. The early Holocene wet period ended at 6.2 ± 0.18 ka. Since that time, the area appears to have remained arid.

The most likely explanation for periods of increased wetness in southern Arabia is a shift in the location of the intertropical convergence to north of present position, allowing the southwest monsoon to bring seasonal rainfall to southern Arabia. Such a shift in the early Holocene is suggested by a number of other marine and continental climate records. Our data show that it also occurred during the previous interglacial. In fact, the U/Th ages of the flowstone and subsequent stalagmite H-4 match very closely the most reliable U/Th ages of peak sea level of the last interglacial, MIS 5e.

Holocene high resolution climate variation

While the $\delta^{18}O$ values of the early Holocene stalagmite H5 fall within a fairly narrow range over the period from 9.7 to 6.2 ka, there is considerable smaller scale variation within these limits, reflecting smaller scale variation in the intensity of the monsoon. Given the excellent age control provided by U/Th measurements, we sought to determine how monsoon intensity might vary on centurial and decadal time scales. To do this, we made 840 stable isotope analyses of the core, giving an average resolution of 4.2 years. Spectral analyses of the resulting $\delta^{18}O$ and $\delta^{13}C$ records were made using a Lomb-Scargle Fourier transform for unevenly spaced time series. The $\delta^{18}O$ results show statistically significant periodicities centred on 585, 248, 130 and 34 years, and the $\delta^{13}C$ record at values centred on 570, 207, 119, 87 51 and 34 years. Comparing these periodicities to those found in other high resolution records shows a number of similarities. The $\Delta^{14}C$ record has periods at 512, 206, 148, 87, and 46–49 years (Stuiver *et al.*, 1993). The 585 and 570 year $\delta^{18}O$ and $\delta^{13}C$, respectively, cycles in the isotopic records of H5 are both well within the error (a 6dB bandwidth of 0.00086 in frequency) of the ^{14}C cycle centred on 512 years. In fact, spectral analyses of the $\Delta^{14}C$ and H5 $\delta^{13}C$ records show a remarkable similarity, with the observed cycles in the H5 $\delta^{13}C$ record at 207, 119, 87 and 51 years all being within the error of cycles at 208, 126 (just outside of the 2 significance level), 87 and 49 in the $\Delta^{14}C$ record. The 248 year cycle seen in the H5 ^{18}O record is statistically distinct from the 208 year ^{14}C cycle. The 130 year cycle in $\delta^{18}O$ is close to the 126 year period the $\Delta^{14}C$ record. The Holocene GISP2 $\delta^{18}O$ record also has some cycles in common with the H5 records. The former includes periodicities at 550, 264, 242, 211, and 120 years.

References

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