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Late Quaternary speleothem pollen in the British Isles

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ABSTRACT: As with many terrestrial areas, the British Quaternary sequence is characterised by incomplete, fragmentary records, whose correlation is based on stratigraphic or biostratigraphic techniques due to the lack of radiometric ages beyond the ~40 kyr limit of ^{14}C dating. Speleothems (secondary cave calcite deposits) offer a significant advantage over many sources of palaeoenvironmental information; they can be dated to a high precision and accuracy by uranium-thorium (^{238}U-^{230}Th) thermal ionisation and inductively coupled plasma (ICP) mass spectrometry in the time period back to 500 kyr. They may also contain sufficient well-preserved pollen representative of contemporary vegetation above the cave to allow palaeoenvironmental reconstruction. This study adopts the novel approach of combining pollen and thermal ionisation mass spectrometric (TIMS) U-Th dating of British speleothems to produce well-constrained palaeoenvironmental records. We report for the first time precisely dated records of pollen assemblages from speleothems suggesting the presence of thermophilous arboreal species in phases previously considered to have been consistently cool or cold and devoid of trees. Copyright © 2007 John Wiley & Sons, Ltd.

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KEYWORDS: speleothem; pollen; U-Th dating; British late Quaternary.

Introduction

In contrast to the long, orbitally tuned pollen records of northern and central Europe (e.g. La Grande Pile (Woillard, 1978; de Beaulieu and Reille, 1992) and Les Echets (de Beaulieu and Reille, 1984) in France and Oerel in Germany (Behre and van der Plicht, 1992), the late Pleistocene biostratigraphy of the British Isles is characterised by its lack of continuous, well-dated records, due largely to the incomplete nature of the deposits. The available biostratigraphical data are mostly from fluvial sediments, and owing to the nature of the deposition in the shifting sequences of braided rivers, individual deposits may be laid down rapidly and normally have unconformities above and below them. Thus the lenses of fine sediment represent only brief episodes within long periods of time, and it may be impossible to judge the completeness of the depositional record (e.g. Simpson and West, 1958; Coope *et al.*, 1961; Morgan, 1973; Bryant *et al.*, 1983; Maddy *et al.*, 1998). Further difficulties in correlation arise from the occurrence of reworked fossils in fluvial sediments. Added to this, early Devensian (Weichselian) deposits are beyond the limits of the ^{14}C technique, making precise dating difficult, with correlation between deposits in the British Isles and northwest Europe largely being undertaken on comparability of sequences or events rather than within a genuine chronology. As a consequence of this lack of a secure geochronology, the occurrence of thermophilous trees at times other than the recognised warm forested periods may go totally undetected.

There is therefore a need for palaeoclimate/palaeoenvironmetal records from the early Devensian of the British Isles that can be constrained by high precision ages. Speleothems (stalagmites, stalactites and flowstones – secondary mineral deposits in caves) can grow over extended periods of time and have the capability to provide terrestrial palaeoclimate information (e.g. Bar-Matthews *et al.*, 1999, 2003; McDermott *et al.*, 2001; Baldini *et al.*, 2002). They also have the potential to enhance biostratigraphical records, as it has been demonstrated that well-preserved pollen, representative of surface vegetation, may be extracted from speleothems in sufficient quantities to allow reconstruction of palaeovegetation (e.g. Carrión *et al.*, 1999, 2003; and see review by McGarry and Caseldine, 2004). However, the major advantage speleothems have over many other palaeoclimate records is that they may be dated radiometrically, using high-precision thermal ionisation mass spectrometric (TIMS), and more recently ICP-MS, uranium-thorium (U-Th) dating. This allows a precise absolute geochronology to be established effectively an order of magnitude further back in time than is possible by radiocarbon dating of organic sediments.

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In this study we report for the first time palynological and radiometric geochronological data combining pollen and TIMS U-Th analyses of British speleothems. These demonstrate the possible presence of previously unidentified thermophilous species in the British Isles between Marine Isotope Stages (MIS) 5e and 1, identified by the improved geochronology TIMS U-Th dating provides for these new palynological records.

Sites and methods

Sites

Previously dated flowstone samples from two caves in Yorkshire and Lancashire, Stump Cross Caverns and Lancaster Hole, respectively, were selected for this study. They allowed selection of precisely dated material which spans much of the Devensian period. Furthermore, the large size of the available samples allows sufficiently large subsamples for pollen analysis to be obtained. This material was supplemented by previously undated speleothem samples from the same systems with additional samples from Holcombe Quarry.

Lancaster Hole

Lancaster Hole cave is located in Lancashire in northwest England (Fig. 1). It is part of the Ease Gill Caverns system on Casterton Fell, Lancashire (SD 664807). The cave is at an altitude of 294 m a.s.l. and has developed in the White Scar Limestone, overlain by till. The till is in turn overlain by peat, and the area is presently covered by upland bog vegetation, although *Quercus*, *Fraxinus*, *Betula* and *Corylus* may be found in local valley woodland.

Flowstone LH-90-4/5/6 was collected from the start of the Collonade Passage, an abandoned high-level passage about 35 m below the surface and within 300 m of the Lancaster Hole entrance. The entire flowstone sequence, as analysed by Baker *et al*. (1995) was 30.5 cm in length, consisting of seven growth phases of which the lowest six were analysed in this study, separated by layers of sediment less than 1 mm thick. It was not actively forming when it was collected: further details can be found in Baker *et al*. (1995, 1996).

Sample LH-90-16 is a previously undated detrital block that may have fallen from higher levels, taken from Stop Pot streamway, about 1 km from the Lancaster Hole entrance. This sample is a 10.5 cm thick flowstone sequence composed of crystalline calcite, which is pale in colour and contains a number of darker bands. There is one distinctive hiatus 7 mm from the base, below which material was not analysed, as there was not sufficient calcite available from the lower unit for pollen analysis.

Stump Cross Caverns

Stump Cross Caverns are located on Greenhow Hill, between Wharfedale and Nidderdale, Yorkshire in northwest England (Fig. 1) at an altitude of 361 m a.s.l. (SE 089634). This cave forms part of the Stump Cross/Mungo Gill cave system, and has developed in an outlier of the Upper Carboniferous Great Scar Limestone in the Greenhow Anticline. It is situated 45 km west-southwest of Lancaster Hole and at an altitude 67 m higher. The cave is overlain by discontinuous till which is covered by isolated patches of peat and the vegetation of the area is dominated by typical moorland communities comprising ericaceous taxa, sedges and grasses. Again isolated woodland is present in the area comprising *Fraxinus*, *Betula* and *Corylus*.

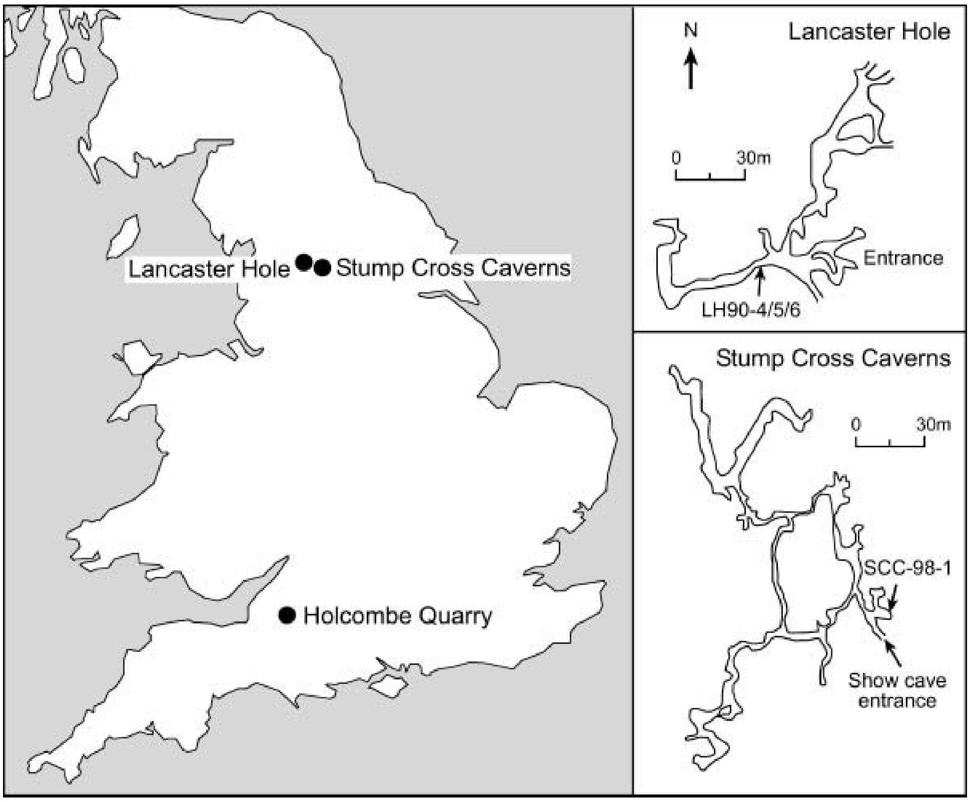

Figure 1 Location map and cave survey showing exact sampling locations

The artificial entrance to the cave goes through about 1 m of till, which varies in thickness over the hillside and 1–2 m of limestone fault breccia, and then intersects a solution fissure that continues to about 16 m below the surface to the level of the show cave. The cave was originally discovered by Victorian lead miners and was artificially drained; the active cave stream is 30 m below the show cave level, but may rise up to 12 m after heavy rain (Sutcliffe *et al.*, 1985).

Sample SCC-98-1 is a ~18 cm section of a stalagmite that was collected from the Coal Chute (see cave survey in Fig. 1). It was not found *in situ*, but as a large detrital block which had been moved a short distance during show cave extension. It comprises clean crystalline calcite with no obvious hiatuses.

Holcombe Quarry

Holcombe Quarry is located in the Carboniferous Limestone of the eastern Mendip Hills, Somerset (Fig. 1). The natural vegetation of the Mendips is dominated by *Quercus*, *Fraxinus*, *Fagus*, *Ulmus glabra* and *Tilia* woodland. Specifically, the limestone slopes are dominated by *Fraxinus* and *Quercus* and the plateaux have well-developed *Quercus* woodlands along with numerous calcicolous shrubs and herbs.

The flowstone collected from this site was a detrital block from shattered caves intersected by quarrying and therefore its original location, depth below surface or distance from surface opening is unknown. HQ-90-6 is a 16 cm thick flowstone with five distinctive darker bands. It is quite porous in parts.

Methods

Pollen was extracted from the speleothems using a technique modified after Bastin (1978) and Faegri and Iversen (1975); a full description of the method may be found in McGarry and Caseldine (2004). Care was taken to avoid any obviously porous or recrystallised calcite. Taking into account the low pollen concentrations obtained by previous workers, subsamples of the four flowstones and one stalagmite ranged in size from ~30 g to >1 kg. Generally samples were less than 5 cm thick. This sample size represents variable time periods, depending on growth rate, but assuming a growth rate of ~0.05 to 0.2 mm yr^{-1}, the range observed in temperate speleothems today (Baker *et al.*, 1998), this can be assumed to represent 250–1000 years of growth in most of the samples analysed. It was expected that vegetation changes both within and between warm periods could be detected at such a sampling resolution. Further details regarding sample sizes and pollen yields may be found in Table 1. As part of the procedure, blocks of equivalent size of pure calcium carbonate were processed with the speleothem to test for any laboratory contamination.

TIMS U-Th dating was carried out on a Finnigan MAT 262 mass spectrometer at the Open University (Edwards *et al.*, 1986/1987). Full isotopic details are given in Table 2a and Baker *et al.* (1995).

Table 1 Sample details

Sample ID	LH-90-4 (a)	LH-90-4 (b)	LH-90-5 (a)	LH-90-5 (b)	LH-90-5 (c)	LH-90-6 (a)	HQ-90-6 (4)	HQ-90-6 (3)	HQ-90-6 (2)	HQ-90-6 (1)	LH-90-16 (4)	LH-90-16 (3)	LH-90-16 (2)	LH-90-16 (1)	SCC-98-1 (a)	SCC-98-1 (b)	SCC-98-1 (c)	SCC-98-1 (d)
Sample size (g)	348.3	567.8	268.3	373.7	360.0	82.0	394.5	707.3	1742.5	1309.3	242.6	195.7	191.4	613.4	32.1	98.59	173.1	209.8
No. grains	114	176	218	132	138	138	25	45	50	660	168	110	44	243	89	275	432	17
Pollen conc. (grains g^{-1})	2.39	1.10	5.45	4.00	2.27	20.3	0.33	0.13	0.07	1.70	2.18	2.24	1.60	2.92	16.36	53.47	7.66	1.56

Results

U-Th dating

Full details of the dates and isotopic compositions obtained in this study are presented in Table 2a. Table 2b shows the dates

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Table 2a TIMS U-Th dates and isotopic details of the samples dated in this study

Sample	^{238}U (ppm)	^{234}U/^{238}U [act]	^{230}Th/^{234}U [act]	^{230}Th/^{232}Th [act]	Age (kyr) (corrected*)
LH-90-16 Top	0.702 ± 0.001	0.829 ± 0.002	0.576 ± 0.004	366.4 ± 2.7	97.6 ± 1.2
LH-90-16 Mid2	0.511 ± 0.000	0.798 ± 0.001	0.577 ± 0.001	240.6 ± 0.7	$99.0^{*} \pm 1.0$
LH-90-16 Base	1.239 ± 0.003	0.805 ± 0.002	0.591 ± 0.003	19.8 ± 0.1	$99.8\ +0.1/-3.0$
HQ-90-Mid 1	0.028 ± 0.000	1.096 ± 0.006	0.465 ± 0.004	86.5 ± 0.7	67.4 ± 1.0
HQ-90-6 Mid 2	0.035 ± 0.000	1.115 ± 0.005	0.495 ± 0.003	47.9 ± 0.2	73.3 ± 0.7
HQ-90-6 Base	0.053 ± 0.000	1.154 ± 0.005	0.495 ± 0.003	43.9 ± 0.3	72.9 ± 0.7
SCC-98-1 Top	0.176 ± 0.000	1.850 ± 0.005	0.089 ± 0.000	9.4 ± 0.1	$9.2^{*}\ +0.2/-0.8$
SCC-98-1 Mid	0.202 ± 0.000	1.894 ± 0.004	0.086 ± 0.000	57.0 ± 0.2	9.7 ± 0.03
SCC-98-1 Base	0.283 ± 0.000	2.039 ± 0.006	0.101 ± 0.001	9.6 ± 0.1	$10.6^{*}\ +0.3/-0.9$

* The detrital calculation corrects for both U and Th contribution to the sample. It is assumed that the detrital component is in secular equilibrium and that all ^{232}Th present is of detrital origin. A value of 3.8 ± 1.9 is assumed for the ^{232}Th/^{238}U molecular ratio in the detritus.

obtained by Baker *et al.* (1995). Sample SCC-98-1 grew in one growth phase from 10.6 +0.3/−0.9 kyr to 9.2 +0.2/−0.8 kyr, but these dates do not represent the beginning and end of a growth phase as the sample was broken. LH-90-16 was dated to have grown from 99.8 +1.0/−3.0 kyr to 97.6 ± 1.2 kyr, the top and bottom dates overlapping within error with a middle date of 99.0 ± 1.0, indicating that the sample grew rapidly. The similarity of the ages obtained to those from LH-90-5A (103.1 ± 1.7 kyr) suggests that both samples represent the same phase of speleothem growth. The base of sample HQ-90-6 was broken; therefore the bottom date of 72.9 ± 0.7 kyr does not indicate the initiation of a phase of growth. This flowstone grew rapidly, as can be seen from the two middle dates of 71.2 ± 0.5 kyr and 67.4 ± 1.0 kyr obtained on the base of units 3 and 2, respectively. The top unit of this sample (4) was quite porous, and it is possible that it has been leached as indicated by three analyses with ^{230}Th/^{234}U >1. This sample appears to represent a phase of speleothem growth not present in the Lancaster Hole sequence (Table 2b), although similar ages are reported from Stump Cross Caverns by Baker *et al.* (1996).

Speleothem pollen spectra

The two main transport mechanisms for pollen in speleothems are air currents and percolation waters, and a number of studies has been carried out on each. The airborne pollen influx into caves and the modern surface pollen rain have been reported to be encouragingly similar (Coles, 1987; Burney and Burney, 1993; Coles and Gilbertson, 1994). However the recovery of pollen from speleothems up to 600 m from a cave entrance in Belgium (Bastin, 1978) provides good evidence for transport by percolation waters. Van Campo and Leroi-Gourhan (1956) reported that little pollen is carried by draughts beyond 10 m from the cave entrance. Analyses of the pollen content of actively forming speleothems when compared with contemporary surface pollen (from Tauber traps, moss polsters and pond sediments) demonstrate that the speleothem pollen spectra were characteristic of the pollen rain outside the cave (Bui-Thi-Mai and Girard, 1988; Burney and Burney, 1993). Pollen has been extracted from Holocene and late Quaternary speleothems (Brook *et al.*, 1990; Lauritzen *et al.*, 1990; Burney *et al.*, 1994; Brook and Nickmann, 1996; Baker *et al.*, 1997). These workers recovered pollen in the range of <1–30 grains g^{-1} CaCO$_3$. They also found the pollen to be well preserved, and the pollen records in the speleothems agreed with other local contemporaneous surface records, where available.

Tables 3a and b demonstrate that the pollen concentrations are typical of those presented by previous workers (average concentration 8 grains g^{-1} CaCO$_3$). Taphonomic influences obviously have a part to play in determining pollen concentrations, but not necessarily to the detriment of the representativeness of the spectra, as discussed in McGarry and Caseldine (2004). As the amounts of pollen getting into the speleothem per year, and hence the concentrations are so low, it is likely that it is those species which are most abundant on the surface that are most likely to be represented in the speleothem.

Details of the pollen extracted from each speleothem are presented in Tables 3a and b. Among the trees and shrubs (Table 3a), *Pinus* is the most abundant in all samples, ranging from ~50% in LH-90-4/5C and SCC-98-1, to a minimum of 12% in LH-90-16. This high frequency is to be expected as *Pinus* is a highly productive and anemophilous taxon. The second most common taxon is *Quercus*, again present in all samples and at its highest (~20%) in LH-90-4/5C and SCC-98-1, and lowest in samples LH-90-16, LH-90-5A and HQ-90-6. *Fraxinus* is highest (13%) in HQ-90-6, and its presence in this and other samples—despite it having low pollen productivity and a tendency for under-representation in spectra—would suggest it was local to the sites, as might be expected on calcareous substrates. LH-90-6 shows elevated levels of *Alnus*, *Corylus* and *Hippophaë*. The presence of two grains of *Abies* in LH-90-16 (3) is significant as this is a particularly large grain (100 μm), indicating that pollen size is not a biasing factor. Non-arboreal pollen are presented in Table 3b and are dominated by open-ground taxa. The presence of aquatics such as *Myriophyllum* is indicative of waterlogging locally, while Ericales, Cyperaceae and *Sphagnum* indicate conditions may have been wet enough to allow development of peat or boggy ground.

In all samples the pollen was well preserved, with the exception of two subsamples. In HQ-90-6 (1) 17% of the *Pinus* grains were broken, and about half of each of the *Quercus*, *Corylus* and Poaceae grains showed signs of degradation. In these cases it would appear that taphomomic conditions prior to entrapment in the calcite were not conducive to good pollen preservation. This is further supported by the very high numbers of the extremely resistant taxon Lactuceae (63% of the pollen) grains present. This finding is in accord with the poor condition of the calcite comprising this unit owing to leaching which as discussed earlier, precluded its dating. The pollen in the basal unit (4) of LH-90-16 comprises 8% degraded grains, with *Alnus*, *Corylus*, *Hippophaë*, Poaceae and *Rumex* as well as *Quercus* being particularly affected. This would suggest that while the well-preserved pollen in the upper levels was transported rapidly to the speleothem, that in the bottom level may have

Table 2b Speleothem dates from Baker *et al*. (1995)

Sample	LH-90-4 Base	LH-90-4 Mid	LH-90-4 Top	LH-90-5A	LH-90-5B Base	LH-90-5B Mid	LH-90-5B Top	LH-90-5C Base	LH-90-5C Mid	LH-90-5CMid 2	LH-90-5CTop	LH-90-6ABase	LH-90-6ATop
Age	132.8 ± 2.4	125.6 ± 3.3	127.7 ± 2.1	103.1 ± 1.7	84.9 ± 1.3	84.4 ± 0.6	83.6 ± 0.9	58.7 ± 1.0	57.1 ± 0.9	57.7 ± 1.6	56.8 ± 1.1	51.9 ± 1.2	49.2 ± 0.9

been exposed to aerobic conditions for a longer period of time, allowing degradation to take place. All other pollen samples were well preserved, with little evidence of any grain breakage, degradation or corrosion, and there was no particular bias to resistant taxa. We therefore believe that these pollen assemblages are representative of those entrained in the speleothem drip water at the time of deposition and that syn-transport or post-depositional changes in the pollen spectra have not significantly affected the assemblages, implying a lack of storage within the hydrological system.

Summarising our speleothem pollen results for different MIS, the pollen spectrum from LH-90-4-A/B, dated to the early part of the Last Interglacial (MIS 5e) (Baker *et al*., 1995) is dominated by *Pinus* and *Quercus*, with other thermophilous species of note being *Alnus*, *Fraxinus* and *Corylus*. The pollen spectrum in speleothem LH-90-4 appears to correlate with the early temperate phase of this interglacial (Phillips, 1974; West, 1980*;* Gao *et al*., 2000*)*, as would be expected from the U-series ages. *Quercus*, *Corylus*, *Fraxinus* and *Alnus* have developed, but the absence of taxa found later in the interglacial, *Ulmus*, *Abies*, *Corylus* and *Carpinus*, support the U-series ages for deposition at the beginning of MIS 5e. In MIS 5c and 5a, the palynological data from the speleothem dated to these interstadials (LH-90-5A and B, LH-90-16) indicate the existence of a significant number of relatively thermophilous woodland species, in particular *Pinus* and *Quercus*. This is maintained further into the last glaciation. At ~73 kyr, HQ-90-6 presents pollen evidence of *Quercus* and *Fraxinus*. Following an assumption of a local pollen source, this would mean that trees of these species were present in the Mendip Hills in southern England. At ~58 and ~51 kyr, further north at Lancaster Hole (LH-90-5C/6A), *Quercus* and *Pinus* pollen are found, although *Fraxinus* is now absent. Finally, early Holocene speleothem deposition of SCC-98-1, deposited between ~10.6 and 9.2 kyr, contains *Quercus* and *Pinus*, together with some *Corylus*, as might be expected from a smoothed low-concentration pollen record covering this early period from the Holocene.

Discussion

There is obviously a considerable discrepancy between some of the dated speleothem pollen records presented here and the existing late Quaternary pollen biostratigraphy of the British Isles. There is good agreement for MIS 5e and 1, especially given the smoothed record of pollen deposition in speleothem because of their slow growth, but the thermophilous species/taxa found in speleothems dated to MIS 5c, 5a, 4 and 3 do not have obvious comparators in the conventional pollen sequences of the late Pleistocene. Correlations of speleothem and surface pollen records during MIS 5-3 are problematic for a number of reasons: the lack of adequate dating for the surface sites; the speleothem records are integrating hundreds (possibly thousands) of years of environmental history; it is likely that speleothem pollen records are biased to near-entrance species; and the paucity of analogous pollen data from calcareous sites in the fossil record, especially ones that can be reliably dated to the same periods. Most such data are conventionally obtained from non-calcareous wetland locations, which will produce very different records. Much uncertainty exists as to the sort of communities that could survive in limestone regions, and present communities on limestone do not have obvious sub-fossil comparators, thus it is not possible to say with certainty what existed in such environments at specific times in

Table 3a Summary of speleothem pollen data. See Table 3(b) for actual counts

Age (kyr)	Sample	Most common taxa (trees/shrubs) (%)							Open ground taxa	Less common taxa
		Betula	*Pinus*	*Quercus*	*Alnus*	*Fraxinus*	*Corylus*	*Hippophaë*		
10–9	SCC-98-1(AD)	0.6	45.7	21.7	0.4	0.3	0.9	1.7	27.6	0.1
51	LH-90-6(A)		28.2	13.7	<0.01		<0.01	<0.01	55.7	0.72
58	LH-90-5(C)		49.2	23.9					26.8	
73	HQ-90-6(4-2)	2.5	38.9	5.9		13.5	2.5	2.5	33.3	
84	LH-90-5(B)	0.7	28.0	14.3		0.7			55.3	
99	LH-90-16(3-1)	1.0	14.8	7.1	4.0	1.7	7.5	2.7	60.2	1
103	LH-90-5(A)		30.2	5.0		0.4	0.9	0.9	62.3	
132–127	LH-90-4(A/B)	0.3	51.3	19.3	0.6	1.7	0.6		25.8	0.3

Table 3b Pollen counts for all taxa

MIS	5e	5c	5c	5a	4	3	3	1
Sample/Pollen	LH-90-4 (A/B)	LH-90-5 (A)	LH-90-16 (3-1)	LH-90-5 (B)	HQ-90-6 (4-2)	LH-90-5 (C)	LH-90-6 (A)	SCC-98-1 (A-D)
Betula	1		4	1	3			5
Pinus	149	66	61	39	48	68	40	382
Quercus	56	11	29	19	8	33	21	191
Alnus	3		16				1	5
Fraxinus	5	1	7	1	16			3
Corylus	2	2	30		3		1	8
Hippophaë		2	2		3		1	14
Picea	1							
Salix							1	
Ulmus			1					
Abies			2					
Ilex								1
Sorbus			1					
Poaceae	20	15	47	26	23	18	22	69
Cyperaceae	2	3	6	1				9
Calluna			11					
Ericales	9	20	42		1			2
Artemisia			1					1
Aster type	3	3	16	1			2	8
Lactuceae		3	9		3			4
Polygonum					1			
Caryophyllaceae		1	1					
Epilobium		1						
Filipendula	3		7			2	3	5
Onobrychus			1					
Labiatae	1							
Ranunculus	1	1	30	3		2		8
Campanula			10					2
Rumex	27	30	1	7	2	8	21	8
Rumex acetosa								2
Oxyria		10		31	3	5	12	44
Apiaceae		1	1					
Cornus		9	1					
Rhinanthus					2		15	
Sucissa		34						
Chamaenerion		1						
Chenopodiaceae					1			
Dryas type		1						
Cruciferae	1	1						
Plantago spp.	3	1		1		2	2	7
Geranium								1
Saxifraga oppositifolia								4
Potamogeton								11
Myriophyllum	2		2					
Polypodium			6					

(*Continues*)

Table 3b (continued)

MIS	5e	5c	5c	5a	4	3	3	1
Sample/Pollen	LH-90-4 (A/B)	LH-90-5 (A)	LH-90-16 (3-1)	LH-90-5 (B)	HQ-90-6 (4-2)	LH-90-5 (C)	LH-90-6 (A)	SCC-98-1 (A-D)
Pteridium			2					
Thelypteris			1					
Selaginella	1							
Sphagnum	1		1					
Filicales	1	1	12	3	3			20

the past. Murton *et al.* (2001), when working on pollen derived from tufa at Marsworth, found difficulty in correlating the pollen spectra with others from the Quaternary because of this lack of pollen records from calcareous sites. Similar difficulties have also been encountered in the present study.

What currently exists in the British Isles is a pollen record biased towards wetland environments and additionally biased towards warm periods (interglacials) when organic matter accumulation would have been at its maximum, with very few interstadial records before the Lateglacial Interstadial. Not only is this record biased but it is also extremely fragmentary and poorly dated. Speleothems have the potential to provide dated pollen records from previously understudied environments and, because of their ability to form outside of interglacial periods, for time periods from which we otherwise would have very little pollen data. The speleothem evidence presented here obviously conflicts in part with our current understanding of the British late Quaternary biostratigraphy. Without the overtly thermophilous elements present in the speleothems in MIS 5c, 5a and 3, there would be few problems of correlation with existing records of British interstadial vegetation, but our data suggesting the presence of local thermophilous elements would mean the existence of surviving species not previously recognised. Common arguments against this speleothem evidence are that it is a taphonomic artefact, for example the thermophilous taxa are a result of the storage of pollen in the groundwater system from the previous interglacial, or derive from long-distance transport to the sites in cold periods with little or no surface vegetation. Both hypotheses are considered unlikely due to the excellent preservation of the pollen, which suggests rapid transport to the speleothem, the need for speleothem formation in periods of extreme cold when little or no vegetation survived above the cave, as well as the absolute lack of modern-day hydrological analogues for long ($>10^3$ yr) residence time waters feeding shallow flowstones. A further explanation might be that laboratory contamination is possible owing to the low counts of some pollen; however laboratory blanks showed the absence of any contamination. Therefore we propose that our results are genuine, and in the absence of refuting, well-dated datasets, represent real assemblages present during interstadial conditions in the British Isles.

Recent fluid inclusion isotopic data derived from Lancaster Hole from the same sample as analysed here (LH-90-4 and 5) and for the same time periods (Atkinson *et al.*, 2005) infer climatic conditions possibly supportive of more warmth-demanding vegetation than previously considered. This includes δ^{18}O data for MIS3, 52–49 kyr suggesting temperatures as warm as today. Given such emerging data for periods from which we previously have had so little data, we would suggest that it is worth keeping a more open mind about climatic and environmental conditions in the British Isles during Devensian interstadials rather than inferring ubiquitous 'cool' conditions and consequent vegetation types based on very fragmentary evidence.

Conclusions

In the absence of compelling evidence for alternative explanations for the pollen assemblages found here from dated speleothems, we argue that localised thermophilous vegetation may have existed in Britain in interstadials during the Last Glaciation, some of which are analogous to those seen in pollen sequences elsewhere in northern Europe. These have been recognised and constrained in the British Isles for the first time through the analysis of dated speleothem pollen spectra, in particular from parts of MIS 5c, 5a, 4 and 3. This study has brought to light evidence for the probable presence of thermophilous trees in karstic areas of Yorkshire, Lancashire and the Mendip Hills, confirmed through U-Th analyses to date to periods which British records had previously indicated to be cool temperate at best in terms of the available vegetation evidence. The new results obtained in this study highlight the inadequacies in the existing British stratigraphy, in particular because of the lack of absolute dates. It is argued here that the highly fragmentary, poorly dated British record has led to a potential misunderstanding of the nature of terrestrial conditions during periods in MIS 5-3, particularly on a microclimatic scale. Overall this study illustrates the need for a better geochronology within which to place palaeoenvironmental records in the British Isles. The findings presented here have shown the potential which the analysis of karstic areas as unique palaeoenvironmental archives and in particular speleothem pollen combined with TIMS U-Th dating hold in resolving such problems.

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