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Mass spectrometric dating of flowstones from Stump Cross Caverns and Lancaster Hole, Yorkshire: palaeoclimate implications

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ABSTRACT: A terrestrial flowstone sequence 97 cm thick from Stump Cross Caverns, Yorkshire, has been dated by both mass spectrometric and alpha spectrometric ^{238}U–^{234}U–^{230}Th dating, and is demonstrated to have been deposited predominantly during interstadial periods over the last 170 ka, with no growth in periods of glaciation or within the Oxygen Isotope Stage 5 interglacial. Growth also occurs within Oxygen Isotope Stages 4 and 6, the former possibly correlating with interstadials recognised in high-resolution ice and ocean-core records. Comparison with the timing of growth of a mass spectrometrically dated Lancaster Hole flowstone, also from the same region, demonstrates only limited agreement. These differences are due to two factors limiting deposition at Stump Cross: flooding of the cave passage in warm periods, and the development of continuous permafrost or glacier cover in periods of severe climatic deterioration. Deposition at Lancaster Hole was controlled by limitations in ground-water supply rather than flooding of the cave passage. The results presented here demonstrate that in addition to regional palaeoclimate factors, local site conditions may limit speleothem growth. We conclude that in future palaeoclimate studies, the growth record from several coeval speleothem samples must be considered before a regional palaeoclimate interpretation can be made.

KEYWORDS: speleothems; mass spectrometric uranium-series dating; Stump Cross Caverns; flowstone growth phases; palaeoclimate.

Introduction

Speleothems, which consist of stalagmites, stalactites and flowstones, are secondary carbonate deposits that form in cave systems. A correlation between the timing of speleothem growth and interglacial and interstadial periods has been demonstrated from regional compilations of alpha-spectrometric dates (Gordon *et al.*, 1989; Baker *et al.*, 1993a). Spectral analysis of these chronologies has revealed a correlation between speleothem growth frequency and the 20 000 and 40 000 yr Milankovitch insolation frequencies, as predicted by Berger and Loutre (1991) (Kashiwaya *et al.*, 1991). Such associations of speleothem growth and palaeoclimate rely on two critical requirements for active speleothem deposition. Firstly there must be development of an elevated soil atmosphere CO_2 in excess of atmospheric CO_2 equilibrium values in order to provide a geochemical drive for limestone dissolution. Such conditions pertain when there is active vegetation growth and temperatures are sufficient to provide a prolonged growing season and high rates of bacterial decomposition of soil organic matter and root respiration. Secondly there must be a significant ground-water recharge, conditions being neither too arid in periods of warm climate to create a soil moisture deficit, nor sufficiently cold in times of climatic deterioration to allow the development of continuous permafrost or glacial conditions. The latter are generally recognised as inhibiting all speleothem growth, whereas the water budget and geochemical controls may determine both the rate of speleothem growth and speleothem abundance.

Recent developments in thermal ionisation mass-spectrometric ^{238}U–^{234}U–^{230}Th (TIMS ^{230}Th) dating have allowed the more precise determination of the timing of speleothem growth. The technique, which was developed first for coral samples (Edwards *et al.*, 1987), has been applied more recently to other deposits, such as vein calcite (Winograd *et al.*, 1992) and speleothems (Li *et al.*, 1989; Dorale *et al.*, 1992, Baker *et al.*, 1993b, 1995; Richards *et al.*, 1994). Previous studies have demonstrated that 2σ errors of under 1% can be obtained from samples of 0.5–2.5 g only. Such small samples can be cut to a thickness of approximately 1–2 mm using diamond bladed cutting equipment, decreasing the time-averaging effect. For instance, a sample 1 mm thick would span a time range only ±100 yr if the sample grew at 0.01 mm yr^{-1}, which is typically smaller than any error from the counting statistics.

Initial TIMS ^{230}Th dating results on the timing of speleothem growth have been encouraging. We have previously reported results on a flowstone from Lancaster Hole, Yorkshire, England (Fig. 1), which grew for periods of only 1–3 ka duration over the last 140 ka (Baker *et al.*, 1995). Six growth phases were dated to128.8 ± 2.7, 103.1 ± 1.8, 84.7 ± 1.2, 57.9 ± 1.5, 49.6 ± 1.3 and 36.9 ± 0.8 ka. A remarkable correlation was observed between these periods of active speleothem growth and the timing of solar insolation maxima, derived from orbital parameters. The active growth was considered to be due to changes in either precipitation intensity or volume, which caused switching in the routing of water flow in the unsaturated zone above the cave. However, it was not known whether this growth pattern could be observed in other speleothem samples, or

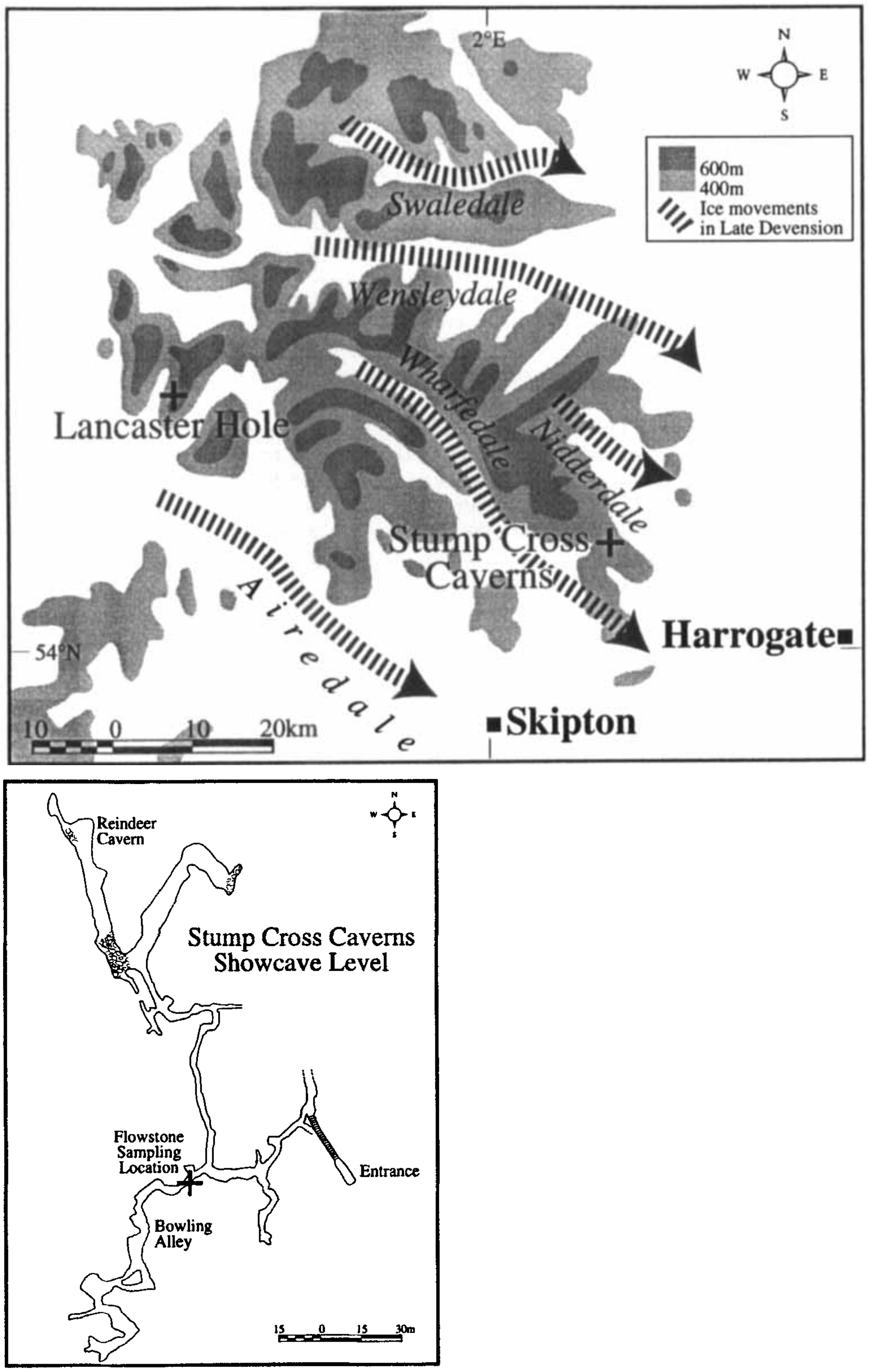

Figure 1 Location of Stump Cross Caverns and Lancaster Hole, Yorkshire. The direction of ice movement in the Late Devensian glaciation is taken from Catt (1991). (Inset) Survey of the Showcave Level of Stump Cross Cavern, showing the sampling location.

whether it was a local or regional phenomenon. In order to assess this, the timing of speleothem growth is examined here using a second coeval sample, a long flowstone sequence collected from Stump Cross Caverns in Yorkshire, England. This had been dated previously by alpha-spectrometry (Sutcliffe *et al.*, 1985), and was known to be deposited over the same time period as the sample from Lancaster Hole. Furthermore, Stump Cross Caverns is in the same region (less than 50 km from Lancaster Hole) and is at a similar elevation, and would therefore have experienced similar trends in regional palaeoclimate.

Stump Cross site and sample description

Stump Cross Caverns are situated in the Yorkshire Dales on Greenhow Hill, between Wharfedale and Nidderdale, at an altitute of 361 m a.s.l. (UK National Grid Reference SE 089634). The cave is located 45 km west-southwest of Lancaster Hole, and at an altitude 67 m higher (Fig. 1). Flowstone sample SC-90-5/6 was collected from the entrance to Bowling Alley passage, one of two main fossil streamways in the high-level series of the cave at a depth of 16 m below the surface (Fig. 1; see inset). The lowest point on the Bowling Alley is 13 m from the sample location, where a narrow fissure carried water down to the middle levels of the cave; the passage descends gently to this point from either end. The flowstone sampling site is stratigraphically consistent with sample sites IIIA/B of Sutcliffe *et al.* (1985), where equivalent flowstone samples were dated alpha-spectrometrically in order to determine the age of a *Gulo gulo* (wolverine) deposit found at several locations within the Bowling Alley (sites IIIA/B/C in Sutcliffe *et al.*, 1985).

Sample SC-90-5/6 consists of a flowstone 97 cm thick, the base of which sites upon finely laminated muds containing flowstone fragments. The flowstone contains many sediment bands (Fig. 2), which were thought to signify palaeoclimate events. The sediment band below section SC-90-6A contains much detrital material, stalactites, stalagmite fragments and limestone clasts. Broken straw stalactites are also visible in the sediments between sections 6F and 6G, 6J and 6K, and 6K and 6L. Samples SC-90-5 (growth sections A to D) and SC-90-6 (sections A to D) comprise pure white, massive, coarsely crystalline columnar calcite. In sections E to K in SC-90-6 there is a gradation to more detritally contaminated, cream or light brown colour calcite; and the crystal structure becomes less massive and appears more porous. The sequence is capped by section L, which is only 3 mm thick, and consists of pure, white, dense, columnar calcite that appears to be actively forming under present-day conditions.

Samples were taken initially for alpha-spectrometric uranium-series dating (ASU dating) from growth sections SC-90-5A/6B/6F/6G/6H/6J/6K; typically they consisted of bulk samples of 50–100 g of the purest calcite available, taken from between the sediment bands. The samples were dissolved and analysed using standard alpha-spectrometric procedures. The ASU dates were obtained either to provide an initial age estimate (samples analysed by Angus Tillotson, University of Bristol), or to provide ages for bands with a high detrital content, which would have exceeded the $^{232}Th^{+}$ ion-counting capability on the mass spectrometer. Subsequently, samples for TIMS ^{230}Th analysis were also cut, comprising 1–2 g of calcite from layers 2–3 mm thick at a distance of 1–2 mm from the sediment bands. Analyses were run using standard methods as described in Edwards *et al.* (1987).

Results

The ASU and TIMS ^{230}Th analyses obtained on the sequence are presented in Tables 1 and 2 respectively. Where sections of the sequence have been dated by both ASU and TIMS ^{230}Th techniques (SC-90-5A and SC-90-6B), agreement is good within 2σ errors. Additionally, both the TIMS ^{230}Th and ASU analyses show good stratigraphic consistency, with the age of samples decreasing systematically from top to base of the sample, confirming that this flowstone sample is a closed system suitable for uranium-series dating.

In several locations, multiple age analyses overlap at 2σ errors, representing rapid growth both within individual sections (e.g. 6E) and across sediment bands (e.g. sections 5A–D) (Table 2 and Fig. 2). Where age analyses on different growth sections are indistinguishable within 2σ errors, they are assumed to define periods of continuous growth. Thus the timing of growth can be considered to fall within eight periods. These are growth phase S at 168.4 ± 3.4 ka (flowstone sections 5A–5D; five analyses), phase T at 78.0 ± 2.9 ka (flowstone sections 6A–B; three analyses), phase U at 71.6 ± 1.9 ka (flowstone section 6C), phase V at 59.7 ± 2.8 ka (flowstone section 6D), phase W at 53.4 ± 2.4 ka (flowstone section 6E; four analyses), phase X at 35.1 ± 9.9 ka (flowstone section 6F) and phase Y at 9.9 ± 3.7 ka (flowstone sections 6G-K; four analyses). The errors on the timing of the growth phases are the mean of the 2σ age determinations or twice the standard error, whichever is greater. An additional growth phase Z is associated with the actively forming speleothem growth present at the top of the sequence (flowstone section 6L). This 3 mm of growth represents speleothem deposition possible since the nineteenth century, when the ground-water level in the aquifer was lowered by mining activity, allowing the cave to become exposed (Dickinson, 1972).

The timing of speleothem growth demonstrates that the sediment bands represent events of variable duration. For example, sediment bands within growth phase S (flowstone sections 5A to 5D) exhibit ages that overlap at 2σ errors and do not therefore appear to mark events of significant temporal duration. However, sediment bands that are identical in appearance between growth phases T and U and W and X represent periods of significant cessation of speleothem growth of 6.4 ± 4.8 and 18.3 ± 7.5 ka respectively. Significant time gaps are also associated with two bands that contain allogenic debris (such as stalactite fragments) between growth phases S and T and X and Y, but two comparable bands within phase Y do not represent significant hiatuses. There is therefore no clear association with either the presence or type of sediment band and duration of depositional hiatus.

The alpha-spectrometric and TIMS ^{230}Th dates presented here are in agreement within 2σ errors with those obtained by Sutcliffe *et al.* (1985), although the earlier workers reported one additional phase of growth that was not recorded in sample SC-90-5/6. They analysed a stalagmite, sample SC193 in Sutcliffe *et al.* (1985), that was present within the flowstone and dated at 116 ± 9 ka (1σ errors). Three other samples were also dated to this time by Sutcliffe *et al.* (1985) from the far side of the fissure in the Bowling Alley, and two of these samples were *in situ*. This suggests

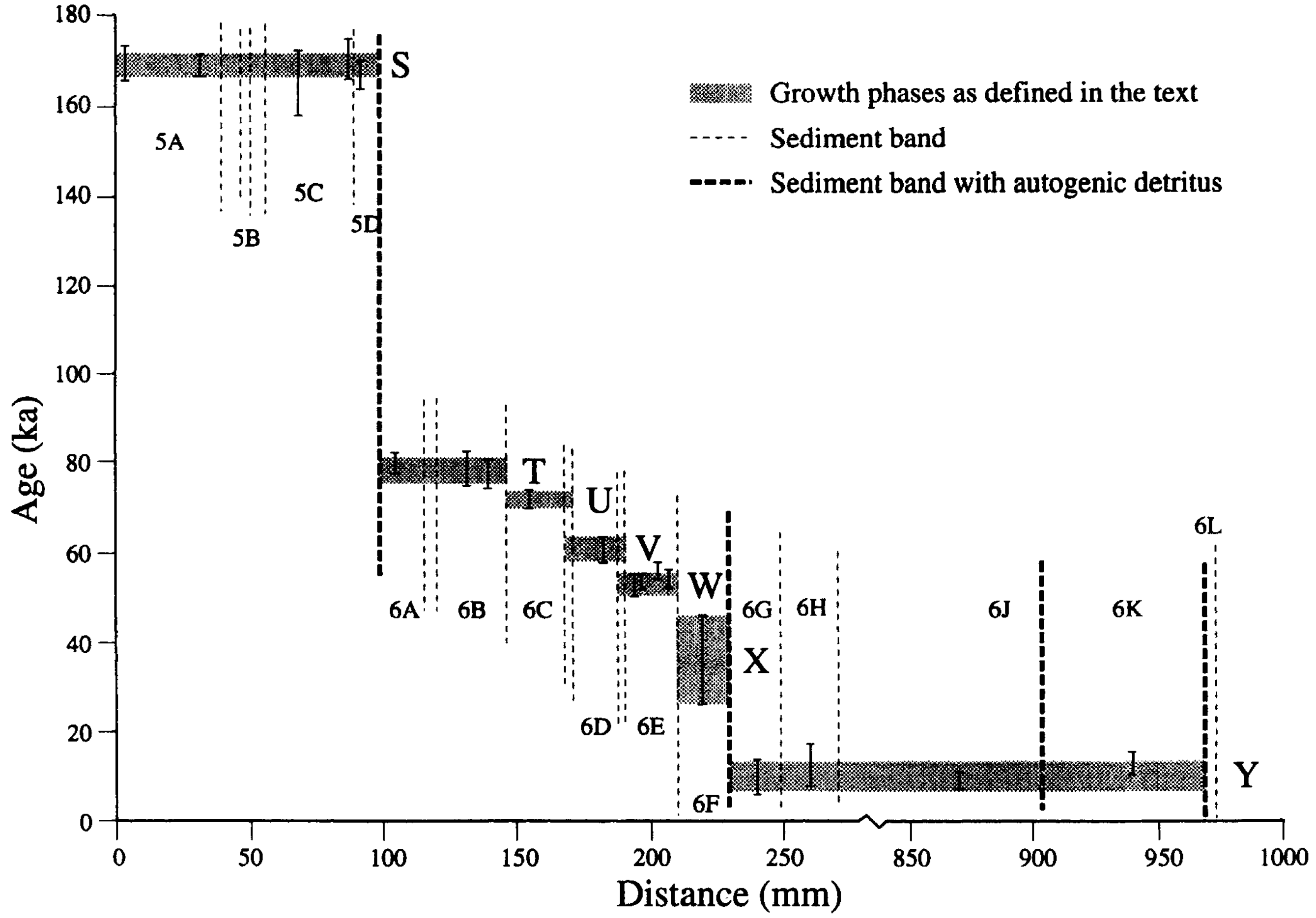

Figure 2 Graph of flowstone age versus distance through the sequence. Error bars represent 2σ counting errors of the age determinations. X-axis errors (from the sample thickness) are not shown because they are less than ± 1.5 mm. The location of sediment bands are also shown, together with the growth sections, which are labelled from 5A to 6L. The growth phases, calculated where the age determinations on different growth sections are indistinguishable with 2σ error as defined in the text, are shown by the shading and labelled from S to Y.

Table 1 Alpha-spectrometric age determinations for the Stump Cross flowstone

Sample[a]	Distance[b] (mm)	Uranium Concentration (ppm)	^{230}Th/^{234}U [activity]	^{234}U/^{238}U [activity]	^{230}Th/^{232}Th [activity]	Age (ka)	Corrected Age[c] (ka)
SC-90-5A	15	1.03 ± 0.01	0.792 ± 0.021	1.517 ± 0.0053	203 ± 28	148 ± 23	—
SC-90-6B	135	0.070 ± 0.001	0.571 ± 0.014	1.311 ± 0.026	63 ± 8	88.0 ± 9.1	—
SC-90-6F	220	0.166 ± 0.001	0.381 ± 0.011	1.146 ± 0.014	2.8 ± 0.1	51.4 ± 4.6	35.1 ± 9.9
SC-90-6G	240	0.140 ± 0.002	0.106 ± 0.009	1.227 ± 0.018	8.3 ± 1.7	12.1 ± 2.6	8.9 ± 3.5
SC-90-6H	260	0.085 ± 0.001	0.120 ± 0.013	1.195 ± 0.020	10.5 ± 4.4	13.8 ± 3.6	11.7 ± 4.7
SC-90-6J	870	0.071 ± 0.002	0.085 ± 0.003	1.113 ± 0.021	4.3 ± 0.2	9.6 ± 0.8	7.8 ± 1.6
SC-90-6K	940	0.052 ± 0.001	0.113 ± 0.004	1.113 ± 0.017	6.3 ± 0.5	13.0 ± 1.1	11.3 ± 2.8

[a] Sample location and distance are shown in Fig. 2, except for samples 5A and 6B which have large errors and are omitted for clarity. Samples 5A and 6B were analysed by Angus Tillotson.

[b] Mean distance is quoted; actual sample size is ± 10 mm owing to the large sample sizes associated with ASU determinations.

[c] Corrected ages assume an initial ^{230}Th/^{232}Th atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$ (method 1, equation 8 from Schwarcz (1980)). This is the value for a material at secular equilibrium, with a crustal ^{232}Th/^{238}U of 3.8. The error is arbitrarily assumed to be 50%; errors also include those from counting statistics.

that growth was occurring in the cave at this time, but that local factors caused non-deposition at our sample site. The Sutcfliffe *et al.* (1985) stalagmite may therefore possibly be detrital, as is the broken speleothem material observable between growth phases S and T and deposited between 168.4 ± 3.4 ka and 79.2 ± 2.4 ka.

Interpretation of the timing of growth phases

Figure 3 presents the timing of the Stump Cross flowstone in comparison with other palaeoclimate records: the speleo-

Table 2 Uranium/thorium isotopic data and mass spectrometric ages for the Stump Cross flowstone

Name[a]	Distance[a] (mm)	^{238}U (ng g^{-1})	^{234}U/^{238}U (x10^{6})	^{230}Th/^{232}Th (x10^{6})	^{230}Th/^{232}Th (activity)	δ^{234}U[b,e] ‰	^{230}Th/^{238}U[c,e] (activity)	Age[d,e] (ka)
SC-90-5A(B)	3.0	1067 ± 1	83.5 ± 0.1	7830 ± 140	1455 ± 25	525.4 ± 2.0	1.2895 ± 0.0137	169.2 ± 3.9
SC-90-5A(T)	32.0	929 ± 3	82.5 ± 0.2	12580 ± 110	2338 ± 21	506.9 ± 4.0	1.2699 ± 0.0076	168.6 ± 2.4
SC-90-5C(B)	69.0	727 ± 5	82.6 ± 0.8	8140 ± 660	1512 ± 123	509.5 ± 4.0	1.2593 ± 0.0214	165.0 ± 7.0
SC-90-5C(T)	88.0	830 ± 2	80.6 ± 0.2	1930 ± 30	359 ± 5	472.5 ± 3.8	1.2416 ± 0.0133	169.9 ± 4.0
SC-90-5D	92.0	1038 ± 3	79.5 ± 0.3	190 ± 2	35 ± 0.3	452.4 ± 5.0	1.2102 ± 0.0097	166.3 ± 3.1
SC-90-6A	105.0	161 ± 1	66.6 ± 0.5	370 ± 8	69 ± 1.4	216.4 ± 9.7	0.6412 ± 0.0124	79.2 ± 2.4
SC-90-6B(B)	132.0	69 ± 1	64.6 ± 1.7	291 ± 5	54 ± 0.9	180.6 ± 30.2	0.6148 ± 0.0111	78.2 ± 3.7
SC-90-6(M)	140.0	94 ± 1	63.0 ± 1.1	24950 ± 5110	4640 ± 950	151.7 ± 20.0	0.5905 ± 0.0090	76.7 ± 2.6
SC-90-6C	155.0	60 ± 1	62.0 ± 0.5	63 ± 1	11.8 ± 0.2	133.6 ± 8.6	0.5792 ± 0.0072	71.6 ± 1.9
SC-90-6D(T)	183.0	160 ± 2	62.0 ± 1.6	340 ± 7	63 ± 1.0	133.5 ± 29.5	0.4836 ± 0.0104	59.7 ± 2.8
SC-90-6E(B)	195.0	142 ± 2	65.7 ± 1.6	4250 ± 180	790 ± 33	200.9 ± 28.9	0.4646 ± 0.0085	52.4 ± 2.1
SC-90-6E(M)	197.0	122 ± 1	65.7 ± 0.5	2690 ± 200	500 ± 37	201.3 ± 9.0	0.4668 ± 0.0093	52.7 ± 1.4
SC-90-6E(T2)	203.5	88 ± 1	64.4 ± 1.3	2360 ± 120	439 ± 22	176.2 ± 23.1	0.4728 ± 0.0105	55.1 ± 2.2
SC-90-6E(T1)	207.5	72 ± 1	64.3 ± 0.4	210 ± 6	40 ± 1.0	174.6 ± 6.3	0.4605 ± 0.1220	53.4 ± 1.8

[a] (B), (M) and (T) signify basal, middle and top samples within each growth section. Distances are the mean value; actual sample distance is ± 1.5 mm owing to the size of sample cut. Sample location and distance shown in Fig. 2.

[b] $\delta^{234}U = \{[(^{234}U/^{238}U)/(^{234}U/^{238}U)eq] - 1\} \times 10^{3}$, where $(^{234}U/^{238}U)eq$ is the atomic ratio at secular equilibrium and is equal to 5.472×10^{-5}.

[c] Calculated from the atomic ^{230}Th/^{238}U ratio by multiplying by $\lambda_{230/238}$.

[d] Ages are calculated using $[^{230}Th/^{238}U]act - 1 = e^{-\lambda_{230}T} + (\delta^{234}U(0)/1000)(\lambda_{230}/\lambda_{230} - \lambda_{234})(1 - e^{-(\lambda 230 - \lambda 234)T})$, where T is the age in years. Where there is a high concentration of detrital ^{232}Th, then corrected ages are calculated. These assume an initial ^{230}Th/^{232}Th atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$ (method 1, equation 8 from Schwarcz (1980)). This is the value for a material at secular equilibrium, with a crustal ^{232}Th/^{238}U value of 3.8. The error is arbitrarily assumed to be ±50%. Only SC-90-6C required a detrital age correction, the quoted error includes that from the counting statistics.

[e] Values for decay constants are $\lambda_{238} = 1.551 \times 10^{-10}$ yr^{-1} (Jaffey *et al.*, 1971). $\lambda_{234} = 2.835 \times 10^{-6}$ yr^{-1} (de Bievre *et al.*, 1971; Lounsbury and Durham, 1971), and $\lambda_{230} = 9.195 \times 10^{-6}$ yr^{-1} (Meadows *et al.*, 1980)

them cumulative-growth-frequency record (Baker *et al.*, 1993a); insolation for July, 60°N (Berger and Loutre, 1991); the Greenland ice-core record for the period up to 110 ka (the time for which both the GRIP and GISP2 records are in agreement (Grootes *et al.*, 1993)); and the timing of the Lancaster Hole flowstone growth phases, labelled A to F (Baker *et al.*, 1995).

The active growth recorded at Stump Cross in Oxygen Isotope Stage 3 (V, W and X) agrees well with that observed in the Lancaster Hole record (D, E and F) within 2σ errors, and with the northwest European alpha-spectrometric uranium-series speleothem and travertine compilation. We interpret these concordant growth phases as indicative of general palaeoclimate conditions conducive to speleothem growth. They therefore represent interstadial events with significant ground-water recharge and temperatures sufficiently high to promote generation of biogenic CO$_2$. There is an absence of flowstone deposition at both Stump Cross and Lancaster Hole during Oxygen Isotope Stages 2 and 6. This can be associated with known periods of glacier cover in the UK. The stage 6 glaciation is considered to have had a greater spatial extent than that of stage 2, with deposits ascribed to this advance as far south as Norfolk and the Isles of Scilly (Rice and Douglas, 1991). The Stump Cross site would in all probability be glacierised during this glacial advance. During the stage 2 (Late Devensian) glaciation in Yorkshire ice streams flowed down Nidderdale and Wharfedale into the Vale of York, but were more limited in Airedale, the next valley to the south of Stump Cross Caverns (Catt, 1991); see Fig. 1, but it is not known whether ice covered the interfluves between the valleys. In these areas drift deposits underlie the blanket peat, but could be formed by periglacial processes or derive from a pre-Devensian ice sheet. In contrast significant quantities of Devensian till and moraines can be found in the valley floors. Thus it is not known if ice covered the surface at Stump Cross at this time, although glaciers were present in the main valleys.

Of particular note is the absence of growth at Stump Cross during Oxygen Isotope Stage 5, when Lancaster Hole showed three periods of active deposition (growth phases A to C). Active deposition generally is observed in speleothems from northwest Europe (see the cumulative-growth-frequency record; Fig. 3), and indeed stage 5 growth has been reported elsewhere at Stump Cross, as discussed above. In addition, faunal evidence from Victoria Cave in Yorkshire, only 25 km from Stump Cross, including the presence of a 'hippopotamus fauna' that is constrained by associated speleothem dates between 135 ± 8.5 and 114 ± 5 ka (1σ errors; Gascoyne *et al.*, 1981), suggests that warm temperatures and consequently high soil CO$_2$ production would occur at Stump Cross at this time. Clearly the sample site must be affected by local conditions. The stage 5 hiatus between growth phases S and T (between 168.4 ± 3.4 and 79.2 ± 2.4 ka at Stump Cross is in fact marked by detrital material comprising of limestone clasts, broken fragments of stalagmite and straw stalactites, and dissociated remains of wolverine. This suggests the occurrence of flooding, the size of many of the stalagmites and limestone clasts indicating the presence of a significant stream. Furthermore, the presence of straw stalactites suggests that water reached the roof of the passage (a depth of ca. 3 m). Because there is evidence of stalagmite growth within Oxygen Isotope Stage 5 in other parts of the cave (Sutcliffe *et al.*, 1985), this suggests that flooding was a local effect. Possibly blockage of the narrow fissure within the Bowling Alley leading to the lower levels of the cave could have caused a localised backing-up of

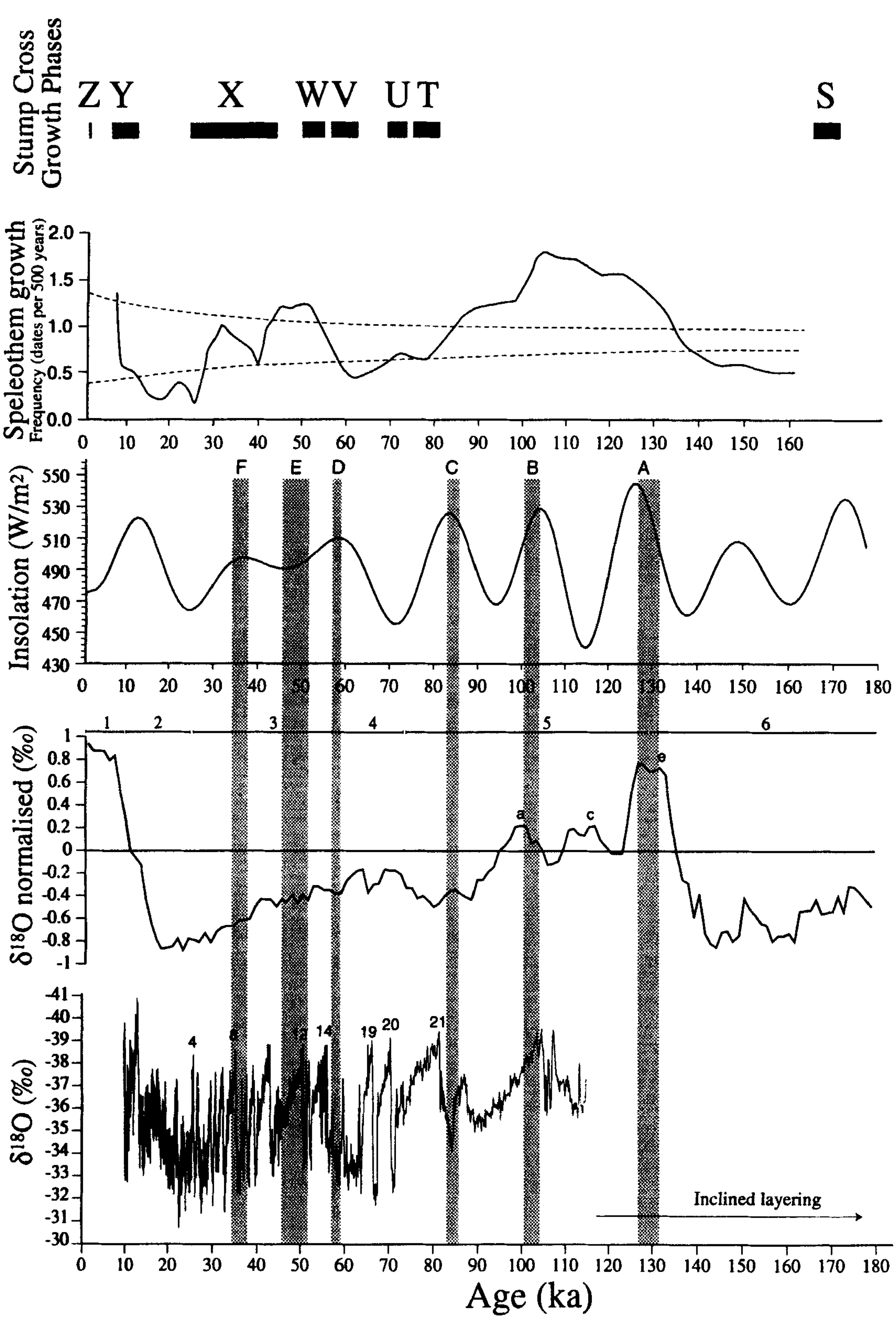

Figure 3 Comparison of palaeoclimate records. From the top: timing of deposition of the Stump Cross flowstone; the speleothem cumulative growth frequency record (Baker *et al.*, 1993a); insolation for 60°N (Berger and Loutre, 1991); the orbitally tuned oxygen isotope record (Martinson *et al.*, 1987); and the Greenland ice-core record (Grootes *et al.*, 1993). Timing of the Lancaster Hole flowstone is represented by vertical shading.

waters in the passage. However, a more systematic effect is suggested by the presence of similar broken stalactite material between phases Y and Z between 9.3 ± 3.4 ka and the present, when surface conditions were again interglacial (there is no record for Lancaster Hole at this time). This suggests that flooding occurred due to an increase in groundwater flow, which could be caused by increased precipitation. In northwest Europe precipitation is known to be higher in interglacial than in glacial periods. For example, annual precipitation at Grande Pile reaches a maximum similar to that of today during both the Ipswichian and early Holocene (Guiot *et al.*, 1989). Although some 900 km south of Yorkshire, similarly high precipitation may be expected in Yorkshire because climate models demonstrate that this is a regional effect, with up to 50% increases in precipitation occurring from glacial to interglacial periods owing to the re-establishment of the jet stream over mid-latitudes (Kutzbach and Wright, 1985).

A final contrast between the growth record of the two samples is the presence of additional growth phases at Stump Cross compared with Lancaster Hole. In some instances these fall outside the timespan of the Lancaster Hole flowstone, and so no comparison can be made. For example, growth phase S (168.5 ± 3.1 ka) pre-dates any deposition at Lancaster Hole, and was deposited before the Oxygen Isotope Stage 6 glacial maxima. Examination of the oxygen isotope record (Martinson *et al.*, 1987) suggests that this growth phase probably correlates with an interstadial period of similar characteristics to that of Oxygen Isotope Stage 3. Growth phase Y (9.9 ± 3.7 ka), by contrast, post-dates deposition at Lancaster Hole, and has poor temporal constraint owing to the lower precision ASU analyses and detrital contamination. Finally, two growth phases, T (78.0 ± 2.9 ka) and U (71.6 ± 1.9 ka), occur during the time of deposition at Lancaster Hole, and yet are not represented in that record. Based on our palaeoclimate interpretation of the stage 3 growth phases at both sites, this suggests the presence of interstadial conditions within Oxygen Isotope Stage 4. They may correlate with those recognised in the GRIP and GISP2 ice-core records (two of interstadials 19–21; Fig. 3), also observed recently in high-resolution ocean core GPC9 (Keigwin *et al.*, 1994); although dating limitations of the latter two records prevent precise correlations. The sensitivity of the Lancaster Hole flowstone to changes in ground-water supply is probably the factor limiting speleothem deposition at that site at this time, suggesting that recharge rates were probably lower during growth phases T and U than during phases A to F.

Conclusions

A particular feature common to both of the flowstones that we have dated to high precision is that growth was relatively rapid but restricted to periods of quite short duration. This pattern shows good agreement with the duration of the interstadial events in the ice-core record, but much less affinity with the more smoothed marine isotope stratigraphies (Fig. 3). We believe this pattern may relate to limitations on available ground-water recharge at other times, rather than to control by soil P_{CO_2}, reflecting the general association between flowstone deposition and high capacity hydrological routes in the unsaturated zone. Unlike the more constricted inlets with lower discharge capacity that feed smaller stalagmites, such high capacity routes are responsible for the majority of ground-water discharge as rates of discharge increase (Smart and Friedrich, 1987). In general, growth phases are more prolonged at Stump Cross, indicating operation of a lower capacity threshold than at Lancaster Hole. This could also explain the presence of growth during Oxygen Isotope Stage 4 interstadials at Stump Cross, which are not recorded at Lancaster Hole.

Such differences in response at the level of individual samples raises questions as to the reliability of any general palaeoclimate interpretation of sample growth history. Indeed it is evident that there are substantial differences between the two records, which we have explained in terms of the operation of site-specific controls, such as interglacial flooding at Stump Cross, that have overridden the regional palaeoclimate signal. Thus for individual samples, determination of a regional palaeoclimate signal is difficult because deposition is strongly dependent on site-specific local thresholds in the hydrological pathways, geochemical controls on the P_{CO_2} of recharge waters (e.g. local soil thickness) and in conditions at the site of deposition. Site-specific effects thus modulate the regional palaeoclimate signal in a complex way, which may be inferred in a general manner only, if at all. We therefore urge caution in the palaeoclimate interpretation of the growth record from any single speleothem.

Conversely, there are many similarities in the growth patterns exhibited by the two flowstones discussed here, and between these and the temporal distribution of speleothem abundance (Fig. 3). The latter shows a generalised but secure relation to regional palaeoclimate because statistically it is determined at the population level, including results from a large number of individual speleothems. At this level, it appears that the many local controlling factors which may operate constitute an essentially random noise through which the palaeoclimate signal can still clearly be perceived.

Further analysis of both flowstones and stalagmites from the Yorkshire area is needed to confirm the patterns of growth reported in this study, and to determine the extent, nature and effect of local and site-specific factors in controlling speleothem deposition.

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