Paleoclimate implications of mass spectrometric dating of a British flowstone

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ABSTRACT

The timing of growth phases in a cave flowstone from Yorkshire, England, has been precisely dated by thermal ionization mass spectrometric ^{238}U-^{234}U-^{230}Th dating. Six growth periods of both short duration and fast growth rate are separated by nondepositional hiatuses. The ages of these phases were determined to be 128.8 ± 2.7, 103.1 ± 1.8, 84.7 ± 1.2, 57.9 ± 1.5, 49.6 ± 1.3, and 36.9 ± 0.8 ka. There is a remarkably good correlation between the periods of active speleothem growth and the timing of solar insolation maxima, derived from orbital parameters, which has not previously been reported. Speleothem growth theory and evidence from other terrestrial paleoclimate records suggest that episodic, rapid growth phases at the insolation maxima are most likely to be caused by changes in either precipitation intensity or volume, which caused switching in the routing of water flow in the unsaturated zone above the cave. Such a result provides new evidence of the importance of variations in solar insolation for terrestrial paleoclimate and offers the potential for derivation of a paleowetness index from speleothem growth.

INTRODUCTION

Speleothems, cave secondary carbonate deposits, are formed by the degassing of ground waters that contain elevated carbon dioxide concentrations (Holland et al., 1964). Recent compilations of the timing of speleothem growth in Britain and northwest Europe (Gordon et al., 1989; Baker et al., 1993) have demonstrated a strong correlation between these records and other indicators of paleoclimate change such as the marine oxygen isotope and terrestrial pollen records (Martinson et al., 1987; Guiot et al., 1993). Here we employ the greatly improved precision (2σ errors in age <2%) and much smaller sample size possible by using thermal ionization mass spectrometric ^{238}U-^{234}U-^{230}Th (TIMS ^{230}Th) dating (Edwards et al., 1987) to investigate the time of growth phases in a long flowstone sequence from northwest England.

SAMPLE DESCRIPTION AND ANALYSIS

Flowstone sample LH-90-4/5/6 was obtained from the start of Collonade Passage, an abandoned high-level passage ~35 m below the surface, adjacent to the entrance of the Lancaster Hole cave system, west Yorkshire Dales (grid reference SD/664807, altitude 294 m above sea level). The base of the sample rested on >20 cm of coarse, poorly sorted gravels containing rounded to subangular sandstone clasts and a large amount of angular limestone. The flowstone sequence was in turn overlain by finer-grained sediment, comprising 40 cm of finely bedded sand, followed by 75 cm of horizontally bedded mud. Subsequent to deposition of this sediment-flowstone-sediment sequence, erosion to the bedrock passage floor occurred, exposing the sequence and giving rise to some cracking of the flowstone. The flowstone was deposited beneath a large inlet shaft or aven, but this is not hydrologically active at present. The only present-day speleothem deposition is a small stalagmite, which postdates erosion of the gravels. The water source for this is not the main aven, and the volume of deposition is much smaller than during active flowstone growth.

Three samples were obtained. LH-90-4 comprised the basal 9.4 cm, which had broken from the remainder of the sample and was laterally displaced. This sample was overlain by LH-90-5 and LH-90-6. Total sampled flowstone thickness was 33 cm and consisted of seven pure calcite growth phases separated by thin (<1 mm thick) bands of fine mud (Fig. 1). These appear to represent nondepositional hiatuses, as there is no evidence of erosion or dissolution of the underlying calcite. Prominent ripple marks were visible in all growth layers, indicating a fast-flow regime when deposition occurred.

Twenty ~1 g subsamples were cut parallel to growth layers. Samples were cut both adjacent to prominent growth hiatuses (to determine the precise timing of growth termination) and within

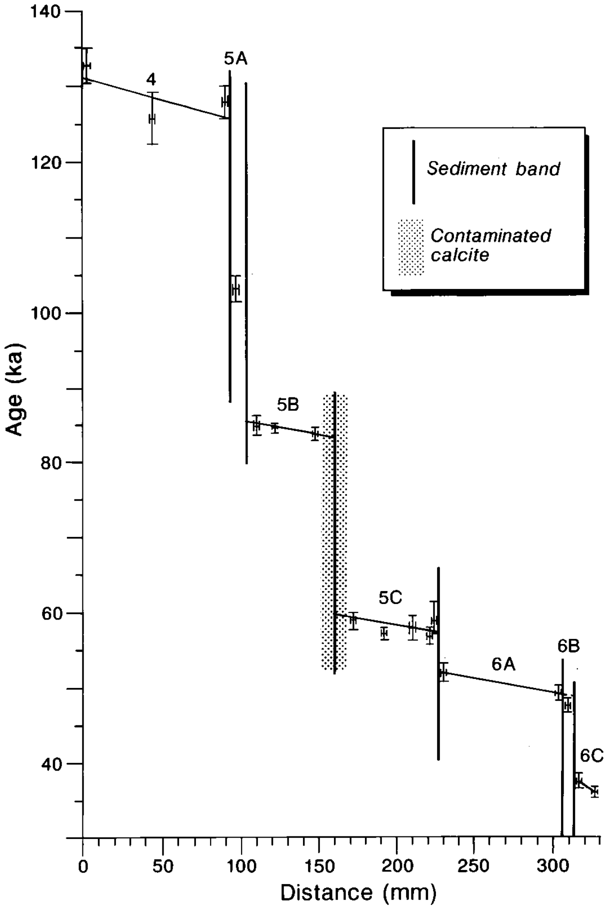

Figure 1. Graph of flowstone age vs. distance through sequence. Error bars represent 2σ counting errors of age determinations and thickness of cut sample. For clarity, only higher precision of duplicate analyses is shown.

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growth phases (to obtain a measure of growth rate). Standard analytical techniques (Edwards et al., 1987) were used to prepare the samples for analysis on a Finnigan MAT 262-RPQ mass spectrometer. Three sample pairs—LH-90-5C(T1) and 5C(T2), 6A(B) and 6A(B)dup, and 6A(T) and 6A(T)dup—provided sample duplicates from the same growth layer; another sample, 5B(M), was analyzed as a machine duplicate to determine machine reproducibility. The sampling locations and results are shown in Figure 1 and Table 1.

RESULTS

All analyses from the Lancaster Hole flowstone gave ages in correct stratigraphic order, and all duplicates showed agreement within 2σ for errors based on counting statistics. Initial results from phase 6A showed poor precision, perhaps owing to high organic contamination, and the analyses were repeated. The second set of results were considerably better and are used to define the age of this phase of growth. Multiple age determinations from within the major phases 4, 5B, 5C, 6A, and 6C indicate that growth was rapid and episodic. Each growth phase was so short that it could not be accurately resolved with the TIMS ^{230}Th ages, the upper and lower ages typically overlapping at 2σ uncertainties. Conversely, none of the ages for separate phases overlap; periods of deposition are separated by substantial nondepositional hiatuses represented by the mud bands. Only one analysis is available for each of the two thin growth phases 5A and 6B. In the case of the former this clearly represents a separate phase intermediate in age and entirely separate from phases 4 and 5B. Phase 6B is not, however, separable in age from phase 6A, although it is distinct from the subsequent phase 6C. Thus, we conclude that the flowstone grew in six or possibly seven brief growth phases at 128.8 ± 2.7, 103.1 ± 1.8, 84.7 ± 1.2, 57.9 ± 1.5, 49.6 ± 1.3 (or 50.6 ± 1.0 and 47.6 ± 1.0 if two separate phases), and 36.9 ± 0.8 ka (errors are either the mean of 2σ standard deviations or 2σ standard error of the multiple age determinations within each growth phase, whichever is larger).

Some correlations between the timing of these growth phases and other paleoclimate records (Fig. 2) are visible between the speleothem growth phases and periods of climatic amelioration from the ice-core record (Dansgaard et al., 1993). However, the most remarkable correlation is that with predicted July solar insolation levels for lat 60°N, calculated from astronomical forcing (Berger and Loutre, 1991). Of the six definite phases of rapid growth between 140 and 30 ka, five correspond exactly to peaks in the astronomically predicted June insolation at 60°N. The remaining growth phase (49.6 ± 1.3 ka) corresponds to an unusual period of the insolation record, during which insolation remained high between adjacent maxima rather than declining significantly as is the more general pattern.

INTERPRETATION

The close correlation between the flowstone growth phases and the timing of insolation maxima suggests the predominance of this factor in influencing deposition of this sample. Such short periods of rapid flowstone growth have not been previously reported, the only other sample precisely dated by TIMS ^{230}Th dating having grown continuously for 10–100 ka (Li et al., 1989; Richards et al., 1994). They are also much shorter than the conventional duration ascribed to interglacial (10–20 ka) and to a lesser extent interstadial (5–10 ka) events (Martinson et al., 1987), being rather more similar to the

TABLE 1. U/Th ISOTOPIC DATA AND MASS-SPECTROMETRIC AGES FOR THE LANCASTER HOLE FLOWSTONE

Sample	Distance (mm)	^{238}U conc. (nm g^{-1})	^{234}U/^{238}U (x 10^{6})	^{230}Th/^{232}Th (x 10^{6})	^{230}Th/^{232}Th (act)	δ^{234}U(0)*† (per mil)	^{230}Th/^{238}U† (act)	Age†§ (yr x 10^{3})
LH-90-4B	2	16.22 ± 0.11	67.18 ± 0.30	39 000 ± 1400	7300 ± 300	227.7 ± 5.6	0.8929 ± 0.0074	132.8 ± 2.4
LH-90-4M	45	5.49 ± 0.011	70.04 ± 0.28	62 000 ± 14 000	>10 000	280.0 ± 5.3	0.9079 ± 0.0132	125.7 ± 3.4
LH-90-4T	91	7.27 ± 0.039	66.23 ± 0.35	294 000 ± 28 000	>10 000	210.5 ± 6.5	0.8604 ± 0.0062	127.8 ± 2.2
LH-90-5A	97	5.28 ± 0.021	79.83 ± 0.38	594 000 ± 386 000	>10 000	458.9 ± 7.0	0.9316 ± 0.0089	103.1 ± 1.8
LH-90-5B(B)	110	7.12 ± 0.030	86.02 ± 0.38	175 000 ± 35 000	>10 000	572.0 ± 7.0	0.8869 ± 0.0085	84.9 ± 1.3
LH-90-5B(M)	122	4.82 ± 0.011	86.53 ± 0.26	233 000 ± 20 000	>10 000	581.4 ± 4.8	0.8896 ± 0.0040	84.5 ± 0.7
LH-90-5B(M)mdup	122	4.84 ± 0.021	85.95 ± 1.05	>1 000 000	>10 000	570.7 ± 19.1	0.8924 ± 0.0072	85.8 ± 1.9
LH-90-5B(T)	148	2.07 ± 0.006	86.66 ± 0.38	15 920 ± 340	3000 ± 60	583.7 ± 6.9	0.8851 ± 0.0054	83.7 ± 0.9
LH-90-5C(B)	172	1.55 ± 0.005	84.61 ± 0.75	1137 ± 19	211 ± 3	546.3 ± 13.88	0.6638 ± 0.0073	58.8 ± 1.1
LH-90-5C(M1)	192	1.53 ± 0.004	83.03 ± 0.61	1610 ± 23	300 ± 4	517.4 ± 11.2	0.6366 ± 0.0063	57.1 ± 0.9
LH-90-5C(M2)	210	1.70 ± 0.013	80.86 ± 1.58	2550 ± 130	475 ± 25	477.7 ± 28.8	0.6245 ± 0.0061	57.8 ± 1.7
LH-90-5C(T2)	221	1.53 ± 0.007	81.22 ± 0.57	1840 ± 38	340 ± 10	484.3 ± 10.5	0.6194 ± 0.0090	56.8 ± 1.2
LH-90-5C(T1)	224	1.47 ± 0.029	80.87 ± 2.07	5560 ± 7	103 ± 1	478.0 ± 37.9	0.6328 ± 0.0138	58.8 ± 2.6
LH-90-6A(B)	230	1.76 ± 0.037	77.59 ± 3.70	2130 ± 150	395 ± 30	418.0 ± 67.5	0.5805 ± 0.0202	55.6 ± 4.3
LH-90-6A(B)dup	230	1.75 ± 0.003	80.89 ± 0.30	2670 ± 190	497 ± 36	478.3 ± 5.4	0.5744 ± 0.0109	52.0 ± 1.3
LH-90-6A(T)	304	0.67 ± 0.001	75.31 ± 0.29	259 ± 23	48 ± 4	376.2 ± 5.4	0.4850 ± 0.0403	46.3 ± 4.7
LH-90-6B	310	0.93 ± 0.001	76.45 ± 0.39	1090 ± 31	203 ± 6	397.0 ± 7.1	0.5044 ± 0.0081	47.6 ± 1.0
LH-90-6C(B)	316	1.91 ± 0.004	77.02 ± 0.44	2960 ± 350	550 ± 65	407.5 ± 8.1	0.4172 ± 0.0093	37.6 ± 1.0
LH-90-6C(T)	327	1.56 ± 0.003	76.12 ± 0.37	2280 ± 130	423 ± 25	391.0 ± 6.7	0.3982 ± 0.0060	36.1 ± 0.7

Note: Sample location and distances shown in Figure 1; LH5(B) and LH5(B)mdup are replicate analyses of different aliquots of the solution derived from sample LH5(B); LH6A(T) and LH6A(T)dup and LH6A(B) and LH6A(B)dup are duplicate analyses of different samples from the same growth layer. (act) is the activity ratio, which is the atomic ratio multiplied by the ratio of the decay constants.

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

† Ages are calculated using $[^{230}Th/^{238}U]act - 1 = e^{-\lambda 230T} + (\delta^{234}U(0)/1000)(\lambda_{230}/\lambda_{230}-\lambda_{234})(1-e^{-(\lambda 230-\lambda 234)T})$ where T is the age in years.

§ 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).

2 ka duration of events recently recorded by Dansgaard et al. (1993) for the Summit ice core. Thus two features of the growth of the Lancaster Hole flowstone must be explained. First, why are the recorded growth periods so brief and associated with times of the insolation maximum in the period 140–30 ka? Second, why has no subsequent flowstone growth occurred at this site during the Holocene?

Lack of Holocene Growth

Observations made in the cave today show that out of six massive fossil flowstones in the Collonade Passage–Bill Taylors Passage region of the cave, none is hydrologically active. Furthermore, nearby drip waters are all undersaturated with respect to calcite and, thus, are actively dissolving the limestone bedrock (average late summer [maximum] calcium concentration of the drip waters measured today is 0.78 ± 0.27 mmol L^{-1}, $n = 8$). Both factors prevent speleothem growth at these sites today. Elsewhere in the region, cave drips and flows with a calcium concentration in excess of that required for calcite saturation are present (1.57 ± 0.51 mmol L^{-1}, $n = 25$; from White Scar Cave; T. C. Atkinson and J. W. Hess, unpublished data). This suggests that the effect observed in Lancaster Hole is localized and not a regional phenomenon. We believe that this major change in both unsaturated zone hydrology and geochemistry is associated with glaciation during the Devensian between 26 and 14 ka (Bowen et al., 1986), which emplaced shaly till above this part of the cave, reducing percolation inflow and apparently also reducing the partial pressure of CO_2 (P_{CO_2}) of recharge waters. Prior to the Devensian the area was not glaciated during the period of speleothem deposition (Worsley, 1992).

Episodic Growth (140–30 ka)

Previous explanations of the episodic growth of speleothems in temperate areas have focused on two major factors: availability of water for recharge and development of elevated carbon dioxide concentrations in the soil atmosphere by biological activity. Both of these are dependent on mean annual temperature, the former because recharge ceases once the ground becomes permanently frozen (Kane and Stein, 1984) and the latter because both root respiration and decomposition of soil organic matter are strongly dependent on temperature (Dorr and Munnich, 1986). However, we do not believe such arguments are appropriate in this case. Note that the duration of the phases of active speleothem growth are typically short (~2 ka), whereas available evidence from Grande Pile suggests that during isotope stages 5e and 5a, for instance, temperate mean annual temperatures (8–10 °C) were maintained for ~10 ka before mean annual temperatures fell by as much as 10 °C in the intervening cold stages (Guiot et al., 1993). Furthermore, although mean annual temperatures were substantially lower in isotope stage 3 (typically 4–6 °C) compared to stage 5, these lower temperatures did not appear to restrict speleothem growth. Although slightly cooler conditions would be expected in Yorkshire, this would not be enough to explain the short (~2 ka) duration of the phases of active speleothem growth observed here.

We must therefore consider alternative explanations. Degassing may not occur in the cave if the P_{CO_2} of cave air is elevated because blockage of open entrances restricts ventilation (Ek and Gewelt, 1985). However, it appears very unlikely that this would be directly related to solar insolation. Another possibility is that speleothem deposition was terminated even though paleoclimate was favorable because of flooding of the cave passage or the presence of an erosive stream. The presence of clastic sediments both underlying and overlying the sequence attests to this possibility, as does the veneer of mud that typically marks each hiatus. However, close inspection of the speleothem surface beneath each hiatus shows no evidence of either subaqueous calcite deposition (ponded conditions) or erosive truncation of the growth layers. The latter observation also confirms that changes in the saturation state of inlet waters due to reduced carbon dioxide generation in the soil are unlikely, because this would almost certainly have resulted in some dissolution of the previously deposited calcite.

Given the failure of alternative explanations, we therefore consider that variations in paleoprecipitation controlled deposition of this sequence. A particular feature of the unsaturated-zone hydrology of karstified limestone aquifers is that flow routing is strongly dependent on recharge rate. At low recharge rates, water is transmitted predominantly via seepage routes (slow drips), which provide substantial storage and typically feed stalagmites. As recharge rates increase, the capacity of these routes is exceeded, and flow switches to more open, high-capacity routes (shafts and vadose flows) typically associated with massive flowstone accumulations. This model has been demonstrated in caves in the Mendip Hills (southwest England) via water-budget studies and dye tracing (Smart and Friedrich, 1987), and comparable unpublished studies by T. C. Atkinson and J. W. Hess demonstrate similar behavior for present-day inlets to White Scar Cave, northwest Yorkshire. Furthermore,

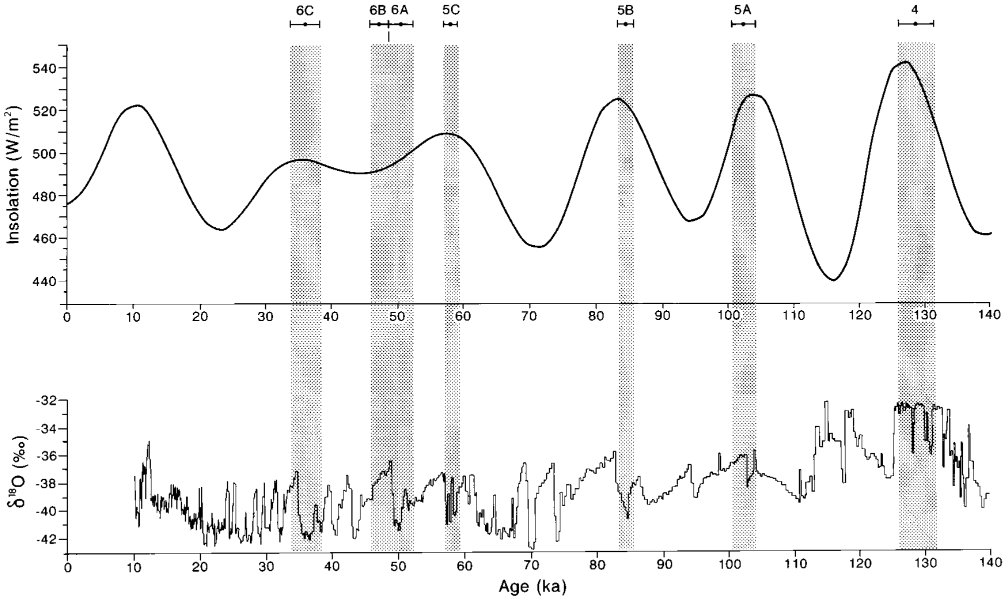

Figure 2. Comparison of Lancaster Hole flowstone growth periods and insolation record for July at 60°N (Berger and Loutre, 1991) and GRIP ice-core record (Dansgaard et al., 1993). Dot pattern indicates timing of 2σ errors of Lancaster Hole age determinations.

Baker (1993) observed that out of ten flowstones monitored for one year in southwest England, seven were active only during the winter when recharge rates were high. Thus, we believe that the initiation and cessation of speleothem growth in our sample may be controlled by a recharge-rate threshold. Growth may, therefore, be sensitive to variations in total precipitation, precipitation rates, seasonal distribution of precipitation, or the rate of evapotranspiration.

DISCUSSION

As we have demonstrated, speleothems can provide very precisely dated terrestrial records. A good correlation is observed here between the timing of the growth phases of the Lancaster Hole flowstone and the insolation record and between the duration of the growth phases and the ice-core interstadial record. The record of six phases of flowstone growth correlates with the longer-term Dansgaard-Oeschger cycles in the ice-core record and also agrees with the accepted European pollen sequence of the Ipswichian-Eemian interglacial followed by five interstadial periods. However, more detailed comparisons with the pollen records are not possible because constraints on their timing are poor in comparison to that of the Lancaster Hole flowstone.

The timing of flowstone growth phases reflects a sensitivity to changes in total precipitation, precipitation rate, or seasonal distribution of precipitation and demonstrates a link between solar insolation and precipitation. Rates of poleward energy transport are greatest at times of high insolation, particularly when these follow cold periods that steepen poleward temperature gradients. This transfer is accomplished by increased poleward transport of warm moist air generated by higher surface temperatures in the tropics and by changes in the pattern and rate of oceanic circulation. The importance of insolation in driving climatic change has been demonstrated by GCM modeling of the summer climate at 126 ka, where an increased mid-Atlantic gyre was calculated at this insolation maximum (Prell and Kutzbach, 1987). This would lead to increased Gulf Stream transport and hence increased sea-surface temperatures around the coasts of the British Isles. This in turn could cause increased cyclogenesis and provide a mechanism for explaining speleothem growth. However, Gulf Stream warming is also dependent on the presence of active North Atlantic deep water (NADW) circulation; recent ocean core records demonstrate that significant variations in NADW production have occurred both over the past 130 ka and within the last interglacial and that they do not necessarily correlate with insolation maxima (Bond et al., 1993; McManus et al., 1994). However, evidence of unstable NADW circulation within the last interglacial is not observed here, and this suggests that relatively high insolation as well as NADW production may also be a prerequisite for triggering the precipitation regime causing the growth of the Lancaster Hole flowstone. Further studies now need to be undertaken into the timing and duration of the growth of other speleothem samples, especially for those with different hydrological characteristics and from a wide spatial area, in order to more precisely constrain the correlation of the timing of speleothem deposition with insolation and ocean-circulation parameters.

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