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Supporting Information

Appendix S1

Isotopic record from speleothem MOD-21

• Sample description

Analysis of visible changes in the carbonate petrography of MOD-21 indicates that there were at least three stages of deposition. All distances discussed here are measured from the actively growing tip of the speleothem. Changes in the colour and hardness of the calcite coincide with probable hiatuses. The ‘early stage’ (142.5 to 235 mm) with very hard and clean calcite without visible laminae, the ‘middle stage’ between 7.5 and 142.5 mm with less compact calcite and darker in colour, and the ‘late stage’ (0 to 7.5 mm) that comprises very clean, compact and translucent calcite.

• Methods

A 0.1 mm diameter dental drill bit was used to obtain ~3 mg of carbonate powder from stalagmite MOD-21 at 2.5 mm intervals along their growth axis, producing 97 samples from MOD-21. The time interval between successive drill holes represents approximately 203 years on average in MOD-21. However the latter varies dramatically due to various growth rates of MOD-21 between the three depositional stages.

• Results

Age model for MOD-21

Stalagmite MOD-21 by contrast to stalagmite MOD-22, does not exhibit a linear growth rate (Figure S1a). Its uncorrected $^{14}$C dates (uncal BP) are not in linear alignment, suggesting depositional hiatuses (Figure S1a). It is not possible therefore to calculate a DE value for this stalagmite using on the method applied to MOD-22. The DE value of $9 \pm 3.5\%$ is simply an average value obtained from the DE value for MOD-22 (12.5 %) and previously calculated DE value for another modern stalactite (MOD-27) from Modrič.
cave (Rudzka and McDermott, unpublished), but is highly uncertain. Probability density functions of calibrated dates from stalagmite MOD-21 based on this DE value are shown in Figure S1b and Table S1. Irrespective of the choice of DE value, stalagmite MOD-21 indicates very fast growth rates during the interval between 82.5 and 12.5 mm from the top. A similarly, fast growth rate interval also exists in stalagmite MOD-22 and was recognized as the LIA. If the fast growth phase in MOD-21 (82.5 and 12.5 mm from the top) corresponds to the LIA its $^{14}$C data need to be corrected using a high DE value of 20%. Due to uncertainties in DE values, $^{14}$C dates presented in Table S1 need to be used cautiously.

U-series and corrected/calibrated radiocarbon measurements from MOD-21 indicate that its deposition started in the late Pleistocene (Marine Isotope Stage -MIS 3). $^{14}$C measurements for the ‘early stage’ of deposition (235 to 142.5 mm from the top) indicate ages > 48,000 b.p. (MOD-21 RC1 - uncorrected) to 44,021 ± 2,760 BC (45,971 ± 2,760 cal BP) (MOD-21 RC2, Figure S1b; Table S1). The > 48,000 b.p. age estimate (beyond the range of radiocarbon dating) is broadly consistent with a single U/Th date (MOD-21 U1) for the same growth layer as sample MOD-21 RC1 that yields a detrital corrected age of 54,593 ± 1,600 BP (Tables 1). The growth phase in MIS 3 was followed by a long depositional hiatus until the late Holocene (Figure S2b). The ‘middle stage’ is constrained by two $^{14}$C dates: at a distance of 82.5 and 12.5 mm from the top, showing corrected, calibrated radiocarbon ages of 505 ± 709 AD (1445 ± 709 cal BP) (MOD-21 RC4) and 575 ± 685 AD (1376 ± 685 cal BP) (MOD-21 RC3) respectively (Table S1). These $^{14}$C age estimates are within error of each other indicating very rapid growth during this period of the late Holocene (Figure S2b). Large age uncertainties in this stalagmite reflect the large uncertainties in the DE (c. 3.5%).

Thus, MOD-21 grew erratically, displaying quite slow growth (7.36 µm/yr on average) in the ‘early stage’ of deposition, increasing to 977 µm/yr during the ‘middle stage’. For the ‘late stage’ of deposition, a growth rate of 7 µm/yr was calculated using the MOD-21 RC3 date and the year of collection (year 2008 AD). This growth-rate calculation reflects a minimum rate due a depositional hiatus near the top of the stalagmite which places these last two data points in different depositional intervals. The rather erratic growth
behaviour of stalagmite MOD-21 and its very rapid growth during the so-called ‘Dark Ages cold period’ may reflect the absence of a large storage component in its drip-water feeder system. This is also evident in the modern drip-water data for this site. Its ‘flashy’ behaviour and the apparent absence of a strong ‘base-flow’ component (Figure 3), contrasts with that of the MOD-22 drip-site.

*Stable isotope record from MOD-21*

‘Hendy tests’ on stalagmite MOD-21 (Figure S2a) show no correlation between the $\delta^{18}$O and $\delta^{13}$C along the examined laminae, indicating no evidence for strong disequilibrium (kinetic) isotope fractionation effects (not shown).

The stable isotope record from stalagmite MOD-21 is quite variable (Figure S2b) probably reflecting its erratic growth rate. In the oldest part of stalagmite MOD-21 (between 54, 593 ± 1,600 BP and 41,547 ± 2,180 BC (43,650 ± 2,180 BP), between 235 and 142.5 mm from the top, $\delta^{13}$C indicates strong variations of c. 8‰, with the mean value of -7.98‰ VPDB ($2\sigma = 2.67$). $\delta^{18}$O varies by 4‰ with the mean value of -5.43‰ VPDB ($2\sigma = 1.53$). The last data point, at a distance of 142.5 mm from the top, exhibits higher $\delta^{13}$C (-2.43‰) which most probably reflects gradual drying before the onset of a depositional hiatus.

In the interval from 142.5 to 7.5 mm (fast growth rate ‘middle stage’), $\delta^{13}$C varies by about 4‰, with a mean value of -6.62‰ VPBD ($2\sigma = 2.51$). Here, the $\delta^{18}$O values are less variable than $\delta^{13}$C, with an amplitude of c. 2 ‰, and a mean of -4.20‰ VPBD ($2\sigma = 0.72$). As before, the last data point shows a high $\delta^{13}$C value (-3.75‰) which again probably indicates a gradual drying phase prior to the depositional hiatus. In the last, most probably modern stage of deposition (‘late stage’ in the interval from 0 to 7.5 mm from the top), the average $\delta^{13}$C value is -6.53‰ VPBD ($2\sigma = 1.76$) and average $\delta^{18}$O value is -4.97‰ VPBD ($2\sigma = 0.28$).
Interpretation

MOD-21 by contrast, grew very rapidly during ‘middle stage period’ and it is inferred that this period was wet enough to sustain speleothem growth at this drip site that appears to have a low water storage component (Figure 3).

Using the rationale of Railsback et al. (2011), wetter periods are inferred when a growth layer (or layers) flow down and drape over a previously deposited layer on the flanks of the stalagmite, whilst drying trends are inferred when layers are narrower and are perched upon previously deposited layers. Based on these assumptions, we infer several intervals of different climatic regimes in MOD-21 (drying trends – red arrows in Figure S2b).

Wetter and drier phases in MOD-21, recognized by the inferred changes in the diameter of the stalagmite are usually associated with changes in \( \delta^{13}C \). High \( \delta^{13}C \) values are associated with the inferred drier periods (e.g. above 142.5 mm and at 60 mm from the top, Figure S2b). The lower parts of MOD-21, defined by two dates indicating a growth phase during Marine Isotope Stage 3 indicate relatively wet climatic conditions on the basis of the stalagmite’s petrography. However, increasing \( \delta^{13}C \) values suggest a slight drying out trend which is not confirmed in the stalagmite’s petrography (subsequent layers overlapping the previously deposited). After the hiatus (at the distance 145 mm), there is a dry phase, marked by higher \( \delta^{13}C \) and a petrographic change, which falls in the time frame of Roman Warm Period or Medieval Warm Period if DE value of 9% and 20% are used respectively to correct \( ^{14}C \) data.

This period is followed by a notably wetter phase (at a distance of 105 mm), where the younger layers overlap and drape over the older layers on the flanks of stalagmite MOD-21. Also, \( \delta^{13}C \) values decrease gradually during that interval, suggesting an increase of vegetation intensity above the cave as a result of wetter conditions. These wetter conditions are in good agreement with the timing of the cold/wet Dark Ages period or LIA if 9% and 20% of DE values are used respectively to correct \( ^{14}C \) data. The \( \delta^{13}C \) data are interpreted to reflect two drying-out trends, with peaks in \( \delta^{13}C \) in the middle of that cold period (at a distance c. 60 mm) and another at the end of this period (at a distance c. 7.5 mm). However, overall conditions during this period appear to have been relatively
wet, with a large number of layers overlapping previously deposited lamina (above a
distance of 60 mm, Figure S2b). $\delta^{18}O$ is also relatively low in MOD-21 at this time,
consistent with the inferred wetter conditions and the weak ‘amount effect’ seen in the
present-day rainfall $\delta^{18}O$ data (Figure S2b). Also high porosity in the calcite, as well as
two almost identical radiocarbon dates obtained for this interval indicates a very rapid
growth, which also points to wetter conditions, especially as this drip site has minimal
water storage capacity (Figure 3). The top part of stalagmite MOD-21 (0 – 7.5 mm
distance) exhibits a very wide diameter (the top layer covers and overlaps the previous
growth layers) and lower $\delta^{13}C$ values, as well as similar petrography to the bottom part of
the sample (from 165 mm to the base of the stalagmite), which reflects wetter conditions
(Figure S2b). Because of insufficient data, the age of this growth interval could not be
constrained, but it must be relatively young as the sample was actively growing when
collected.

- Figure and table captions

Figure S1. A) and B) show uncalibrated and uncorrected to the DE value age model for
MOD-21 with different scales applied to plotted data points. Grey bands represent
depositional hiatuses in MOD-21; C) Probability density functions for 14C date
calibrations from stalagmite MOD-21 after correction to the DE (9 ± 3.5%) value. Red
dashed lines indicate calibrated ages based on the range of 14C dates that displayed the
highest probability. Distance from the top of the stalagmite (0 mm) is shown on the right
hand-side Y axis. High age uncertainties in this stalagmite reflect large uncertainties in
the DE (c. 3.5%).

Figure S2. A) Hendy test for stalagmite MOD-21. Each sample set was drilled from the
single growth layer (distances are measured from the top: A-10 mm and B-127mm).
Distance was measured from the stalagmite central axis (schematic diagram inserted). B)
Interpretation of stable isotope records from stalagmite MOD-21. Dashed lines on stalagmite scan highlight the growth layers (also shown on the schematic diagrams next the stalagmites picture). Horizontal dashed lines highlight the intervals of different climatic conditions based on the stalagmite petrography and growth layer pattern after Railsback et al. (2011). Red arrows indicate interpreted drying-out trends recorded by $\delta^{13}$C in the stalagmite. Marine Isotope stage 3 was bracketed by the speleothem $^{14}$C ages and U/Th date, and is displayed as grey band. Fast growth interval at the distance between 82.5 and 12.5 mm from the top is also highlighted.

**Table S1.** Results from $^{14}$C measurements on MOD-21. Measured $^{14}$C activity ($a^{14}$Cm) was corrected to dilution effect (DE%). The raw $^{14}$C age was calibrated to years BP (1950) and AD/BC using OxCal (Bronk Ramsey, 2009) and calibration curves from Reimer et al. (2009). The highest probability age range is shown in bold.