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Phil. Trans. R. Soc. Lond. B 1983 **301**, 143-164
doi: 10.1098/rstb.1983.0024

Phil. Trans. R. Soc. Lond. B **301**, 143–164 (1983) [143]
Printed in Great Britain

URANIUM-SERIES AGES OF SPELEOTHEM FROM NORTHWEST ENGLAND: CORRELATION WITH QUATERNARY CLIMATE

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(*Communicated by H. G. Thode, F.R.S. – Received* 14 *September* 1982)

[Plate 1]

CONTENTS

Over 180 ^{230}Th/^{234}U ages have been obtained for 87 speleothems from caves in the Craven district of northwest England. Periods of abundant speleothem growth, 0–13, 90–135 and 170 to > 350 ka, are correlated with interglacial isotope stages 1, 5 and 7–9 respectively. Periods of zero growth, 14–35 and 140–165 ka, are correlated with glacial stages 2 and 6 respectively. A prominent break in growth of one speleothem, dated at about 260 ka, may be correlated with glacial stage 8. Lower-frequency growth from 35 to 90 ka is correlated with stages 3 and 4. The results may also be related to the British Quaternary sequence within the range of ^{14}C determinations, as follows: 0–13 ka. Flandrian plus late Devensian deglaciation; 14–35 ka, late Devensian glaciation; 35–45 ka. Upton Warren interstadial. Low but finite speleothem abundance during the period 45–90 ka correlates with the early Devensian and is in good agreement with evidence indicating the non-glacial, but tundra-like, climate over this period. The Ipswichian interglacial is broadly related to the abundant

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growth period 90–135 ka, but is more closely defined by the interval 115–135 ka, from results of dating speleothems enclosing remains of Ipswichian fauna in one cave. By analogy with the zero speleothem abundance during the late Devensian glaciation, the period 140–165 ka may be tentatively correlated with the Wolstonian glaciation. Lack of direct stratigraphic relationships with, or absolute ages of, middle to early Pleistocene stages prevents further correlation of speleothem age data. From the frequency of abundance of speleothem basal ages for the period 0–13 ka, it appears that speleothem growth lags ice recession by up to 4 ka.

INTRODUCTION: SPELEOTHEMS AS A CONTINENTAL PALAEOCLIMATIC INDICATOR

At many continental locations, notably those that have been overridden by ice sheets, it is often difficult to determine climatic history earlier than the last glaciation because older surficial deposits have been removed or obliterated by glacial processes. In limestone regions, however, evidence of past climatic events may be preserved in underground caverns, in the form of clastic sediment sequences, bedrock erosional morphologies indicative of a constant or of a changing water level, floral and faunal remains and the chemical and isotopic composition of speleothems.

Speleothems are cave-deposited minerals, usually calcite, in the form of stalactites, stalagmites and flowstones. They are precipitated by loss of CO_2 from calcite-saturated waters entering the cave along fractures or bedding planes. Speleothems can be dated by several radiometric methods, including ^{14}C (Hendy 1969), U-series methods (Thompson *et al.* 1974; Harmon *et al.* 1975), thermoluminescence (Wintle 1978) and electron spin resonance (Ikeya 1978). Results, so far, have shown that U-series methods are the most reliable of the above and cover the longest time range.

The occurrence of ancient speleothems in high-latitude caves in the northern hemisphere has been interpreted to indicate periods of non-glacial conditions in the past (Harmon *et al.* 1977). This is because processes of limestone dissolution at the surface, followed by reprecipitation in the cave below, may only proceed if groundwater can drain freely through the soil and bedrock. Furthermore, vegetation must be present to generate the CO_2 needed for significant limestone removal. Normally, neither of these processes can occur if the area is glaciated or overlain by continuous permafrost. Consequently, periods of low or zero frequency of speleothem growth are inferred to be cold or glacial in character, whereas high abundances indicate a warm, moist climate, conditions such as those encountered today in many of these areas. Additional palaeoclimatic information can be obtained from variations in the stable isotopic content of speleothems and fluid inclusions in the calcite (Schwarcz *et al.* 1976; Harmon *et al.* 1978; Gascoyne *et al.* 1978, 1980). In most previous speleothem work, age frequency distributions and stable isotopic profiles have shown reasonable correlation with isotopic records of deep-sea cores.

This paper presents the results of dating speleothems from caves in northern England and discusses their implications for the palaeoclimatic history of the area. Correlations with the oceanic record and stages in the British Quaternary sequence are also proposed. The speleogenetic and geomorphic significance of the results are considered elsewhere (Gascoyne *et al.* 1983).

$^{230}Th/^{234}U$ *dating of speleothems*

Speleothems generally consist of very pure calcite with little clastic detrital material and, at the time of deposition, contain small amounts of U, without the less mobile daughter elements (Th, Pa). Following deposition, ^{230}Th is formed in the speleothem by decay of ^{234}U such that the radioactivity ratio ^{230}Th/^{234}U increases from zero to near unity within a period corresponding to about five half-lives of ^{230}Th (about 350 ka). The age of a speleothem that is younger than 350 ka may therefore be determined by extracting the Th and U from the calcite and measuring this ratio. The principles of the method are described in detail by Gascoyne (1977) and Gascoyne *et al.* (1978).

(i) *Analytical techniques*

In preparation for analysis, the speleothems are washed, sectioned along the growth axis and acid-etched to clarify the internal stratigraphy. Samples are removed by a pneumatic chisel, and from 5 to 100 g of speleothem calcite is used in the analysis, depending on the U content. U and Th are chemically extracted and each element is plated out onto a stainless steel disc for counting in an alpha particle spectrometer. Ages are calculated from the ^{234}U/^{238}U and ^{230}Th/^{234}U ratios by a computer program.

(ii) *Requirements for dating*

Speleothems that are ideal for U-series dating consist of impervious crystalline calcite that has not recrystallized, is free of clastic sediments, and contains more than 0.1/10^6†U. Presence of clastic detritus often leads to contamination with Th and U isotopes leached from it during dissolution in acid. Several methods have been proposed for correcting an age for detrital contamination. These usually involve multiple analyses of coeval samples that contain differing fractions of detritus (Kaufman & Broecker 1965; Turekian & Nelson 1976; Schwarcz 1980) or analysis of the detritus itself (Ku *et al.* 1979). None of these methods is perfectly satisfactory and for speleothems it is better to use a section of calcite, if possible that is not contaminated but is stratigraphically adjacent to the contaminated portion, so that an age may be obtained by extrapolation from measured growth rates. The sediment-rich layers of calcite that often form the base of a stalagmite or flowstone are best dated by this approach.

An indication of detrital contamination in a speleothem is given by the presence of ^{232}Th in the Th spectrum. In this study, the sample is termed 'contaminated' if the ^{230}Th/^{232}Th ratio is less than 20.

(iii) *Precision and accuracy*

The precision of ^{230}Th/^{234}U ages determined here, quoted for $\pm 1\sigma$, is estimated on the basis of the number of alpha particles counted and the background activity, Poisson statistics being assumed (Evans 1955). Estimated variation in reagent blank correction has also been included in the error. Accuracy of the ages is largely determined by uncertainties in (*a*) the ^{228}Th/^{232}U ratio of the tracer used in the analysis, (*b*) the half-lives of ^{230}Th and ^{234}U, (*c*) the precision of the branching ratio for ^{228}Ra so that allowance can be made for alpha particles with energy equal to that of ^{228}Th (assumed here to be 5.5%).

Seven determinations of the tracer ratio have given a mean value of 1.030 ± 0.014 (Gascoyne 1980), close to the theoretical value of 1.027. The decay constants are assumed to be $\lambda_{230} = 9.2173 \times 10^{-6}\ \mathrm{a}^{-1}$ and $\lambda_{234} = 2.8062 \times 10^{-6}\ \mathrm{a}^{-1}$.

Estimates of the overall precision have been made through 12 identical analyses of a laboratory standard (76001, a powdered flowstone of < 100 mesh size (152 μm) fraction) which gave

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† The symbol /10^6 here stands for 'parts per million', by mass.

a mean age of 47.8 ± 1.7 ka. The Poisson estimate gave $\overline{\sigma} = \pm 2.2$ ka, in satisfactory agreement. Comparison of this laboratory's results with results from other laboratories in the U-series intercomparison project (U.S.I.P. I, II, III; Harmon *et al.* 1979; Ivanovich & Warchal 1981) showed agreement at the 1σ level with the mean result of 14 laboratories for seven of the eight samples analysed, and agreement for 2σ for sample RHKL.

The study area

The Craven district of northwest England (figure 1) contains some of Britain's longest, deepest and best developed cave systems. Most are developed in the Lower Carboniferous Great

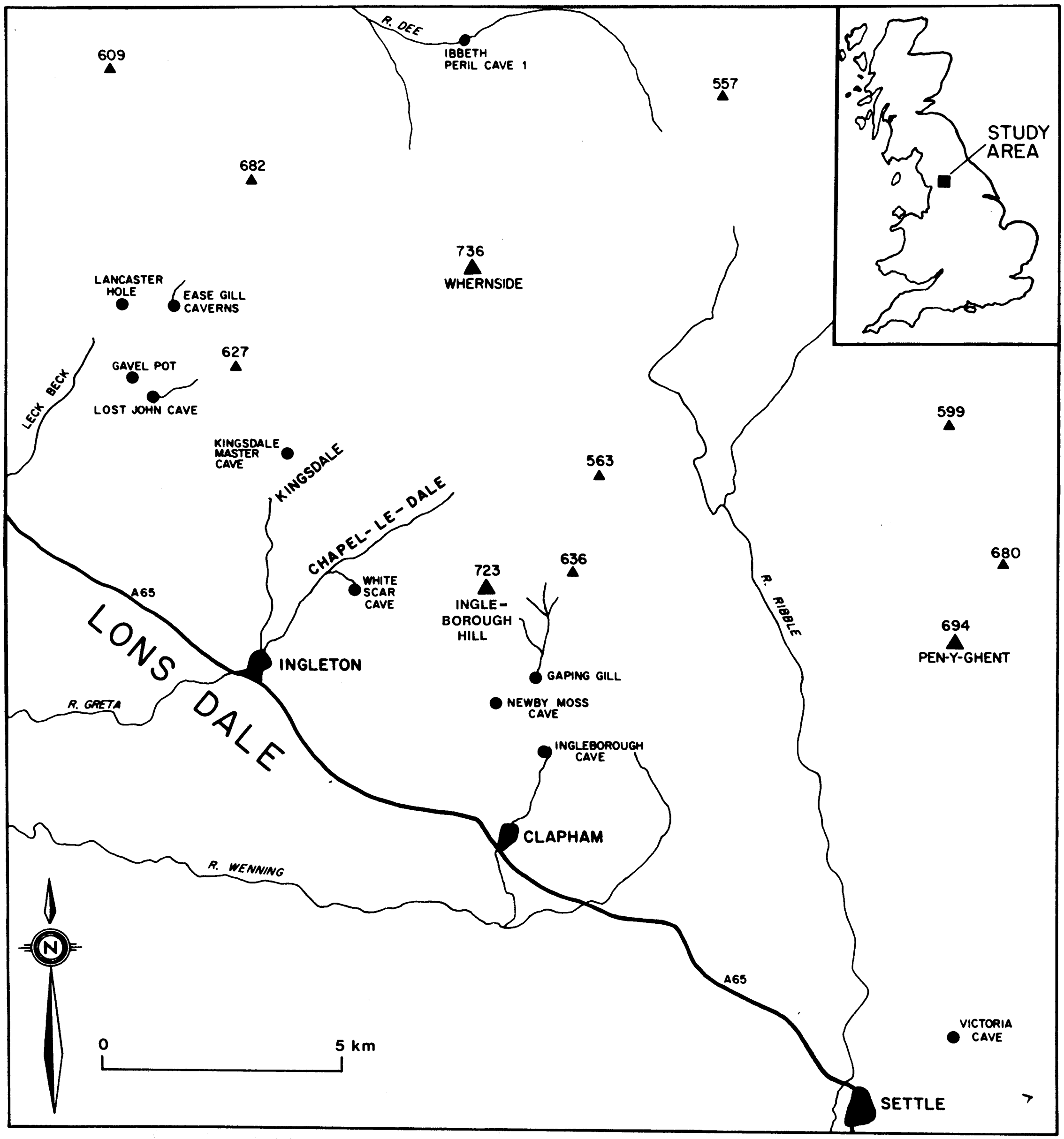

FIGURE 1. Location map showing the Craven district of northwest England, positions of caves investigated in this study, major towns, road and rivers, and altitudes of prominent peaks (in metres above sea level).

Scar limestone, which is 200 m thick. The geology, geomorphology and cave development of the area is described in detail by Waltham (1974).

Little is known of the Quaternary history of the Craven district before the last glaciation because most surficial deposits are derived from the late Devensian ice sheet which covered the area up to 600 m above sea level (Warwick 1956). Most of the caves clearly predate at least one glaciation because many contain sequences of till and glacial outwash deposits. Speleothems can be found in abundance in some of the caves, but those best known for their beauty are usually formed on top of post-glacial sediments and were deposited during the Flandrian warm period. Less decorative, older speleothems can also be found, either undisturbed in their growth position, where they are massive and resistant to erosion (e.g. flowstones), or broken and lying in boulder collapses and streamways. This latter type of material was collected for this study so that the maximum amount of palaeoclimatic information could be obtained with the minimum amount of damage to the caves.

Over 80 individual speleothems were collected from eleven of the major cave systems in the Craven district. Details of their location and the speleogenetic significance of their ages are described elsewhere (Gascoyne 1980; Gascoyne *et al.* 1983).

Results

Speleothem locations, isotope activity data and ^{230}Th/^{234}U ages for 87 individual speleothems are summarized in table 1. In all of the 182 ages listed, chemical yields of U and Th in the extraction procedure were each greater than 10%, except for those analyses marked with an asterisk.

U *concentrations and* ^{234}U/^{238}U *ratios*

A variation of almost three orders of magnitude can be seen in the U content of speleothems listed in table 1 (concentrations range from $0.04/10^6$ to $18.3/10^6$). For a single cave or section of a cave system, however, the U content varies within one order of magnitude. Large variations are also found in ^{234}U/^{238}U activity (from 0.71 to 1.9) but, once again, values are fairly constant within a limited area. A pronounced decrease in ^{234}U/^{238}U ratio is seen in traversing 1.4 km from west to east in the Lancaster Hole, Ease Gill Cavern system. Ratios range from 1.03 to 1.63 in the west, but, in the region of Stop Pot and Easter Grotto in the east, they show strong depletion of ^{234}U to ratios as low as 0.71.

Detrital contamination

Detrital Th contamination (^{230}Th/^{232}Th < 20) was observed in 48 samples. In a few cases (76108, 76124, 77120 and 76190) subsequent analysis of a purer calcite portion near the base of the speleothem showed that the detrital component did in fact displace ages to older values, probably owing to contribution of unsupported ^{230}Th from detrital grains in the calcite. Ages of young speleothems are most strongly influenced by this effect because, for a given U content and initial ^{230}Th/^{232}Th ratio, the ratio of authigenic to detrital ^{230}Th is lowest in a young deposit. Not all duplicate analyses, however, showed the effect of decreasing age with increasing purity of the calcite analysed (for example, 76129, 77201). Those that did not may indicate either the absence of leachable ^{230}Th or the presence of leachable ^{234}U in the detrital component.

Table 1. Sample locations, descriptions and isotopic data for $^{230}Th/^{234}U$ age determinations of speleothems from the Craven district, northwest England

speleothem no.	description	analysis		U	$^{234}U/^{238}U$	$^{230}Th/^{232}Th$	$^{230}Th/^{234}U$	age ± 1σ
		no.	location	(/10^6)				ka
White Scar Cave								
76100	fs, in streamway	E-1	base	1.46	0.976	126	0.976	> 350
		E-2	top	0.88	0.946	103	0.956	> 350
76102	fs, Western Front	-1	top	0.06	1.096	2	1.083	> 350
76106 A	fs, Sleep-Walker Passage	-1	top	0.58	1.018	36	0.870	218^{+29}_{-23}
		-2	base	0.61	0.995	21	0.903	256^{+62}_{-39}
76106 B	fs, near to 76106 A	-1	top	0.80	0.857	37	1.030	> 350
76108	sg, Far Streamway	-1	base	1.39	1.201	7	0.102	11.6 ± 0.7
		-2	top	2.11	1.082	23	0.053	6.0 ± 0.3
		-3	base	1.17	1.192	25	0.098	11.1 ± 0.4
Ibbeth Peril Cave I								
76110	*fs*, false floor	-1	top	0.72	0.996	25	0.089	10.1 ± 0.5
76111	*fs*, near to 76110	-1	bulk	0.30	1.067	15	0.238	29.4 ± 2.2
		-2	top	0.31	0.947	> 200	0.118	13.7 ± 1.3
		-3	base	0.40	1.003	13	0.051	5.7 ± 0.6
76112	thin *fs* bridge	-1	bulk	1.21	0.960	> 200	0.068	7.6 ± 0.7
Lancaster Hole, Ease Gill Caverns								
76121	sg, Bill Taylor's Passage	-1	top	2.42	1.073	110	0.656	114 ± 7
		-2	base	1.49	1.130	129	0.661	114 ± 7
76122	sg, near to 76121	-1	base	2.12	1.203	54	0.578	91 ± 5
		-2	top	2.59	1.386	37	0.491	71 ± 3
76124	sg, near to 76121	-1	base	0.62	1.229	13	0.116	13.3 ± 1.0
		-2	base	0.63	1.330	24	0.087	9.8 ± 0.5
76125	sg, near to 76121	-1	base	2.01	1.628	105	0.302	38 ± 1
		-4	top	1.17	1.518	66	0.306	39 ± 2
76126	sg, Stop Pot	-1	top	13.7	0.719	> 200	0.007	0.8 ± 0.1
		-2	base	13.3	0.713	22	0.085	9.7 ± 0.3
76127	fs, Stop Pot	-1	top	13.1	0.878	> 200	0.843	225^{+25}_{-20}
		-2	base	5.8	0.911	> 200	0.963	> 350†
		-4	near base	14.5	0.848	> 200	0.846	237^{+22}_{-18}
76128	sg, Easter Grotto	-1	base	18.3	0.745	43	0.100	11.5 ± 0.5
		-2	top	2.7	0.727	3	0.011	1.2 ± 0.2
76129	sg, near to 76128	-1	top	3.1	0.789	3	0.008	0.9 ± 0.1
		-2	base	1.8	0.749	10	0.099	11.4 ± 0.6
		-3	base	2.7	0.799	31	0.104	12.0 ± 0.5
76130	sg, Stake Pot	-1	base	2.77	1.222	72	0.084	9.6 ± 0.3
		T-2	top	1.90	1.232	153	0.049	5.5 ± 0.2
76131	*sg*, Stop Pot	-1	base	17.1	0.760	45	0.080	9.0 ± 0.3
76133	fs, Eureka Junction	-1	top	4.9	0.820	3	0.054	6.5 ± 0.2
		-2	base	9.5	0.778	> 200	0.086	9.8 ± 0.5
76135	large *fs* boss, Bill Taylor's Passage	-1	upper middle	0.97	1.192	52	0.594	95 ± 4
		-2	top	1.32	1.240	> 200	0.558	86 ± 3
77120	2 overlying *fs* samples: A lower; B upper, hiatus in B; Colonnade Passage	A-1	base	2.71	1.242	> 200	0.750	140^{+10}_{-11}
		A-2	top	1.90	1.161	124	0.647	109 ± 4
		B-2	base	1.64	1.417	> 200	0.640	104 ± 4
		B-3	below hiatus	0.43	1.577	> 200	0.574	87 ± 4
		B-4	above hiatus	0.42	1.577	11	0.476	67 ± 2
		B-5	near top	0.41	1.380	4	0.567	87 ± 5
		B-1	top	0.38	1.473	> 200	0.468	66 ± 5
79005	*fs*, overlies 77120 B	-3	base	0.57	1.425	23	0.399	54 ± 3
		-1	top	0.43	1.429	12	0.333	43 ± 3
77121	*fs*, Bridge Hall	-1	top	0.22	1.198	24	0.418	58 ± 4
		-3	near top	0.23	1.314	44	0.389	52 ± 2
		-4	above hiatus	0.51	1.518	47	0.423	58 ± 2
		-5	below hiatus	0.59	1.178	> 200	0.736	137 ± 8
		-6	same as -5	1.18	1.373	89	0.640	104 ± 3
		-2	base	1.24	1.313	73	0.656	109 ± 5

TABLE 1 (*cont.*)

speleothem no.	description	analysis no.	analysis location	U (/10^6)	$\frac{^{234}U}{^{238}U}$	$\frac{^{230}Th}{^{232}Th}$	$\frac{^{230}Th}{^{234}U}$	$\frac{\text{age} \pm 1\sigma}{\text{ka}}$
77122B	fs, Bill Taylor's Passage	-1	base	1.04	1.284	20	0.525	78 ± 3
77123B	*fs*, pool deposit, Bill Taylor's Passage	-1	bulk	1.32	1.565	75	0.280	35 ± 1
77126	sg, Bill Taylor's Passage	-1	base	6.11	1.031	160	0.691	126 ± 5
		-2	top	3.93	1.152	> 200	0.635	106 ± 4
79003	*fs*, boss entrance shaft	A-1	top	0.21	1.117	62	0.860	199^{+21}_{-17}
		C-1	near base	0.42	1.178	29	0.944	257^{+22}_{-18}
79120	same as 79003	-1	top	0.38	1.313	> 200	0.942	236^{+20}_{-17}
		-3	middle	3.38	1.156	69	0.984	313^{+69}_{-48}
		-2	base	0.44	0.993	178	0.928	288^{+63}_{-27}
79121	sg, on fs, Bill Taylor's Passage	-1	fs base	0.83	1.622	103	0.324	44 ± 1
		-2	sg top	1.42	1.553	> 200	0.278	35 ± 1
		-1	base	1.17	1.113	> 200	0.698	126 ± 6
79124	sg, near Graveyard	-5	top	1.05	1.131	> 200	0.699	126 ± 6
		-3	outer	0.43	1.420	49	0.604	95 ± 5
		-2	overgrowth	0.37	1.297	> 200	0.499	73 ± 4
Ingleborough Cave								
76140	*sg*, Giant's Hall avenue	-1	base	0.10	1.270	6	0.784	152^{+35}_{-27}
76141	fs, Giant's Hall avenue	-1	base	0.07	1.462	10	0.668	111 ± 11
		-2	top	0.10	1.341	19	0.475	68 ± 5
76142	*fs*, Giant's Hall avenue	-1	below hiatus	0.04	1.306	14	0.798	156^{+45}_{-33}
		-2	base	0.04	1.287	8	0.623	101^{+14}_{-13}
		-3	above hiatus	0.10	1.132	4	0.728	136^{+43}_{-31}†
76143	*fs* Giant's Hall	-1	base	0.07	1.267	3	0.857	186^{+41}_{-30}
76144	sg, Show Cave	-1	base	0.37	0.952	2	0.100	11.5 ± 1.2
		-2	top	0.41	1.078	3	0.185	22.2 ± 1.2
76145	sg, Show Cave	C-1	middle	0.95	0.784	2	0.103	11.9 ± 0.6
77143	2 overlying *fs* samples	-1	base	0.07	1.480	26	0.621	98^{+14}_{-13}†
	A upper, B lower Giant's Hall avenue	A-2	top	0.06	1.392	22	0.617	98 ± 10
		B-1	base	0.12	1.192	41	0.702	125 ± 8
		B-3	middle	0.14	1.343	72	0.677	115 ± 8
		B-2	top	0.11	1.337	24	0.658	110 ± 10†
Victoria Cave								
76151	fs, from block pile in loop	-1	base	0.38	0.974	46	0.954	> 350
76152	fs, near to 76151	-1	base	0.38	1.006	3	0.869	219^{+45}_{-32}
76153	sc, on block pile	-1	top	0.18	1.301	4	0.162	19.0 ± 1.6
76154	fs, near to 76151	-1	top	0.52	1.049	53	0.818	180^{+16}_{-14}
76155	*fs*, veneer on wall, in in tube	-1	top	0.61	1.028	81	1.009	> 350
77150B	*fs* layers in laminated clays, near entrance	-1	bulk	0.39	1.019	9	1.104	> 350
77151	3 overlying *fs* samples, A base, B middle, C top; hiatus near base of C; in loop	A-1	sg in base	0.36	1.152	59	0.875	205^{+34}_{-26}
		A-2	base	0.50	0.984	26	0.925	287^{+33}_{-25}
		B-1	base	0.43	1.037	47	0.935	281^{+43}_{-31}
		B-2	top	0.45	1.059	130	0.927	265^{+29}_{-23}
		C-4	below hiatus	0.41	1.057	128	0.914	250^{+29}_{-23}
		C-3	above hiatus	0.46	1.081	102	0.836	188^{+13}_{-11}
		C-5	as C-3	0.45	1.112	118	0.930	255^{+28}_{-23}
		C-1	top	0.48	1.081	56	0.848	195^{-19}_{+17}
		C-2	as C-1	0.46	1.020	> 200	0.831	191 ± 9
77159	*fs*, contains 3 hiatuses, on wall in loop	-1	base	0.39	1.104	25	0.969	307^{+54}_{-37}
		-2	top	0.32	1.143	9	0.627	104 ± 7

TABLE 1 (*cont.*)

speleothem no.	description	analysis no.	analysis location	U (/10^6)	^{234}U/^{238}U	^{230}Th/^{232}Th	^{230}Th/^{234}U	age ± 1σ / ka
77230	*fs*/fill layers, on back wall; A basal layer; H top layer	A-1	base	1.97	1.039	21	1.103	> 350†
		F-1	base	0.35	1.138	23	0.933	253^{+66}_{-38}
		H-1	bulk	0.13	0.872	3	0.209	25.5 ± 3.6
77231	*sg*, in loop	-1	top	0.50	0.982	42	0.889	243^{+27}_{-21}
77234	*fs*, in loop	-1	top	0.38	0.947	12	0.848	214^{+32}_{-24}
77236	*fs*, overlying clays in entrance	-1	bulk	0.65	0.915	31	1.157	leached
77237	*fs*, near to 77236	-1	top	0.58	1.001	88	0.968	> 350
77238 B	*fs*, near to 77236, underlies clays	-1	middle	1.00	1.052	43	1.006	> 350
79150	*fs*, in loop, near 77151	-4	base	0.53	1.055	> 200	0.888	226^{+16}_{-14}
		-5	top	0.46	1.003	> 200	0.815	183 ± 10
79151	same as 77151, but single block cut from *fs* boss	-1	above hiatus	0.49	1.087	66	0.922	252^{+23}_{-19}
		-2	below hiatus	0.50	1.061	84	0.926	263^{+19}_{-16}
		-3	base	0.72	1.047	47	0.962	321^{+37}_{-28}
79153	fs, in loop	-1	top	0.49	1.042	52	0.800	171^{+11}_{-10}
79155	*fs*, near 77230	-1	base	1.86	0.999	26	1.087	> 350
79158	*sg*, overlies 79151	-1	base	0.54	1.076	80	0.824	181^{+14}_{-13}
		-3	as -1	0.59	1.072	146	0.830	185 ± 10
		-2	top	0.46	1.043	123	0.804	173 ± 9
Victoria Cave (cont.) (excavated samples now in Pigyard Museum, Settle)								
79000	fs, overlying rhino tooth	-1	adj. to tooth	0.62	1.000	44	0.610	102 ± 11†
		-2	near tooth	0.63	1.019	20	0.672	120 ± 7
79001	fs, overlying rhino jaw bone	-1	adj. to jaw	0.50	1.100	20	0.623	104 ± 6
		-2	near jaw	0.40	1.033	152	0.691	126 ± 9
		-3	as -2	0.43	1.022	34	0.714	135 ± 8
79002	fs, coating red deer antler	-1	bulk	0.50	1.012	16	0.702	131 ± 9
79021	fs, overlying rhino teeth	-1	near teeth	0.43	1.057	31	0.690	125 ± 7
79023	fs, overlying giant deer teeth	-1	near teeth	0.50	0.994	71	0.678	123 ± 7
79025	part of large fs block containing rhino and hippo bones on lower side	-1	at bone level	0.88	1.120	111	0.484	71 ± 3
		-2	top	0.43	1.048	84	0.654	114 ± 5
		-3	near to bone level	0.58	1.037	47	0.672	120 ± 6
79026	fs overlying rhino teeth	-1	top (?)	0.46	1.022	> 200	0.668	119 ± 5
Lost John's Cave								
76160	fs, Lyle Cavern high level	-2	base (?)	0.20	1.295	16	0.717	128 ± 12
		-3	top	0.18	1.283	15	0.702	123^{+29}_{-23}†
76161	sg, Lyle Cavern high level	-1	base	0.25	1.273	0.7	0.106	12.1 ± 5.5
76164	fs, Main Drain	-1	top	3.84	1.003	178	0.598	99 ± 4
		-2	near top	4.31	0.929	> 200	0.612	105 ± 7
		-3	base	5.68	0.945	> 200	0.620	106 ± 4
76165	*fs*, Main Drain	-1	pieces	9.35	0.938	111	0.649	116 ± 12
77162	same as 76165, large section	-1	top	6.23	0.944	127	0.568	92 ± 4
		-4	near top	7.16	0.898	> 200	0.597	101 ± 3
		-6	near top	7.29	0.941	> 200	0.584	96 ± 3
		-9	upper middle	8.85	0.914	85	0.581	96 ± 3
		-8	middle (porous)	7.00	0.862	45	0.668	126 ± 5
		-10	upper middle	8.43	0.927	> 200	0.628	109 ± 5
		-7	base	9.33	0.947	37	0.638	112 ± 3
		-3	base	7.21	0.916	92	0.638	113 ± 5

Table 1 (*cont.*)

speleothem no.	description	analysis no.	analysis location	U ($/10^6$)	$^{234}U/^{238}U$	$^{230}Th/^{232}Th$	$^{230}Th/^{234}U$	age $\pm 1\sigma$ ka
Gavel Pot								
76190	sg, Glasfurd's Passage	-1	base	0.57	1.398	5	0.127	14.7 ± 0.6
		-2	top	0.50	1.368	5	0.046	5.1 ± 0.6
		-3	base	0.37	1.409	27	0.089	10.1 ± 0.6
76191	sg, Glasfurd's Passage	-1	base	0.44	1.238	65	0.114	13.1 ± 1.4
		-3	near base	0.37	1.235	29	0.095	10.7 ± 0.5
		-4	near top	0.22	1.204	13	0.082	9.3 ± 0.9
76192	sg, near to 76191	-2	near base	0.30	1.326	28	0.085	9.6 ± 0.4
Gaping Gill								
76201	sg, Stalagmite Chamber	-1	base	2.07	1.279	16	0.068	7.6 ± 0.4
		-3	base	1.89	1.337	16	0.063	7.0 ± 0.3
76202	fs, Mud Hall	-2	base	0.46	1.056	40	1.074	> 350
76206	*fs* veneer, Hensler's Upper Passage	-1	bulk	1.81	1.181	48	0.333	44 ± 1
76207	sg, Nevada Passage, Far Country	-1	base	0.89	1.290	76	0.672	114 ± 8
		-2	top	0.30	1.233	27	0.735	135^{+16}_{-14}
76207	sg, Stalagmite Chamber	-1	top	0.42	1.512	3	0.017	1.9 ± 0.2
		-T	top	0.91	1.580	8	0.007	0.8 ± 0.2
		-3	base	0.74	1.542	6	0.031	3.4 ± 0.3
76209	*sg*, overlying varves, Sand Cavern	-1	base	9.38	1.120	6	0.008	0.8 ± 0.1
76210	sg, Old East Passage	-1	base	1.39	1.370	99	0.303	39 ± 2
		-2	top	2.38	1.200	122	0.297	38 ± 1
76211	*fs* on wall, Old East Passage	-1	bulk	0.39	1.164	28	0.938	253^{+30}_{-24}
77209	same as 76211	-3	top	0.25	1.185	20	0.995	$319^{+\geq 43}_{-44}$
76212	fs, Old East Passage	-2	base	2.10	1.218	4	0.126	14.6 ± 0.7
		-3	top	0.90	1.274	7	0.107	12.2 ± 0.4
76215	sc, on fill, West Chamber	-1	bulk	3.92	0.972	3	0.012	1.4 ± 0.1
76216	sg, Old East Passage	-1	base	8.93	1.144	6	0.012	1.3 ± 0.1
77200	fs, North Craven Passage	-1	top (?)	0.95	1.296	181	0.994	289^{+24}_{-20}
		-2	base (?)	1.94	1.239	69	1.032	> 350
77201	fs, Old East Passage	-1	bulk	1.47	1.337	15	0.091	10.3 ± 0.3
		-2	bulk	1.44	1.351	55	0.095	10.8 ± 0.4
77205	sg, Far East Passage	-1	base	1.85	1.842	95	0.358	46 ± 1
		-2	top	1.84	1.858	29	0.379	50 ± 1
77210A	sg, Far East Passage	-1	top	0.44	1.927	12	0.097	11.0 ± 0.6
Newby Moss Cave 76220								
76220	fs, near entrance	-1	top (?)	1.34	1.257	82	1.065	> 350
Kingsdale Master Cave								
77240	*fs*, on roof arch, Roof Tunnel	-2	bulk	0.20	1.145	83	0.989	$324 \pm > 100$
77241	*sc*, Roof Tunnel	-1	below hiatus	0.41	1.123	35	0.804	168^{+11}_{-10}
77242	fs, below avenue, Roof Tunnel	-1	bulk	1.55	1.015	74	0.941	$300^{+>70}_{-43}$
77243	fs, Roof Tunnel	-1	base (?)	1.17	1.053	73	0.891	230^{+23}_{+19}

† Low U or Th yields (5–10 %).

Abbreviations: sc, stalactite; sg, stalagmite; fs, flowstone. *Italic symbol* indicates that the *in situ* or growth position is known.

Stratigraphic agreement of ages

Where more than one analysis has been made on a speleothem whose growth direction is known (42 cases), most results show that the ages decrease in the direction of growth (33 cases), while in three of the remaining cases, the age error limits overlap at the 1σ level. In the other six cases, one overlaps within 2σ limits (77205), three are anomalous because of contamination by U leached from adjacent bone remains (79000, 79001, 79025) and a fifth is grossly contaminated with detrital Th (76144); the remaining speleothem (76111) shows no relation between ages and stratigraphy and may therefore have suffered post-depositional nuclide migration.

These results clearly demonstrate that the principles of the ^{230}Th/^{234}U dating method are sound, when applied to pure speleothem deposits, and that massive, impervious speleothems remain a closed system with respect to radionuclide migration following deposition.

The limits of the ^{230}Th/^{234}U dating method

The results indicate that, at its lowermost limit of precision, the ^{230}TH/^{234}U method gives reproducible ages for detritus-free, impervious speleothem containing as little as 0.05/10^{6} U. The lowest age limit that may be determined depends on the ability to isolate and count small quantities of ^{230}Th, and the lack of detrital ^{230}Th. Results in table 1 suggest that ^{230}Th/^{234}U ages as low as 200 a can be determined with good precision for speleothems moderately rich in U. For instance, 76209 contains 4.9/10^{6} U and its basal age of 0.8 ± 0.1 ka was determined from a ^{230}Th count rate of 0.2 min^{-1} at 50 % yield, an activity that was more than ten times greater than background level. As regards of an upper age limit, the 1σ error based on counting statistics approaches 10–15 % of the age near 350 ka, even for ideal samples (see table 1), and therefore the distinction between finite and 'infinite' ages disappears close to this limit. Furthermore, errors in tracer ratio and decay constants contribute greatly to the inaccuracy of the age near the upper limit. Therefore, a maximum age limit of 350 ka has been used in the present study.

Age-frequency distributions

The ages shown in table 1 are considered in terms of their palaeoclimatic significance in the remainder of this paper. Because of the low U concentrations and high detrital Th contents, all ages of speleothems from Ingleborough Cave, excepting 77143, have been omitted in the following sections.

Figure 2 presents a histogram of the ages for samples with ^{230}Th/^{232}Th > 20. Frequency of speleothem growth is shown rather than frequency of determined ages to avoid the extra weighting given to multiple age determinations on a single deposit.

Speleothem deposition was episodic rather than continuous, over the entire range of the dating method, 0–350 ka. There is a bias towards younger ages, partly owing to the fact that the likelihood of preservation of a speleothem decreases with its age, owing to post-depositional erosion or burial. This bias is partly offset by the tendency to 'overcollect' apparently ancient deposits so that an adequate representation of old samples could be ensured. Unfortunately, in a cave, it is often impossible to differentiate between a truly ancient speleothem and one that is recent but has suffered aging effects such as re-solution in a streamway or the accumulation of muddy bootprints of previous cave explorers.

Ideally, for the purposes of a palaeoclimate study such as this, speleothems should be sampled randomly throughout an area to reduce the weighting given to caves that have suffered less erosion than others and that, for various reasons unrelated to climate (e.g. geological or hydrological factors), contain more speleothems than others. In practice, of course, speleothems could be collected only if they were present in a cave, and the number and size of those collected often depended on human factors (proximity of the collection site to the cave entrance, type of passage to be negotiated, number of assistants, etc). These limitations are largely responsible for the fact that many speleothems were collected from Victoria Cave, and that these included almost no Recent deposits.

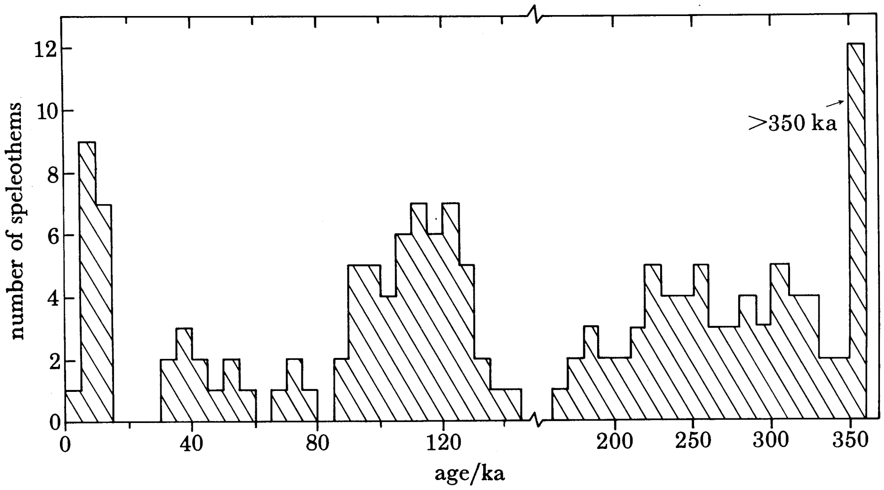

Figure 2. Age–frequency distribution for all speleothems from caves in the Craven district except those showing detrital contamination (seen as $^{230}Th/^{232}Th < 20$). Histogram interval is 5 ka for the period 0–150 ka and 10 ka for > 150 ka (this compression of scale was used because of the exponential increase in analytical uncertainty as ages approach 350 ka). Top and basal ages of a speleothem are used to define limits of growth, and continuous growth between these ages is assumed unless a hiatus is evident in the sectioned sample. In this case, ages above and below the hiatus have generally been used instead.

The above factors apply to most speleothem age–frequency distributions and their effects are best minimized by collection of a sufficiently large sample from the study region. The presence of regional (climate-controlled) maxima and minima in speleothem abundance will then least obscured. The population in figure 2 is the largest that has yet been published for a single, small geographical area.

Palaeoclimate and chronology of northwest England

Interglacial and glacial episodes

As noted, abundant growth of speleothem appears only to occur during warm, interglacial-type climates. The many deposits dated between 0 and 15 ka clearly show that considerable speleothem deposition has taken place since the last glaciation in this area. By analogy, the other intervals of abundant growth in figure 2 are also likely to be of an interglacial nature, although the lower abundance and poorer age precision in the period 170–350 ka may obscure some depositional breaks in the record.

Further indication of the relation between speleothem growth and warm climates is found in the absence of ages in the period 15–30 ka. This interval is well known from ^{14}C chronology to correspond to the period of the last glaciation in northern England (Shotton 1977). A thick ice cover above the caves would preclude vegetational development and inhibit groundwater movement, thus causing all speleothem deposition to cease. A similar period of zero speleothem growth occurred between 140 and 165 ka and this is likely also to have been a full glacial event in the area.

A period of lower growth frequency occurs between 35 and 85 ka with a slight increase in the number of deposits at about 40 ka, suggesting conditions of intermittently cold to mild climate.

Correlation with other climatic records

Our results are compared with other records of inferred climate change in figure 3: speleothem frequency distributions from the Rocky and Mackenzie Mountains of Canada (Harmon *et al.* 1977); the global palaeoclimate records of oxygen isotopic variations in deep sea cores (Shackleton & Opdyke 1973); and eustatic sea level high stands as recorded by coral reef terraces (Mesolella *et al.* 1969; Bloom *et al.* 1974; Fairbanks & Matthews 1978).

Good agreement can be seen between the two speleothem records over the period 0–130 ka, but the depositional break between 140 and 165 ka is not clearly found in the Canadian record. Furthermore, the frequency high between 200 and 250 ka in this work occurs as a frequency low in the Canadian results. These anomalies may be explained simply in terms of sampling procedure or differences in preservation between the two regions. However, there also may be spatial variations of climate intensity during northern hemisphere glacial and interglacial events. For example, Harmon *et al.* (1977) noted that speleothems older than 275 ka in mountainous regions of Canada were appreciably larger, more ornamental and more abundant than those from younger periods. They suggested that this might be evidence to support the concept of a 'great interglacial' older than 200 ka, as first proposed by Penck & Bruckner (1909). Ancient speleothems from northern England, however, show no such relation and in general tend to be smaller than recent deposits, probably because of extensive erosion since formation (most ancient deposits do show erosional features, e.g. discontinuous growth layers, solution pitting). Differences between the two speleothem records can also be attributed to inadequate sample population size and localized geological and hydrological variations which inhibit speleothem formation even though climates may be optimal.

Excellent agreement can be seen in figure 3 between the deep sea core/coral reef data and the northern England speleothem age distribution over the period 0 to about 200 ka. Maximum speleothem growth occurred between 0 and 10 ka and 105 and 135 ka, closely corresponding to the thermal maxima represented by isotope stages 1 and 5 respectively. Low-frequency growth between 35 and 80 ka is consistent with the cooler conditions of stage 4, and the slight warming of stage 3. Relatively high speleothem frequencies correlate with isotope substages 5e and 6c; zero growth during stage 5a may be explained by the fact that this substage may represent the lowest of the high sea stands (Fairbanks & Matthews 1978) and therefore the coolest period.

With one exception (77162), all the speleothems that grew in the period 130–90 ka contain a growth hiatus marked by a thin layer of clastic sediment or an erosion surface (figure 4). While the precision of dating does not allow us to define the episode very precisely, the renewal of growth is dated at about 105 ka. This district-wide, synchronized hiatus is presumably due to a brief climatic shift, such as a cool phase, a period of intense flooding, or a period of regional aridity.

Flooding appears unlikely because 77162 was situated only 2 m above a stream in a main

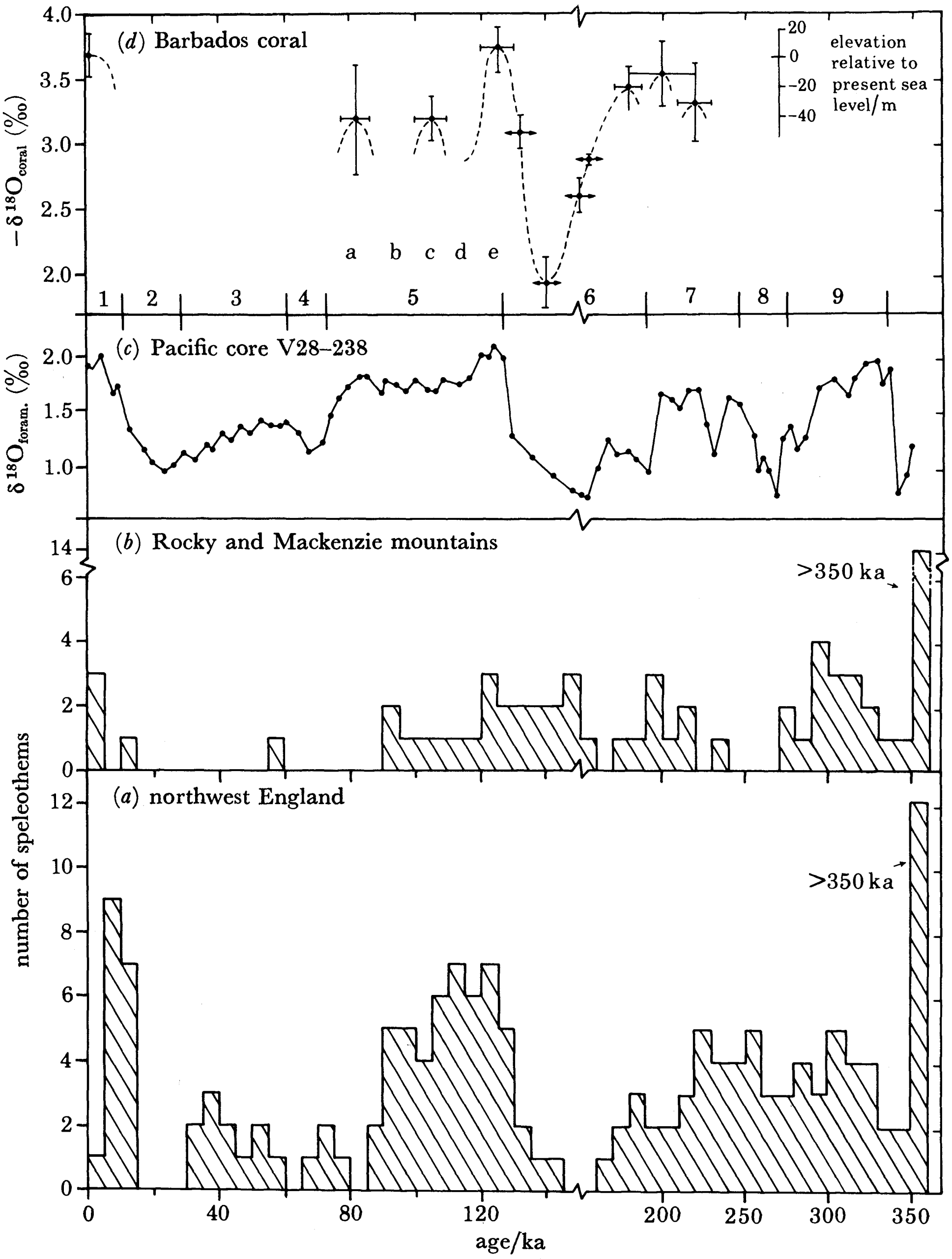

FIGURE 3. Comparison of other palaeoclimate records with the speleothem record ((*a*), from figure 2) from northwest England; (*b*) age–frequency distribution of speleothems from the Rocky and Mackenzie mountains (data from Harmon *et al.* (1977), with use of the same criteria as used in constructing figure 2); oxygen variations in oxygen isotope contents of foraminifera in deep sea core V28–238 (Shackleton & Opdyke 1973), based on the assumption of constant sedimentation rate between dated stage boundaries (Kominz *et al.* 1979); and (*d*) palaeosealevel record from dated coral reef terraces in Barbados, with use of oxygen isotope content of corals as an indicator of relative sea stand (Fairbanks & Matthews 1978).

drainage route and yet grew continuously throughout this period. A cooling in the interval 110–105 ka is independently confirmed by stable isotopic studies of two of these deposits (M.G., unpublished results). The hypothesis of arid conditions would permit isolated speleothems to continue growth, such as 77162, and might correlate with isotope substage 5c; however an arid interglacial stage in northwest England seems climatically unlikely.

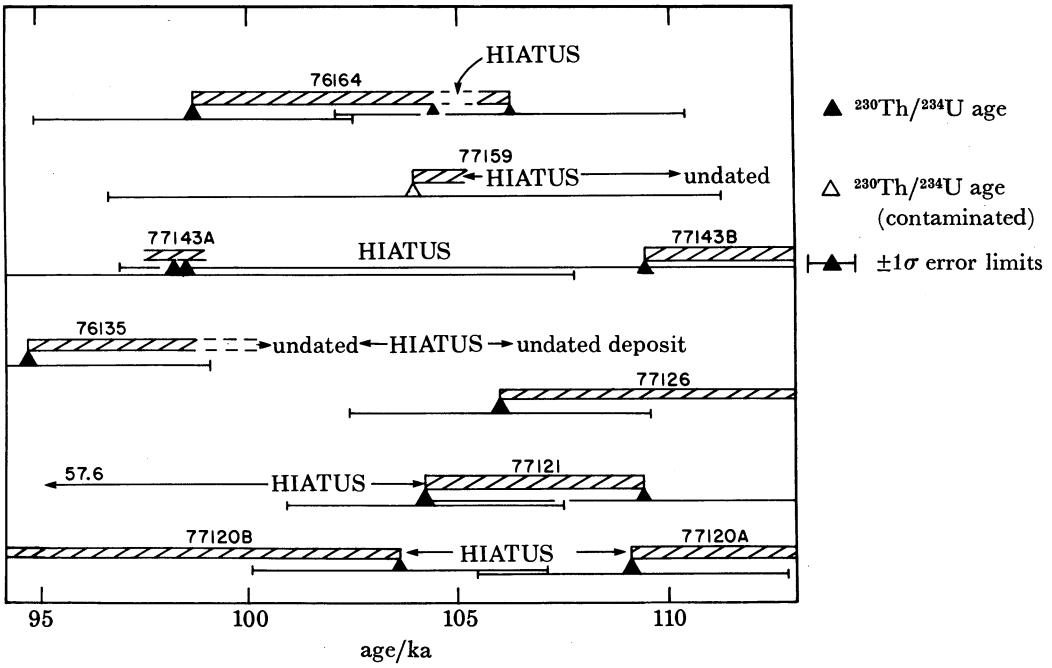

FIGURE 4. Growth characteristics of speleothems showing a hiatus, erosion layer or clastic sediment layer in longitudinal section, at about 105 ka. Solid triangles indicate ages uncontaminated by detrital Th, open triangles show ages with some contamination (where $^{230}\text{Th}/^{232}\text{Th} < 20$). Horizontal bars indicate continuous growth (no visible hiatus present) and horizontal lines are $\pm 1\sigma$ error limits.

Two of the deposits in table 1 have grown for a considerable portion of the period 170 to > 300 ka. Speleothem 79120 (and 79003, an earlier sampling of the same speleothem) is a flowstone approximately 55 cm thick. It grew from about 290 to 200 ka and contains 15 hiatuses marked by layers of clastic sediments. Unfortunately, because of the fairly low U content of this deposit ($0.2–0.4/10^6$), it is difficult to obtain precise ages of these breaks in deposition and hence assess their palaeoclimatic significance. A more interesting deposit is the 30 cm thick, three-piece flowstone 77151 (collected again as a single block, 79151) and an overlying stalagmite, 79158. A total of 15 ages have been obtained for this composite deposit (table 1), 13 of them showing agreement with stratigraphic succession (figure 5, plate 1). A period of continuous deposition occurred from 321^{+37}_{-28} ka to about 260 ka, when growth temporarily ceased. During this hiatus, stalactites were displaced from the cave roof onto the surface of the deposit, and were cemented in place along with detrital sediments when growth recommenced at about 250 ka. The speleothem also suffered dissection and erosion along one edge, which was later covered by calcite. The deposit continued to grow until about 190 ka, when a stalagmite (79158) formed on top of it, finally ceasing to grow at about 170 ka.

The period covered by the growth of this composite speleothem includes isotope stages 9

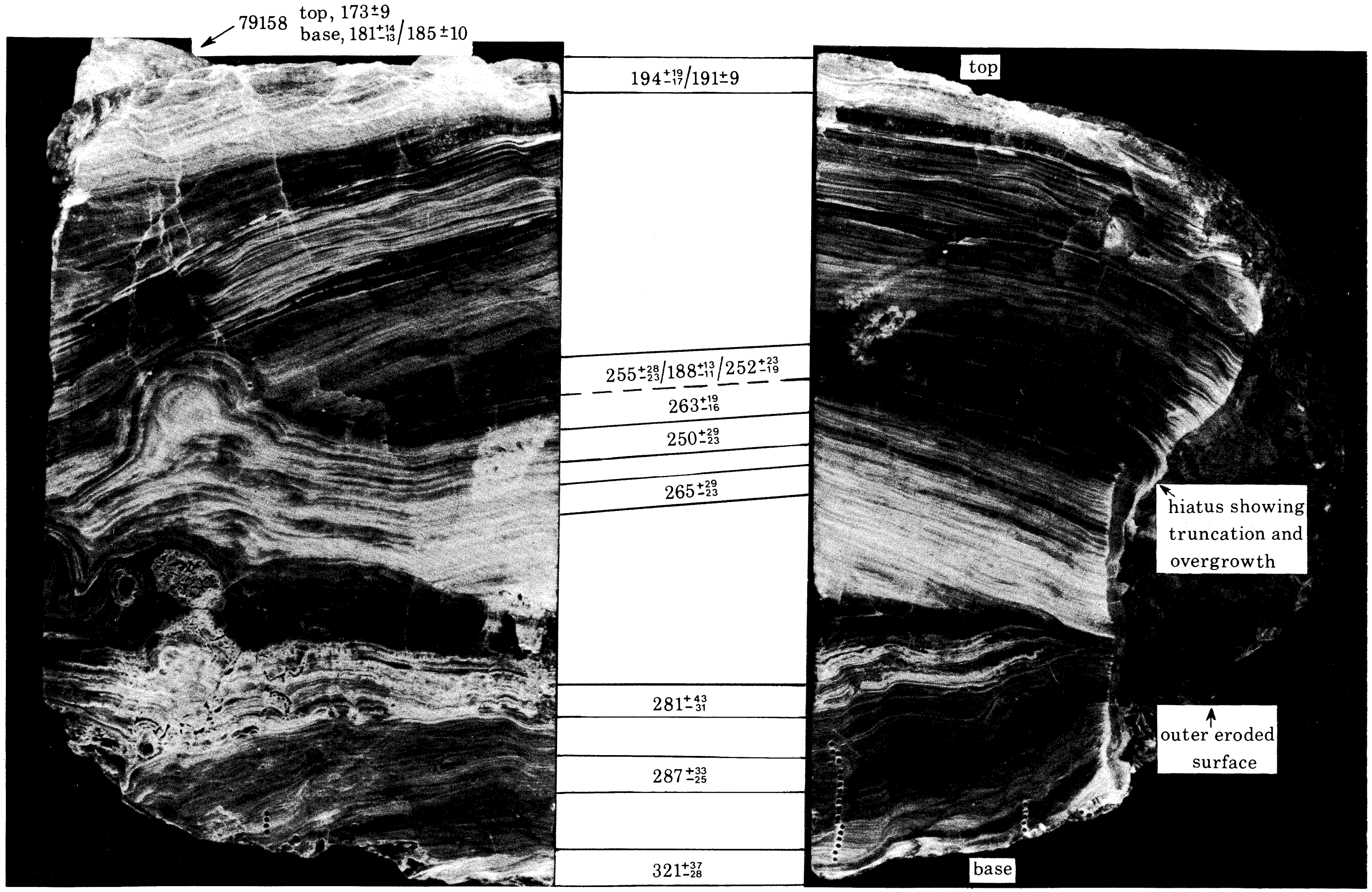

FIGURE 5. Section along the growth axis of flowstone 79151 from Victoria Cave showing ^{230}Th/^{234}U ages and their location (ages determined on the initial sample, 77151, of this deposit are transposed by using visual correlation of growth layers). The longitudinal sections, adjoining at right angles to one another, are shown: the section on the right clearly shows the break in growth and truncation of the lower part, followed by overgrowth, correlated with glacial stage 8 (see text). Other faces of 79151, not shown here, contain broken stalactites at this horizon.

through 7 and the beginning of 6. The break in growth, coupled with erosion and stalactite breakage (frost shatter?) at about 260 ka may be correlated to glacial stage 8. A stable isotope profile for 77151 can be tentatively correlated to the deep sea core palaeoclimatic record (Gascoyne 1980; Schwarcz *et al.* 1981†).

Correlation with the British Quaternary record

(i) *The late Devensian deglaciation*

Radiocarbon dating of deposits stratigraphically related to tills, lake and kettle hole deposits, has yielded a chronology that suggests that maximum ice cover occurred about 18 ka (Shotton 1977; Coope 1977). This is in excellent agreement with marine evidence for maximum global ice volume determined by CLIMAP (1976). Deglaciation of Britain appears to have taken place rapidly over the following 5 ka. England and Wales were ice-free by about 13.5 ka (Buckley & Willis 1970; Lowe 1981) and Scotland was ice-free before 13.0 ka (Bishop & Coope 1977). Several widely spaced localities in Britain have shown the presence of thermophilous beetle assemblages (Coope 1977) marking a sudden amelioration of climate at about 13.5 ka. This event, termed the Windermere Interstadial, lasted for about 1000 a, during which summer temperatures attained those of the present day. At about 12.2 ka climate deteriorated sharply and remained cool until about 11 ka, when temperatures fell again until 10 ka, marking the Loch Lomond Stadial. Arctic tundra climate prevailed in England over this period and ice readvanced from the Central Scottish Highlands (Coope 1977; Sissons 1981). Climate then ameliorated rapidly so that by about 9.5 ka temperatures were comparable to the present. The temperature profile for the late glacial (Flandrian) period, is shown in the upper part of figure 6 (from Coope 1975).

In previous discussions it has been argued that abundant speleothem growth requires both unrestricted groundwater movement and a vegetal cover at the surface to ensure adequate limestone dissolution, i.e. calcite precipitation. The abundance of speleothem growth during the last 10 ka (figure 2) and the absence of speleothems dating from the Late Devensian glaciation were cited as proof of this requirement. It may therefore be possible to obtain an independently dated estimate of the timing of deglaciation and vegetational development in northern England by closer inspection of the basal ages of young speleothems in caves in the region.

The results of 18 age determinations on 14 post-glacial speleothems are shown in figure 6, including data on speleothems from caves in this region by Atkinson *et al.* (1978). Only samples showing negligible detrital Th contamination (i.e. $^{230}Th/^{232}Th > 20$) are plotted.

As noted earlier the bases of stalagmites are especially prone to such contamination. In this study 'true' basal ages of such speleothems were determined by extrapolation from growth rates calculated from near-basal and top ages of the speleothem (table 2). In most cases, the difference between the measured and extrapolated basal ages in very small (< 0.5 ka) because most samples were taken from within 1–2 cm of the base and because the speleothems grew quickly (growth rate ranged between 2 and 18 cm ka^{-1}).

Within the limits of analytical precision, most speleothem growth in northern England in this study did not begin until between 10 and 9 ka. Four speleothems began to grow between

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† In this work, a younger age (about 210 ka) was estimated for the top of the hiatus based on two initial analyses (C-3, C-5, table 1). Subsequent analyses, described above, show the hiatus to be older and to represent a shorter break in deposition at about 260–250 ka. This is now consistent with estimates of the age of stage 8 (Kominz *et al.* 1979). A full, revised isotopic profile for the composite speleothem is in preparation.

12.6 and 10.5 ka and only one speleothem was initiated earlier (76191, 13.6 ka; although this determination carries a relatively large analytical uncertainty, the age of the calcite 5–9 cm above the base is 10.7 ± 0.5 ka, thus supporting an early date for start of growth). These data suggest that there was some renewal of speleothem growth between 13 and 10 ka coeval with the Windermere Interstadial, but abundant growth did not begin until about 10–9.5 ka when a more lush vegetation was established in the area, as shown by pollen analyses of surficial deposits (Mitchell *et al.* 1973). Speleothems that began to form before 11 ka contain no hiatuses

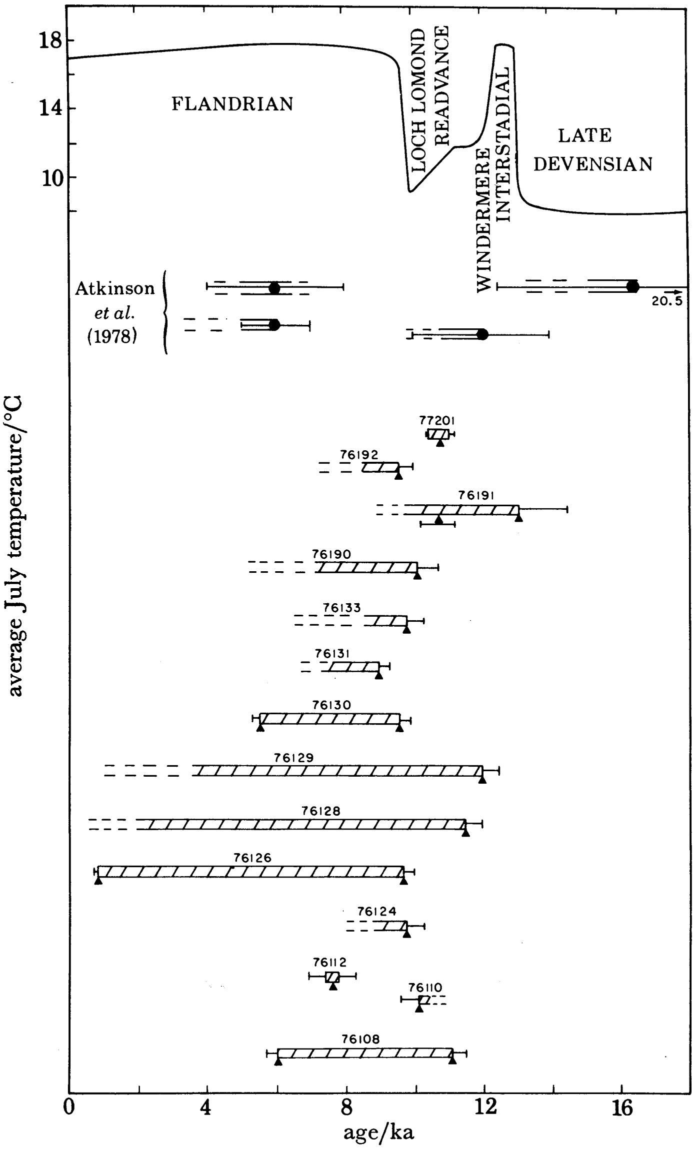

Figure 6. Bar diagram showing determined ages and periods of growth of post-glacial speleothems from caves in the Craven district ($^{230}Th/^{232}Th > 20$ for all ages). Error limits ($\pm 1\sigma$) are shown as horizontal lines. Uncontaminated $^{230}Th/^{234}U$ ages for four speleothems from two caves in this region, by Atkinson *et al.* (1978) are shown above the results of this study, together with post-glacial climatic fluctuations from lowland Britain (from Coope 1975), obtained from beetle data.

in growth, however. It appears that temperatures in northern England were not sufficiently depressed during the Loch Lomond Stadial to prevent seepage groundwater flow.

TABLE 2. SUMMARY OF $^{230}Th/^{234}U$ AGES AND CALCULATED MEAN GROWTH RATES FOR RECENT SPELEOTHEMS FROM CAVES IN THE CRAVEN DISTICT

('True' basal ages (i.e. the age of initiation of growth) are determined by extrapolation from growth rates and distance to the base from the centre of the analysed portion.)

speleothem no.	length / cm	$^{230}Th/^{234}U$ ages/ka		mean growth rate / cm ka^{-1}	distance between basal site and base / cm	extrapolated basal age / ka
		base	top			
76108	30	11.1	6.0	5.5	0–2	11.3
76110	6	n.d.†	10.1	—	—	—
76124	43	9.8	n.d.‡	⩾4.3	0–1	⩽9.9‡
76126	21	9.7	0.8	2.2	0–1	9.9
76128	51	11.5	1.2§	4.8	0–3	11.8§
76129	33	12.0	0.9§	2.6	1–2	12.6§
76130	33	9.6	5.5	7.7	0–3	9.8
76131	32	9.0	n.d.‡	⩾3.5	0–0.5	⩽9.1‡‡
76133	14	9.8	6.5§	4.1	0–0.5	9.9§
76190	89	10.1	5.1§	17.6	0–2	10.2§
76191	31	13.1	9.3§	7.9	3–6	13.6§
76192	30	9.6	n.d.‡	⩾3.1	2–4	⩽10.6‡

Abbreviation n.d. stands for not determined.

† Detritus-rich base.

‡ Top age assumed to be 0 ka; extrapolated basal age is a maximum.

§ Top age shows detrital Th contamination; extrapolated basal age is approximate.

The results obtained here strongly suggest that speleothem deposition did not begin before about 13 ka in northern England, probably owing to the presence of ice and absence of a vegetation cover. This is generally in agreement with temperature estimates obtained from beetle assemblages (figure 6). Abundant speleothem growth appears to have lagged the ice recession by 3–5 ka, probably owing to the need to establish a soil of some maturity above the caves. The results of Atkinson *et al.* (1978) suggest that speleothem deposition in these caves began as early as 16.5 ka (figure 6) although large errors are quoted for these ages (up to ± 4 ka).

(ii) *Devensian palaeoclimates*

The Devensian stage in England was one of generally cold to glacial climate, interrupted by at least two short ameliorations attaining temperate conditions (Coope 1977). Radiocarbon dating of organic deposits from these events has placed them at about 42 ka (the Upton Warren Interstadial) and between 60 and 64 ka (the Chelford Interstadial). Climatic variations for the Devensian are summarized in figure 7 (from Coope 1975) along with speleothem ages for this period.

The total absence of speleothems dated between 13 and 34 ka (table 1, figure 2) has already been correlated with the late Devensian glaciation in northern England. It is interesting to examine the older limit of this period as shown by speleothem ages and ^{14}C ages of surficial deposits. Dates on organic horizons in sediments underlying Devensian till show that most of Britain was ice-free until about 28–30 ka (Shotton 1977). The evidence in figure 7, however, shows that speleothems ceased to grow at about 34 ka. The cessation of growth of the two speleothems active up to this time may be due to changes in local hydrology because they come from the same part of the same cave, although they are morphologically quite different (one is a large stalagmite and the other is part of a pool encrustation). It is possible that cool conditions had prevailed in this area for sufficient time after the end of the Upton Warren thermal maximum that permafrost cut off groundwater supply at about 34 ka. This is consistent with beetle evidence which shows a period of gradual deterioration of climate following the return to cool conditions at about 39 ka (figure 7).

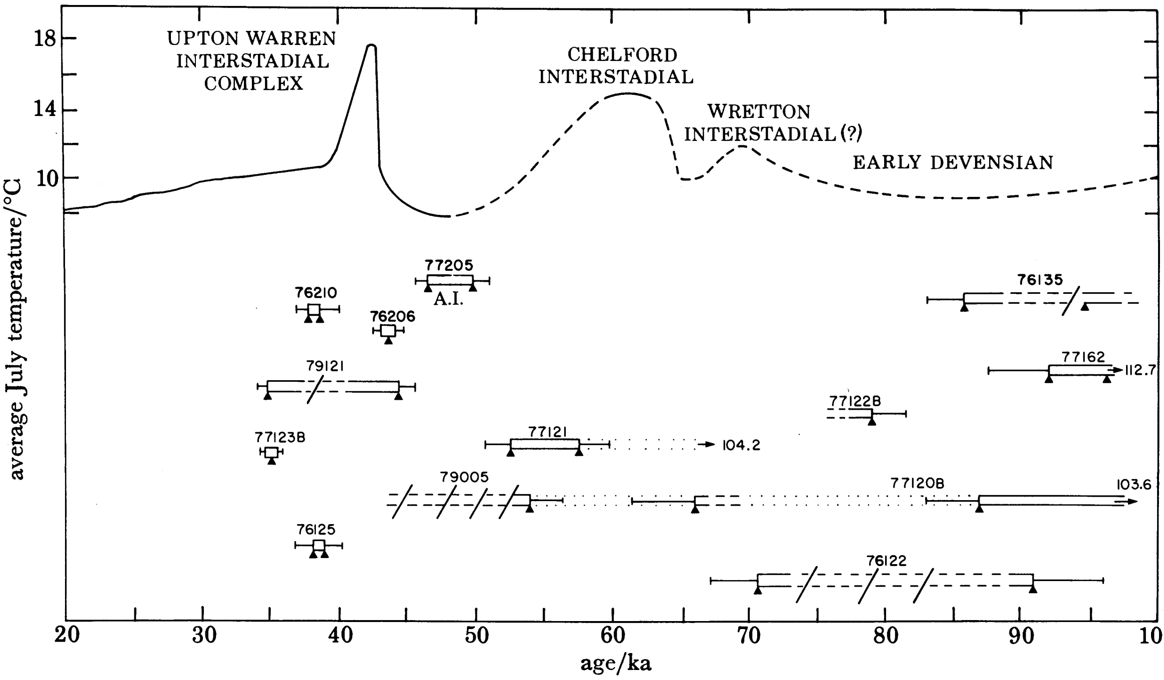

FIGURE 7. Bar diagram showing determined ages and periods of growth for isotope stages 2–4 inclusive (corresponding to the Devensian stage) for speleothems from caves in the Craven district ($^{230}Th/^{232}Th > 20$ for all ages). Error limits ($\pm 1\sigma$) are shown as horizontal lines. Hiatuses evident in sectioned speleothems are shown as diagonal slashes through growth bars. Periods of discontinuous undated growth are represented by dashed lines and extended periods of zero growth by dotted lines. Climatic fluctuations for lowland Britain, from beetle data, are shown above the speleothem data (from Coope 1975). A.I., ages inverted with respect to stratigraphy.

More abundant speleothem growth occurred between 44 and 34 ka. This closely correlates to the Upton Warren Interstadial, a time when the rapidity of climate change caused insect assemblages to reflect temperatures comparable with those of the present day at its peak summer warmth (about 42 ka), while floral and mollusc evidence, coupled with the absence of trees, suggests that much of the period was cooler. Fewer speleothems are found to have grown in the period of 60–45 ka, consistent with the proposal of cold conditions preceding the Upton Warren Interstadial.

No speleothems were found to have grown during the Chelford Interstadial (64–60 ka). Atkinson *et al.* (1978), however, found three speleothems (two from the Mendips, southwest England, and one from Gavel Pot, northern England), that grew at about this time. Unfortunately, large error margins were obtained on two of the ages (±19, ±11 ka).

Sporadic speleothem growth, often marked by depositional hiatuses (e.g. 76122), occurred throughout early Devensian time (*ca.* 90–65 ka). Morgan (1973) contends that most of upland

Britain was experiencing an arctic climate during the early Devensian but without significant glacial activity. The low abundance of speleothems generally supports this proposal, but indicates that deep permafrost and arctic conditions were not continuous during this period.

(iii) *The Ipswichian interglacial*

The last interglacial in the British record is generally known as the Ipswichian and is defined by the floral assemblages at the type section at Bobbitshole, Ipswich. The climatic history of this period is well established from pollen assemblages and faunal remains at many locations in southern England. Remains of large mammals such as narrow-nosed rhinoceros, hippopotamus, lion and giant deer at these sites are generally considered to represent the warmest part of Ipswichian time, zone Ip IIb (Sutcliffe 1960). The possibility that there were two or more warm periods within the last interglacial has been expressed by Sutcliffe (1975), based on relative elevations of faunal sites in the Thames Valley and their varying faunal assemblages. Indirect support for this proposal comes from marine evidence, by the identification of three substages in the last interglacial (described above). However, Stuart (1976) has been able recently to correlate closely floral and faunal data at many of these localities and finds that there is little reason to believe that this large-mammal assemblage was present in England more than once in the last interglacial. If this warm period was in fact a single event in Britain then the question arises as to which isotope substage in the marine record the Ipswichian corresponds.

Several ^{230}Th/^{234}U ages of speleothems encrusting bones of typical Ipswichian mammals from Victoria Cave, near Settle, have resolved this problem (Gascoyne *et al.* 1981). These ages are listed in table 1. Nine out of twelve ages determined for seven flowstones fall in the range 135–114 ka. The remaining three (79000-1, 79001-1 and 79025-1) give younger ages, and on redetermination with use of *younger* calcite (more distant from the bones) gave ages that also fell in the interval 135–114 ka. These results indicate that the Ipswichian Interglacial of the British sequence is correlative with substage 5e of the marine record.

(iv) *The middle Pleistocene*

The results obtained in this study show that speleothems did not grow in northern England during the period 165–140 ka. This interval closely follows the timing and duration of stage 6 in the marine isotopic record (Shackleton & Opdyke 1973), and would appear to represent arctic or full glacial conditions in northern England at this time. If the Wolstonian is regarded in the more general sense as the penultimate glaciation in the British sequence, then these ages clearly define its chronology.

Similar arguments apply to stages older than the Wolstonian. Abundant speleothem growth (allowing for the bias against preservation for older deposits) during the period > 350–180 ka can be correlated to 'warm' isotope stages in the marine records (stages 9 and 7, principally) as previously described. A hiatus in growth in specimen 77151/79151 from Victoria Cave is dated at *ca.* 260–250 ka and correlated with isotope stage 8. This single specimen therefore suggests that the coldest conditions in the period, 350–180 ka, in the Craven district occurred at 260–250 ka. Any correlation between these data and the middle to early Pleistocene of the British record is hindered because of the lack of an absolute chronology for the Hoxnian interglacial and earlier stages, and by the absence of other conclusive maxima and minima in the speleothem record as it stands at the present time.

Summary and conclusions

In this study, the ^{230}Th/^{234}U dating method has been found to give precise and accurate ages when applied to pure calcite speleothems, because:

(i) they contained sufficient U ($>0.1/10^6$) to give good counting precision;

(ii) most samples contained very little detritus and and associated ^{230}Th;

(iii) speleothems were usually massive and impermeable;

(iv) no evidence of recrystallization was found and very few samples showed evidence of post-depositional leaching.

The age distribution frequency based on 182 analyses of 87 speleothems shows periods of enhanced and zero growth. By analogy with the abundant growth of post-glacial deposits, enhanced growth is correlated with interglacial conditions.

Periods of abundant growth are 0–13, 90–135 and 170 to > 350 ka, which can be correlated with isotope stages 1, 5 and 7–9 respectively. The period 0–13 ka is correlated with the late Devensian deglaciation and Flandrian stage in the British Quaternary sequence. The predominance of basal ages of 9.5–10 ka closely correlates with the start of the Flandrian interglacial as shown by floral studies and ^{14}C dates. Some earlier speleothems (13–11 ka) may be correlated with the Windermere Interstadial, a rapid climatic amelioration commencing about 13 ka. They did not cease growth during the Loch Lomond Stadial at 10–11 ka.

Limited growth from 35 to 90 ka is correlated with isotope stages 3 and 4 and is evidence of the cold but non-glacial conditions of middle to early Devensian palaeoclimates. The slight increase in speleothem abundance from 35 to 45 ka compares with the Upton Warren Interstadial complex (maximum warmth at 42 ka), but no evidence of climate amelioration between 60 and 64 ka is seen that will correspond with the Chelford Interstadial.

Abundant speleothem growth from 90 to 135 ka is correlated with the warm conditions during isotope substages 5c and 5e but little growth is found during substage 5a (*ca.* 82 ka). Dating of flowstones associated with an Ipswichian mammal fauna at Victoria Cave has shown that the Ipswichian at this locality is correlative only with substage 5e in the marine record and terminates before stage 5d. The break in growth of many speleothems at about 105 ka may be an indication of rapid cooling or aridity but this event is not observed in the marine record.

The periods 13–35 and 140–165 ka are marked by a complete absence of speleothem ages and may be correlated with marine isotope stages 2 and 6 respectively. The former period has been well established by ^{14}C dating of surficial deposits to be the late Devensian glaciation, when ice covered most of the Craven district and prevented speleothem formation in caves. The period 140–165 ka is shown, by analogy, to have been a time of extensive ice cover and/or frozen ground. This corresponds in time with isotope stage 6 and may be identified with the Wolstonian stage, if the deposits at Wolston in the Midlands are indeed from this glaciation. Despite the destructive effects of flood, glacial injecta, frost, etc., many speleothems from the period 170 to > 350 ka have been found to survive in caves in the Craven district. Their frequency distribution is again interpreted to show preferred growth during interglacial phases, but larger error limits in the dating do not permit as precise determination of these phases as in the more recent deposits. The clustering of ages is related to intervals in isotopes stages 7 and 9. A very prominent erosional break at 250–260 ka in speleothem 77151/79151 is tentatively correlated with the cold or glacial stage 8.

A more exact chronology of the middle Pleistocene, with extension into early Pleistocene times (> 350 ka), can only be obtained by using U-rich speleothems, supplemented with other dating techniques such as electron spin resonance or thermoluminescence methods.

The many cavers and friends who assisted the first author in the collection of speleothems from Craven caves are gratefully acknowledged. This research was financially supported by the Natural Sciences and Engineering Research Council of Canada and the Department of Energy, Mines and Resources, Canada. Ada Dixon and Marija Russell assisted in the laboratory and A. G. Latham and R. R. Glover have given helpful discussions during the early stages of this work. This is contribution number 127 of the McMaster Isotopic, Nuclear and Geochemical Studies Group.

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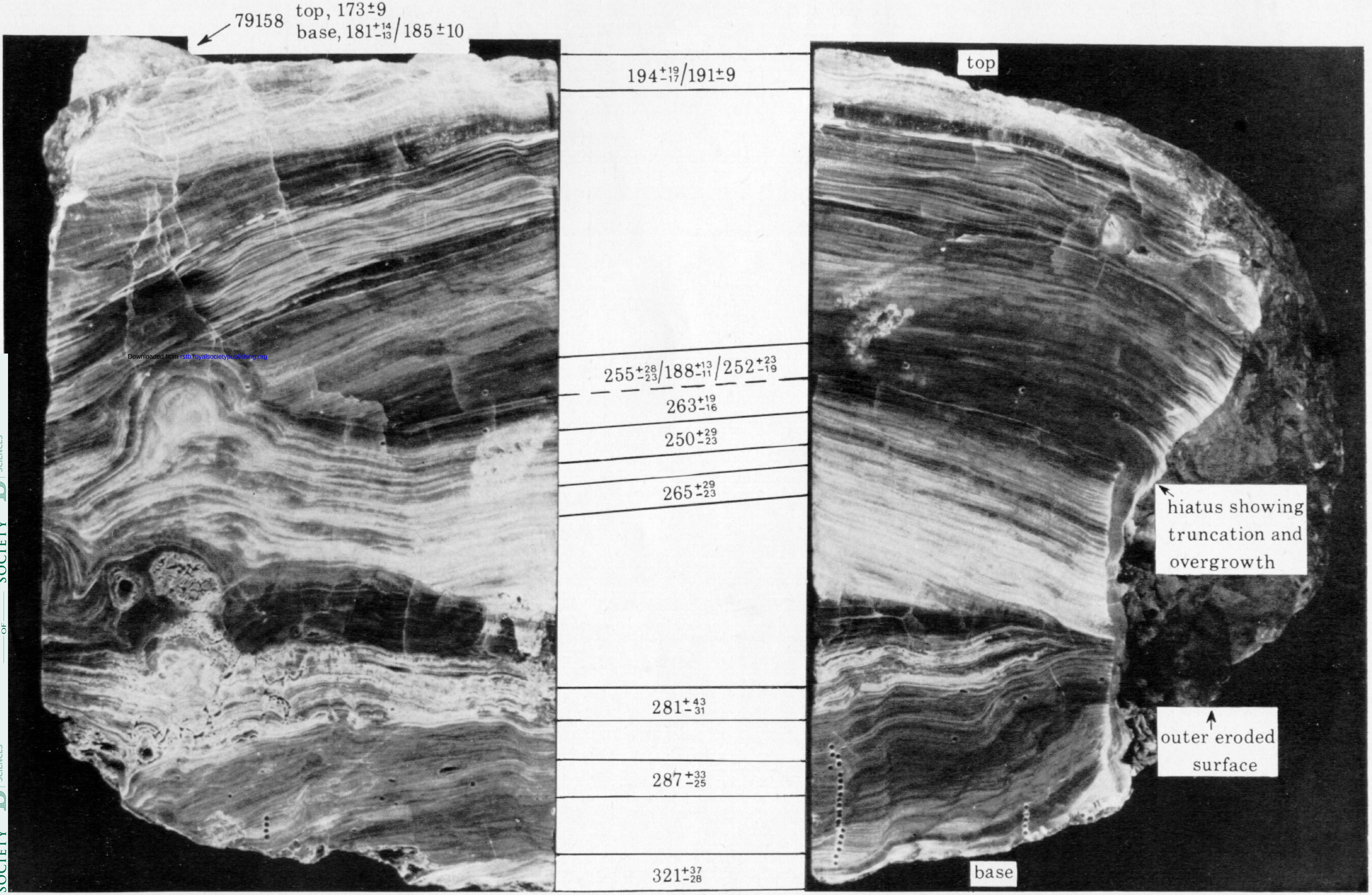

IGURE 5. Section along the growth axis of flowstone 79151 from Victoria Cave showing ^{230}Th/^{234}U ages and their location (ages determined on the initial sample, 77151, of this deposit are transposed by using visual correlation of growth layers). The longitudinal sections, adjoining at right angles to one another, are shown: the section on the right clearly shows the break in growth and truncation of the lower part, followed by overgrowth, correlated with glacial stage 8 (see text). Other faces of 79151, not shown here, contain broken stalactites at this horizon.