A late Middle Pleistocene temperate–periglacial–temperate sequence (Oxygen Isotope Stages 7–5e) near Marsworth, Buckinghamshire, UK

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Abstract

River-channel and colluvial deposits, near Marsworth, Buckinghamshire, record a temperate-periglacial-temperate sequence during the late Middle Pleistocene. The deposits of a lower channel contain tufa clasts bearing leaf impressions that include *Acer* sp., and *Sorbus aucuparia* and containing temperate arboreal pollen attributed to ash-dominated woodland. The tufa probably formed at the mouth of a limestone spring before being redeposited in a small river whose deposits contain plant remains, Mollusca, Coleoptera, Ostracoda and vertebrate bones of temperate affinities. The sediments, sedimentary structures and limited biological remains above the Lower Channel deposits indicate that fluvial deposition preceded climatic cooling into periglacial conditions. Fluvial deposition recurred during a later temperate episode, as shown by the mammalian bone assemblage in stratigraphically higher channel deposits. The Upper Channel deposits are confidently attributed to Oxygen Isotope Sub-stage 5e (Ipswichian) on the basis of their vertebrate remains. However, the age of the Lower Channel deposits is less clear. The mammalian and coleopteran remains in the Lower Channel strongly suggest correlation with oxygen isotope stage 7 on the basis of their similarities to other sites whose stratigraphy is better known and the clear difference of the Lower Channel assemblage from well-established faunas of Ipswichian or any other age. By contrast, U–Th dating of the tufa clasts suggests an age post 160 ka BP, while Aile/Ile ratios on Mollusca point to an Ipswichian age and younger. Four ways of interpreting this age discrepancy are considered, the preferred one correlating the Lower Channel deposits with Oxygen Isotope Stage 7. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

The Pleistocene deposits near Marsworth, Buckinghamshire, in central England (Fig. 1), have particular importance in the British Quaternary because they contain evidence thought to indicate a "previously unrecorded interglacial" (Green et al., 1984, p. 780). The deposits include two fluvial channel fills with biological remains assigned to two temperate episodes and separated by periglacial sediments (Green et al., 1984). The age of the more recent temperate episode is widely accepted as Ipswichian (Oxygen Isotope Sub-stage (OISs) 5e), inferred from the biostratigraphic significance of the mammal

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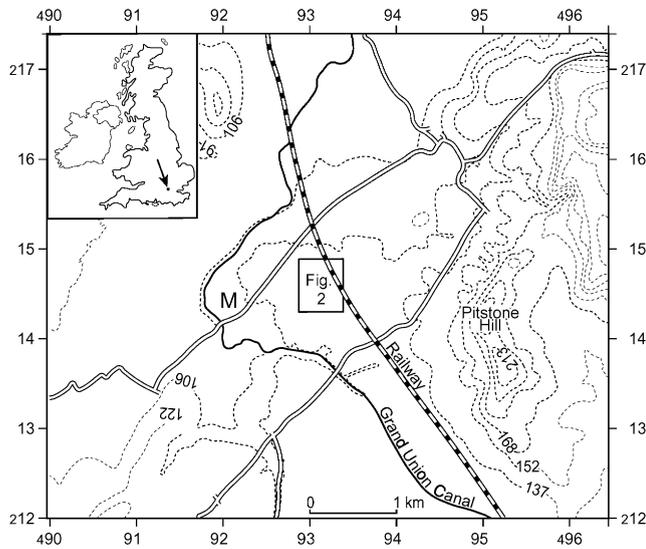*E-mail address:* j.b.murton@sussex.ac.uk (J.B. Murton).

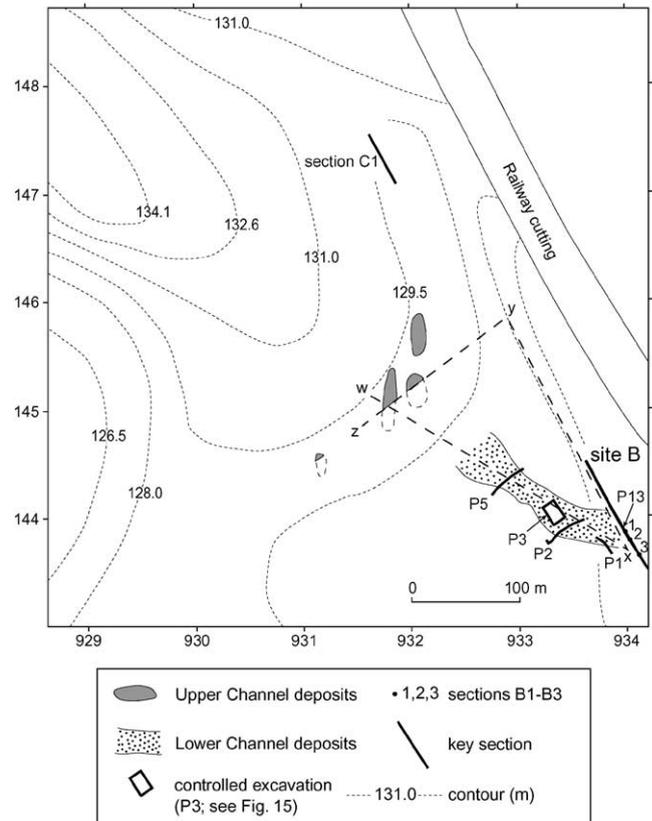Fig. 1. Location map. 'M' denotes Marsworth. Contours in metres.

Fig. 2. Site plan showing location of Upper and Lower Channels, and site B. Location shown in Fig. 1. Stratigraphic sections between 'x', 'y', 'w' and 'z' shown in Fig. 3; sections B1–B3 in Fig. 4; section P1 in Fig. 5; section P5 in Fig. 7; and controlled excavation (P3) in Fig. 15.

fauna in the Upper Channel deposits. However, the age of the older temperate episode is less certain (Bowen et al., 1986; Field, 1993), because U-series age estimates from tufa, bearing leaf impressions of temperate woodland species and occurring as clasts within the Lower Channel deposits, were thought to indicate tufa formation between ca. 170 and 140 ka BP (Green et al., 1984). But this period coincides with the cold stage of full glacial status, from 165 to 140 ka BP, inferred from zero speleothem growth and U-series age estimates on cave sediments in northern England (Gascoyne et al., 1983) and with the cold stage (OIS 6) inferred from the oxygen-isotope record of deep-sea sediments (e.g. Shackleton et al., 1990). However, more recent U-series dating of speleothem in South Devon (Baker and Proctor, 1996) and Yorkshire (Baker et al., 1996) suggests that speleothem may have formed sometime between ca 190 and 160 ka BP, i.e., early in OIS 6. Thus it remains uncertain whether the tufa clasts and younger host sediments in the Marsworth Lower Channel date from the penultimate interglacial and/or to an interstadial during OIS 6 or perhaps to another temperate episode altogether.

This paper gives a full account of the stratigraphy and biota of the Upper and Lower Channels at Marsworth, following the preliminary note on them by Green et al. (1984). The paper describes the tufa clasts from the Lower Channel deposits in terms of their physico-chemical characteristics and contained biological remains in order to establish the palaeoenvironmental conditions when the tufa formed. Fossil vertebrate remains are described from both the Upper and Lower Channel deposits to establish any biostratigraphical differences. Plant, mollusc, coleopteran and ostracod remains are described from the Lower Channel to determine the palaeoenviron-

mental conditions when they were deposited and to correlate them with other sites of known stratigraphical context. The results of new dating studies (U-series and amino-acid) of the tufa and molluscs within the Lower Channel are compared with ages inferred from vertebrate and coleopteran biostratigraphy. Collectively, the evidence suggests a history that includes two temperate episodes (OIS 7 and 5e) separated by a periglacial phase (OIS 6). Comparison of the Lower Channel deposits is made with other British sites attributed to OIS 7. However, close comparisons are complicated by the fact that the depositional environment at Marsworth — small chalkland streams near the foot of a large scarp — is rather specialised.

The Pleistocene deposits described below are in the College Lake Wildlife Centre (UK National Grid Reference SP 933143), formerly the No. 3 (Bulbourne) Quarry of Pitstone Tunnel Cement Ltd, now property of Castle Cement Ltd. The deposits are ca 1–2 km east of the village of Marsworth, and have been examined at three sites, designated site B, the Lower Channel and the Upper Channel (Figs. 2 and 3). Additional Pleistocene
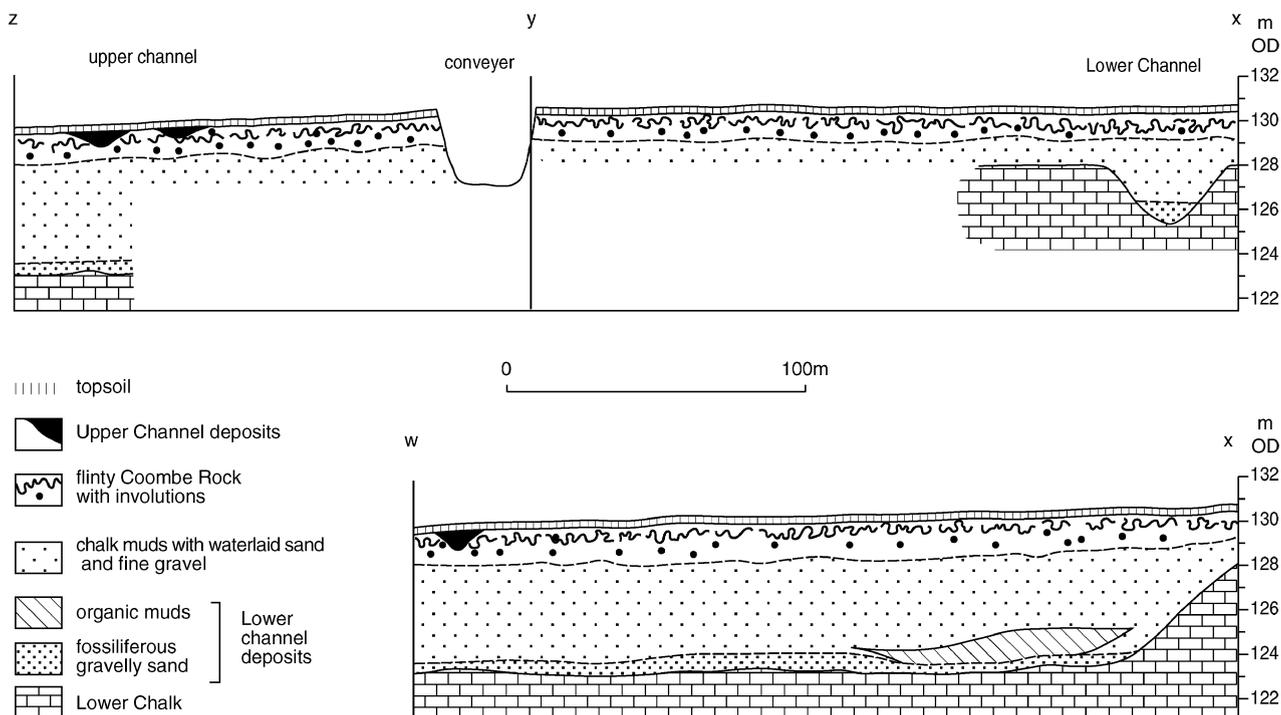
Fig. 3. Composite stratigraphic sections through Lower and Upper Channels and intervening periglacial sediments. Location of sections shown on Fig. 2. Reprinted with permission from *Nature*, 309, 778–781; © 1984 Macmillan Magazines Ltd.

deposits in the same quarry, whose stratigraphic relationships with those described by Green et al. (1984) and in the present paper remain uncertain, are discussed in a companion paper (Murton et al., in prep.). The geologic and geomorphic setting of Marsworth is detailed in that paper and summarised below.

The Marsworth Pleistocene deposits overlie a platform of Cretaceous Lower Chalk (Sherlock, 1922) that separates the Chiltern Hills scarp to the southeast from the Vale of Aylesbury to the northwest. The main Chiltern scarp, rising from ca 150 m to ca 210 to 245 m O.D., comprises Middle Chalk capped by Upper Chalk, and lies ca 3–4 km to the southeast of the Marsworth deposits. An outlier of the main scarp — a ridge running south from Pitstone Hill (ca 215 m O.D.) — occurs ca 2 km to the southeast of the deposits (Fig. 1). Unlike the Lower Chalk, which is typically grey and marly, the Middle and Upper Chalk are white and usually contain more than 97% calcium carbonate, and the Upper Chalk contains abundant flint (Avery, 1964, pp. 6–8). Substantial amounts of chalk and flint have been transported down the Chiltern scarp and onto the platform, forming a thick sheet of colluvium. Near the foot of the scarp emerge small spring-fed streams (see Ordnance Survey 1 : 25 000 Explorer Map 2). Evidence for two former streams, whose deposits are separated by a sheet of periglacial colluvium, is the subject of the present paper.

2. Stratigraphy and sedimentology

2.1. Site B

2.1.1. Description

The stratigraphy of site B, recorded during 1995 in three adjacent sections, is shown in Fig. 4. Details of the sediments are given in Table 1 and their main features summarised below.

Brecciated Lower Chalk (unit B1) formed the base of the sequence, its surface rising nearly 3 m over a lateral distance of 26.5 m between sections B1 and B3. This rise marked the southeast side of the same channel exposed at the nearby Lower Channel site (Fig. 5). The basal fill of the channel, sharply overlying the Chalk, was gravelly silty sand (unit B2; $\leqslant 0.45$ m thick) containing bone fragments and tufa clasts. The sand graded upward into pebbly silty clay and loam (unit B3), a complex and variable unit with abundant Chalk pebbles, crude stratification and, near the top, occasional flint layers. Unit B3 was thickest within the Lower Channel ($\leqslant$ ca 4.5 m), but extended to either side of it as a layer ca 1.0–1.5 m thick. Above it was a flinty coombe rock (unit B4), a massive diamicton ($\leqslant$ at least 2.5 m thick) with abundant flint and Chalk clasts, and traceable laterally for ca 250 m both to the southeast and northwest of site B. Elongate flint clasts in unit B4 were commonly aligned
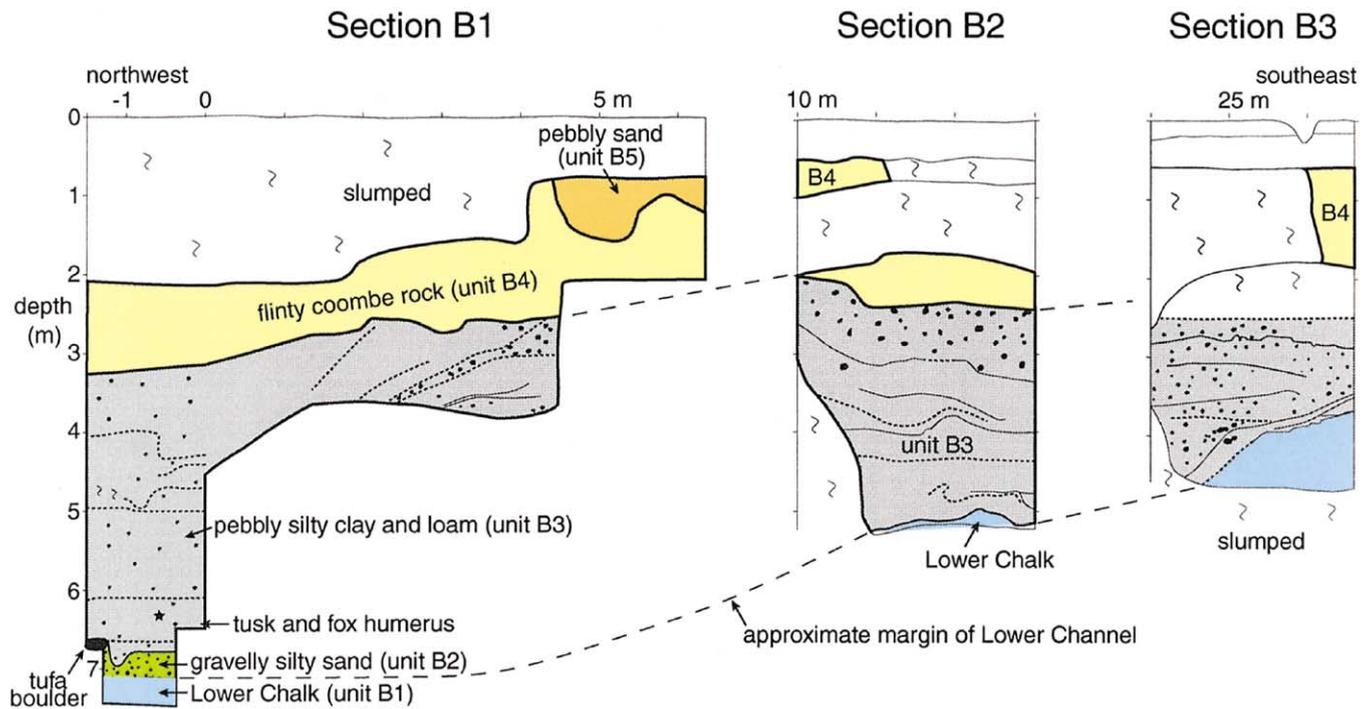
Fig. 4. Stratigraphic sections B1, B2 and B3 at site B. Location shown in Fig. 2. Star marks position of Mollusca samples (*Arianta* sp.) yielding D-alle/L-lle ratio of $\bar{x} = 0.083 \pm 0.012$ ($n = 4$) (UKAL-148A and 156A, 156B and 156C). Dashed lines show correlation of units between sections. Lateral spacing between sections varies, as shown on horizontal scale.

vertically. The uppermost sediment observed was a pebbly sand (unit B5) that locally occurred as involutions in the top of the flinty coombe rock. The sand contained polished quartz grains.

2.1.2. Interpretation

Brecciation of the Lower Chalk (unit B1) is attributed to former ice segregation and frost heave (cf. Murton, 1996), the Chalk having a high frost susceptibility.

The basal sediment of the channel fill, a gravelly silty sand (unit B2), is interpreted as a fluvial deposit above a basal erosion surface. The unit is correlated with the 'fossiliferous gravelly sand' of Green et al. (1984) (Fig. 3) and the 'gravelly calcareous sand' in Fig. 5. The higher, main part of the channel fill — pebbly silty clay and loam (unit B3), which also extended to either side of the channel — is probably colluvial in origin because the molluscan fauna, described below, comprises terrestrial species. Mass movement, possibly by soil creep and/or gentle solifluction, is inferred from massive subunits. Crude stratification and rounding of Chalk pebbles is attributed to slopewash, probably from meltwater. Incorporation of loess is inferred from (1) the elevated silt content of the acid-insoluble residue, (2) the mineralogy of the silt fraction (Table 2) and (3) the occurrence of kaolinite and a trace of quartz in the clay-size fraction. The unit represents the "Chalk muds with waterlain sand and fine gravel" of Green et al. (1984) (Fig. 3).

Above the channel fill, the flinty coombe rock (unit B4) is attributed to solifluction. Reworking of underlying pebbly silt during deposition is inferred from the gradational lower contact and basal mixed zone of flints and pebbly silt. The vertical clast orientation is attributed to frost heave.

The pebbly sand (unit B5) above the flinty coombe rock is interpreted as aeolian coversand. The high percentage of non-calcareous sand-size (i.e. non-local) material, including quartz grains that show rounding and polishing, suggests aeolian transport and abrasion. The coversand has been disrupted by involution formation.

2.2. The Lower Channel

The Lower Channel deposits, first exposed by quarrying in 1980, were examined at sections P1, P2, P3 and P5 (Fig. 2). A controlled excavation in the channel took place between 1980 and 1986 (P3 in Fig. 2). The channel was incised $\leqslant$ ca 4.5 m into the Lower Chalk but the full depth was seen only in the quarry face, at site B; at the Lower Channel site just the lower 1–2 m survived quarrying. The surviving fill, exposed in plan on the quarry floor, was $\leqslant$ 35 m wide and trended south-east to north-west for ca 200 m (Fig. 2).

The lower fill comprised structureless gravelly calcareous sand locally overlain by organic mud (Figs. 5–7). Pebbles were commonly sub-rounded to sub-angular

Table 1
Sediments at site B

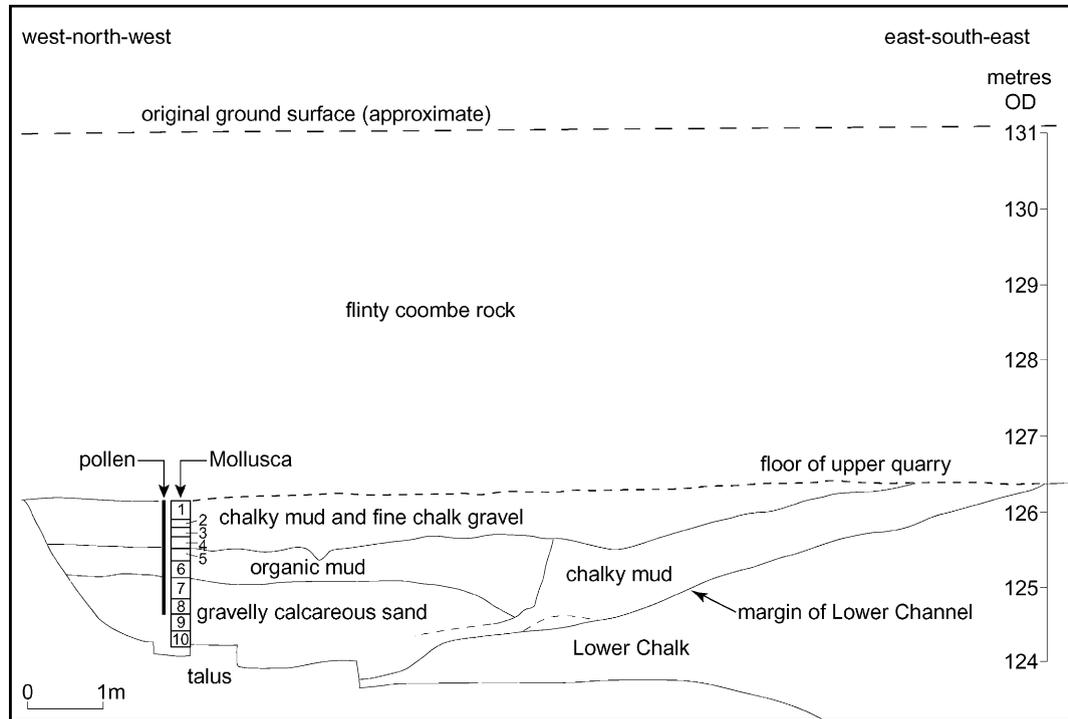| Unit	Deposit	Description	Distribution	Interpretation
B5	Pebbly sand	Yellow (2.5Y 7/6) to light grey (2.5Y 7/2), massive, loose, medium to pebbly coarse sand; 56.4% non-calcareous component (< 2 mm) of which 65.9% is $> 90 \mu$m; quartz sand grains, rounded to sub-rounded, polished; numerous chalk granules to pebbles ($\leqslant 1$ cm), white with orange patina, rounded to subrounded; flint pebbles ($\leqslant 3$ cm), brown and blue, angular to subangular, dispersed.	Within involutions commonly 30–70 cm high that descend into unit B4; some involutions are isolated balls of pebbly sand in unit B4.	Involuted coversand
B4	Flinty coombe rock	Pale yellow (2.5Y 7/4) to very pale brown (10YR 7/4), massive, compact, hard, clast- to matrix-supported diamicton; 44% of < 2 mm fraction is non-calcareous, of which 59% is $> 90 \mu$m; quartz grains in 90–250 μm fraction are mostly subrounded to subangular; flint clasts ($\leqslant 10$ cm), angular to subangular, mainly dark blue-grey ($\pm$ white patina), few orange-brown flints; elongate flints commonly vertically aligned; chalk granules and pebbles ($\leqslant 3.5$ cm), mostly white, subangular to rounded; lower contact gradational and irregular.	Overlies lower channel deposits ($\leqslant$ at least 2.5 m thick); laterally traceable for ca 250 m both to the southeast and northeast of site B.	Solifluction deposit
B3	Pebbly silty clay and loam	Complex and variable unit; colour varies from light grey (2.5Y 7/2; 5Y 7/2), white (2.5Y 8/2; 5Y 8/1), yellow (10YR 7/6), pale yellow (2.5Y 8/4) to brownish yellow (10YR 6/8); 29.5% carbonate content in a silty clay layer whose acid-insoluble residue has a particle-size distribution very similar to that of the Lower Chalk, except that the coarse silt fraction is enriched in the silty clay sample; clay-size fraction consists of smectite (74%), illite (16%) and kaolinite (10%) and a trace of quartz; abundant chalk granules and pebbles ($\leqslant 4.5$ cm), white or light grey, subangular to subrounded, dispersed throughout unit; many of the light grey chalk pebbles are very soft and $\leqslant 2$–3 cm diameter; occasional flint pebbles ($\leqslant 2.5$ cm), blue-grey; massive to crudely stratified; strata a few centimetres to a few decimetres thick, horizontal to gently inclined, including sand (mostly quartz and calcium carbonate), fine white chalk gravel with sub-rounded pebbles or, near top of unit, occasional layers with angular to subangular flints ($\leqslant 6$ cm); small folds locally common.	Thickest within the Lower Channel ($\leqslant$ ca 4.5 m), extending to either side of it as a layer ca 1.0–1.5 m thick.	Colluvial deposit
B2	Gravelly silty sand	Light grey (5Y 7/2), massive, calcareous pebbly silty fine sand; pebbles ($\leqslant 5$ cm) mainly subangular to subrounded, light grey Lower Chalk and occasional pebbles of white chalk; occasional flint pebble, subangular (white with orange to dark grey patina); tufa clasts, typically pebble-sized ($\leqslant 4.6$ cm), commonly laminated; porous tufa boulder (at least 43 cm long and 15 cm high) at top of unit; bone fragments common; lower contact sharp and irregular with relief of a few decimetres.	Observed only at the base of the Lower Channel ($\leqslant 0.45$ m thick).	Fluvial deposit (Lower Channel)
B1	Brecciated Lower Chalk	Light grey (2.5Y 7/2); 30.5% of the < 2.0 mm fraction comprises insoluble residue, of which $> 99.3\%$ is in the $< 90 \mu$m fraction; clay fraction comprises smectite (77%) and illite (23%); subangular blocks with strong brown (7.5YR 5/8) $\pm$ black staining on sides, commonly several to at least 10 cm long set in matrix of powdery chalk.		Frost-shattered bedrock

Fig. 5. Stratigraphic section of Lower Channel at section P1 showing location of pollen and principal mollusc samples. Correlations with sections B1–B3 (Figs. 2 and 4) are: 'gravelly calcareous sand' = unit B2; 'chalky mud and fine chalk gravel' = unit B3; 'flinty coombe rock' = unit B4. 'Organic mud' is absent in sections B1-B3. Location shown in Fig. 2.

(≤ 5 cm), and included numerous fragments of tufa, bone and ivory. Also present were larger pieces of tufa (≤ 0.75 m) and bone, including complete limb bones and tusks of adult mammoth. The overlying organic mud occupied an approximately oval area elongated from south-east to north-west and visible in sections P1–P3 but not at site B and section P5. Both the gravelly sand and the organic mud are probably of fluvial origin because of their contained biota (described below) and basal, channel-fill position.

Above the fluvial deposits was a unit of crudely bedded chalky mud and fine chalk gravel correlated with unit B3 at site B and assigned a colluvial origin. Deposition of this unit appears to have disturbed and partly reworked the underlying sediments. Within the controlled excavation the unit cut through the organic mud and underlying gravelly sand to rest directly on the disturbed Lower Chalk (Fig. 6). At the eastern end of this section, i.e. in the eastern half of the channel, there was a complex interdigitation of the chalky mud and fine chalk gravel with the underlying organic mud. The chalky mud and fine chalk gravel also incorporated fragments of organic mud, sometimes numerous and small (10–20 cm), sometimes large (≤ 80 cm). Where the sediments were bedded, chalky beds alternated in places with thin beds of reworked organic mud.

The sequence was capped by a unit of flinty coombe rock which, in section P3 (Fig. 6), cut down into the

underlying sediments and rested on a well-defined erosional contact. This unit is correlated with unit B4 at site B and attributed to solifluction.

2.3. The Upper Channel

The Upper Channel site, ca 300 m northwest of site B, was observed briefly in 1976 by members of the Pitstone Local History Society during stripping of the Pleistocene overburden (Fig. 2). The outline stratigraphy at the channel centre was as follows:

Depth below surface (m)	Sediment	Comments
0–0.6	Modern soil and colluvium	
0.6–9.0	Flinty calcareous clay loam	Few bone fragments
0.9–1.5	Stratified sand and fine gravel	Channel fill; bones
1.5–2.5	Stony orange sand	Within involutions
2.5–3.5 +	Coarse flint and Chalk gravel/coombe rock	

The base of the channel truncated involutions of stony orange sand (Fig. 8). The channel fill comprised stratified sand and fine gravel and, in the lower part, contained bones (see below). Chalk clasts in the basal sequence were cemented by calcite, but no tufa was observed. Above

Table 2
Mineralogy of sand and coarse silt fractions from pebbly clay and loam (unit B3) and underlying Lower Chalk, site B[a]

Layer	Lower Chalk	Unit B3 Sand	Unit B3 Coarse silt
fraction	—	(60–250 μm)	(16–63 μm)
Light fraction (%)			
Quartz	75	88	89
Alkali feldspar	< 1	6	9
Flint	—	3	1
Chalcedony	—	1	—
Muscovite	< 1	1	< 1
Glauconite	< 1	—	—
Heavy fraction (counts)			
Limonite/haematite	89	46	50
Magnetite	—	141	191
Leucoxene	—	54	131
Collophane	904	557	328
Apatite	—	3	1
Zircon	3	50	150
Tourmaline	—	27	24
Epidote	—	22	21
Zoisite	—	2	9
Garnet	1	62	17
Yellow rutile	—	4	28
Brown rutile	1	12	6
Red rutile	1	3	1
Anatase	—	—	24
Brookite	—	—	1
Green hornblende	—	7	3
Tremolite/actinolite	—	1	—
Chlorite	1	—	10
Biotite	—	—	—
Staurolite	—	7	1
Kyanite	—	2	4
Augite	—	—	—

[a]Sample of pebbly clay and loam (unit B3) was collected from a depth of 4.5 m below the ground surface.

and extending to either side of the channel fill was a flinty calcareous clay loam.

2.4. Stratigraphic relationships between the Upper and Lower Channels

All known deposits of the Upper Channel were destroyed during the quarrying which ultimately exposed the Lower Channel. Hence both channels were never recorded in the same continuous stratigraphic section. However, the recorded position and elevations of the channels (Figs. 2 and 3) indicate beyond all reasonable doubt that the Upper Channel was stratigraphically above the Lower Channel, separated from it by periglacial sediments and structures. Coombe rock and periglacial involutions were stratigraphically above organic mud of the Lower Channel (Fig. 9), whereas similar sediments and involutions were truncated by the deposits of the Upper Channel (Fig. 8).

3. Clast lithology

3.1. Description

Two gravel-rich samples Mw/G5 and S39 were collected from the *gravelly silty sand* [unit B2] directly above the Lower Chalk at section P2 (Fig. 2). Local material overwhelmingly predominates both samples (98.4 and 97.3% in the 11–16 mm fraction; Table 3). Chalk and flint are major components, together with numerous phosphatic nodules from the Lower Chalk, pieces of tufa, and a few fragments of bone and ivory. Both samples contain small amounts of far-travelled material, including quartz, quartzites, sandstones and cherts.
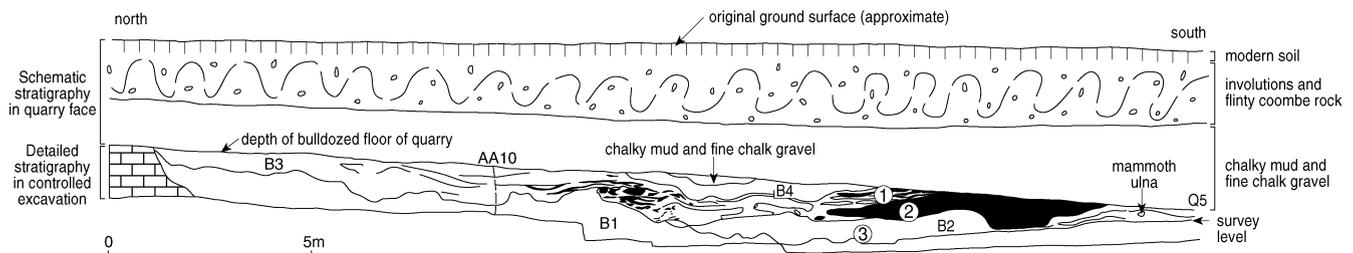
David Parish
Buckinghamshire
County Museum

B4 Chalk and flint gravelly diamicton; well-defined erosional contact at base

B3 very variable unit comprising sands, loams and fine gravel, probably in part waterlaid

⬛ organic mud: seen as continuous, massive unit in the southern part of this channel section but greatly disturbed and only patchily preserved elsewhere by incorporation in B3

B2 variable sandy calcareous gravel or gravelly calcareous sand

B1 rubble of disturbed Lower Chalk

⊞ Lower Chalk *in situ*

Fig. 6. Vertical section through controlled excavation (P3 in Fig. 2) in Lower Channel. Section marked by dashed line in Fig. 15. Encircled numbers 1, 2 and 3 denote levels of excavation.
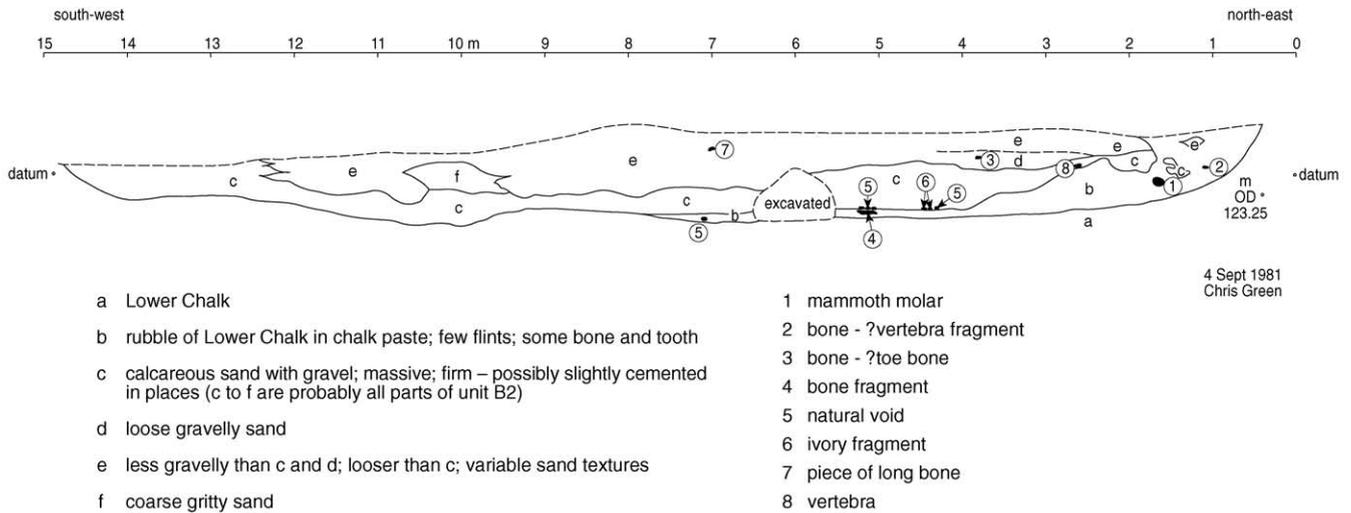
Fig. 7. Full vertical cross section of Lower Channel at section P5. Location shown in Fig. 2. Dashed upper line marks truncation by quarrying.

Fig. 8. Vertical cross section through Upper Channel deposits and underlying periglacial sequence. Channel base truncates periglacial involutions. (David Parish/Buckinghamshire County Museum)

3.2. Interpretation

The composition of samples Mw/G5 and S39 is consistent with their known context. The samples represent the deposits of a small spring-fed stream at a point close to the stream source, probably the focus of tufa formation.

Tufa, little displaced from its position of formation, occurred at site P13 (Fig. 2), only ca 40 m 'upstream' from the sample points, and the deposit itself is a rich source of mammalian remains. The few far-travelled clasts resemble an assemblage observed a few hundred metres to the northwest, at section C1 (Fig. 2; Murton et al., in

Fig. 9. Quarry face near section P13 showing flinty coombe rock (unit B4) and periglacial involutions stratigraphically above organic mud (beside pole) of Lower Channel. (David Parish/Buckinghamshire County Museum)

prep.). A source for these pebbles must have existed in the immediate vicinity, probably the same source as that proposed for the far-travelled material in section C1, namely material introduced into the area by Anglian glacial ice (attributed to OIS 12).

4. Tufa

4.1. Description

The Lower Channel fill contains two types of tufa: (1) densely encrusted bryophyte cushions (Fig. 10) and (2) laminated crusts, stalagmites and flowstones (Fig. 11). The tufa comprises granule to boulder-size clasts within gravelly silty sand [unit B2] at the base of the Lower Channel (Table 1). Some clasts may be almost in situ, given the local concentration of large blocks (1.0 m or more in maximum dimension) and some clasts with angular, delicate edges that would probably have been broken had the tufa experienced significant transport.

4.2. Interpretation

The combination of densely encrusted bryophyte cushions, laminated crusts, stalagmites and flowstones

suggests a paludal environment. A typical limestone spring can be envisaged at the foot of the Chalk scarp, probably similar to active limestone springs nearby. The spring was supersaturated in calcium, depositing tufa in a low-energy environment. Laminated deposits probably formed in a grotto. Tufaceous stalagmites lack evidence of algae and other biological material and thus likely formed in dark conditions. By analogy with contemporary tufa deposits in southwest England (Baker and Simms, 1998), the Marsworth tufa may have formed initially in a small area (e.g. 10 m × 10 m) from a low-discharge stream.

4.3. Morphology

Six laminated clasts were examined for post-deposi-itional weathering. All had an upper surface parallel to laminae within the sample, several showed evidence for physical weathering during reworking of the tufa, but none showed evidence for dissolution. This suggests that tufa deposition did not cease because of lowered groundwater calcium ion concentrations, causing the groundwater to become aggressive with respect to $CaCO_3$. Instead, after deposition ceased, the stream probably became inactive or was at or near to $CaCO_3$ equilibrium, such that the tufa was neither chemically weathered nor experienced renewed deposition.

Table 3
Clast lithology from the Lower Channel deposits, section P2[a]

Sample:	Chalk	Flint	Phos	Tufa	Bone	Qtz	Qzite	Sst	Chert	Misc	n	qz/o	% far
Mw/G5	38.9	22.0	16.4	20.9	0.3	—	1.3	—	—	0.4	378	—	1.6
	39.9	19.7	15.6	24.0	—	0.3	0.3	—	—	0.3	371	0.50	0.8
S39	25.7	37.6	11.9	14.7	7.3	—	0.9	0.9	0.9	—	109	—	2.7
	45.2	30.7	7.8	11.6	1.4	0.2	2.4	—	0.4	0.2	498	0.07	3.2

[a]For both samples, 11.2–16 mm (upper row) and 8.0–11.2 mm (lower row) showing percent composition, quartz/other far-travelled ratio (qz/o), and percent far-travelled (% far). Abbreviations: Phos = phosphatic nodules; Qtz = quartz; Qzite = quartzite; Sst = sandstone; Misc = miscellaneous (igneous, metamorphic, schorl); n = sample size.

Fig. 10. Calcified bryophyte cushion, part of a tufa clast from Lower Channel deposits. Scale in cm.

Fig. 11. Laminated tufa clast (with two enclosed Chalk clasts) from Lower Channel deposits. Scale in cm.

4.4. Luminescent lamination

Luminescent lamination was observed under UV excitation in three tufa samples that appeared laminated in visible light. Bright luminescent laminae correlated with dark visible laminae. This correlation is identical to that observed in annual laminae in cave speleothems (Genty et al., 1997), with compact calcite formed in winter under high flow conditions, and more porous, evaporative calcite deposited in summer, when the tufa has a thinner, overlying water film. This observation is consistent with annual deposition of laminae.

The likely presence of annual laminae in the three samples demonstrates that water supply was maintained for the complete hydrological year. The number of laminae in any one clast ranged from 20 to 200, suggesting that each clast represents a 20–200-year snapshot of
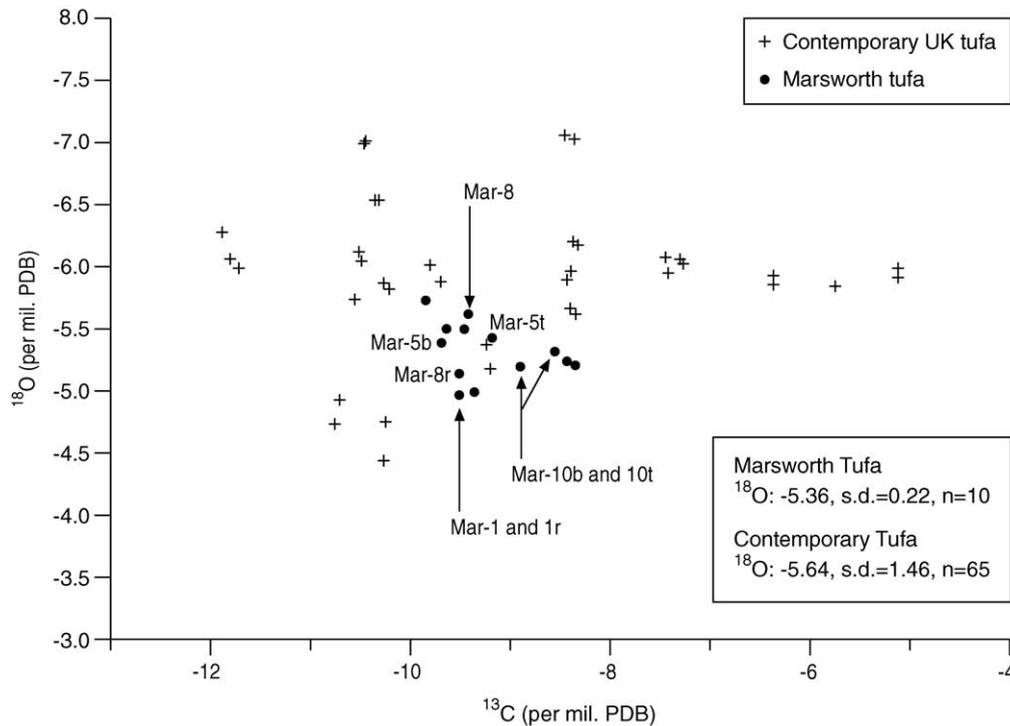
Fig. 12. ^{18}O and ^{13}C of Marsworth tufa and contemporary UK tufa deposits. Replicate analyses ("r") and top and basal analysis pairs ("t" and "b") on Marsworth tufa are presented. All data expressed relative to PDB.

tufa deposition. The width of laminae was uniform. Assuming that the laminae are annual, then their calculated growth rates were similar (Mar-9 : 0.63 mm yr^{-1}; Mar-10 : 0.73 mm yr^{-1}; Mar-5 : 0.82 mm yr^{-1}), in the same order of magnitude as those from contemporary tufa deposits (Herman and Lorah, 1987; Dreybrodt et al., 1992; Zaihua et al., 1995). Tufa growth rate is primarily affected by changes in the flow regime from laminar to turbulent flow (causing increased mixing of the water and thus faster degassing of CO_2), and by increased calcium ion concentration, which provides more calcium for precipitation as tufa (Dreybrodt and Buhmann, 1991). Thus a constant deposition rate suggests no significant changes in groundwater calcium ion concentration or in the flow regime of the waters over the tufa. The similar growth rates inferred from the Marsworth tufa clasts suggests their formation during a single period of tufa deposition under a relatively stable climate.

4.5. Oxygen and carbon isotopes

The ^{18}O and ^{13}C values in 12 sub-samples from eight tufa clasts (including top and bottom pairs and replicates) were measured, using standard techniques, to compare the Marsworth tufa with the Recent calibration data set (Andrews et al., 1993, 1997). The isotopic values are expressed relative to PDB and compared with values from contemporary tufa (Fig. 12).

Fig. 12 clearly shows that the top/bottom pairs replicated oxygen well, and the Mar-10b/10t carbon pair showed good agreement. However, the carbon numbers for Mar-5b/5t differed, at least within analytical error. As with the top/bottom pairs, the replicate samples generally confirmed the same oxygen composition, but carbon was more variable between pairs. These results typify carbon and oxygen isotope analyses on secondary carbonate deposits, where carbon isotopes are more variable than oxygen due to the greater fractionation of ^{13}C during CO_2 degassing and calcite precipitation.

The ^{18}O values from the Marsworth tufa agree closely with those from actively forming and fossil Holocene tufa in Britain (Fig. 12; Andrews et al., 1993, 1997). This suggests that a similar rainfall source area and (interglacial) temperature applied during deposition of the Marsworth tufa. No relationship is observed between the ^{13}C and ^{18}O values from this tufa, which is to be expected as they are determined by different variables: ^{18}O isotopic variations by the precipitation source and temperature, and ^{13}C by vegetation type and groundwater residence time.

4.6. Mollusca

Sixty-eight individual molluscan shells or shell impressions were identified in the tufa (Table 4). The assemblage is wholly terrestrial, from a shaded habitat of scrub or

Table 4
Mollusca from tufa clasts and the Lower Channel deposits, section P1

Sample:	Tufa	1	2	3	4	5	6	7	8	9	10
Aquatic taxa											
Lymnaea truncatula (Müller)	—	—	—	1	—	33	33	65	32	22	8
Anisus leucostoma (Millet)	—	—	—	—	—	—	—	—	1	—	—
Gyraulus laevis (Alder)	—	—	—	—	—	1	2	4	3	3	—
Sphaerium corneum (Linné)	—	—	—	—	—	8	8	11	21	8	1
Sphaerium lacustre (Müller)	—	—	—	—	1	3	14	9	40	8	—
Pisidium casertanum (Poli)	—	—	—	—	—	—	1	2	8	10	—
Pisidium obtusale (Lamarck)	—	—	—	—	—	—	—	—	—	1	—
Land taxa											
Carychium minimum Müller	—	—	—	1	3	—	—	5	3	2	—
Carychium tridentatum (Risso)	3	—	—	—	—	—	—	—	—	—	—
Oxyloma pfeifferi Rossmässler	—	—	1	4	1	88	143	134	64	65	7
Azeca goodalli (Férussac)	17	114	67	44	11	3	6	4	11	8	3
Cochlicopa lubrica (Müller)	1	—	—	—	—	1	—	—	—	1	—
Pupilla muscorum (Linné)	—	79	58	47	19	14	14	40	33	26	5
Vallonia costata (Müller)	—	2	2	—	1	—	—	—	—	13	4
Vallonia enniensis (Gredler)	—	—	—	—	—	—	2	19	18	—	—
Vallonia excentrica Sterki	—	—	2	1	—	7	5	11	5	—	—
Vallonia spp.	—	5	—	3	2	2	8	10	20	4	—
Punctum pygmaeum (Draparnaud)	—	—	—	—	—	—	—	1	—	—	—
Discus rotundatus (Müller)	11	—	1	1	—	—	—	—	2	4	1
Vitrina cf. *pellucida* (Müller)	1	—	—	—	—	—	—	—	—	—	—
Vitrea cf. *crystallina* (Müller)	3	—	—	—	—	—	—	—	—	—	—
Nesovitrea hammonis (Ström)	—	—	—	—	—	1	—	1	3	4	1
Aegopinella cf. *nitidula* (Draparnaud)	7	—	—	—	—	—	—	—	—	—	—
Limax spp.	—	72	81	244	47	31	53	60	65	81	32
Euconulus fulvus (Müller)	—	—	—	—	—	1	—	2	1	—	—
Cochlodina laminata (Montagu)	?1	—	—	—	—	—	—	—	—	—	—
Clausilia bidentata (Ström)	3	20	17	14	2	1	1	1	2	4	4
Trichia hispida (Linné)	12	68	38	14	15	42	73	235	199	135	22
Arianta arbustorum (Linné)	—	11	1	10	10	8	20	14	12	11	1
Cepaea spp.	a	1	1	1	—	—	—	—	—	—	—
Arianta/Cepaea spp.	9	—	—	—	—	—	—	—	—	—	—
Total (31 taxa)	68	372	269	385	112	244	383	627	544	410	89

[a] Non-apical fragments.

woodland. A temperate climate is inferred from the occurrence of *Aegopinella nitidula*, *Discus rotundatus* and *Azeca goodalli*, which currently have a fairly western distribution in northwest Europe (Kerney and Cameron, 1979).

4.7. Frog bones and impressions of plant and insect remains

The tufa contains frog bones (*Rana* sp. indet.) and plant and insect impressions. Leaf impressions identified comprise *Salix* spp., *Alnus/Corylus*, *Acer* sp., and *Sorbus aucuparia*, suggesting a temperate woodland environment. Also identified were impressions of mosses and liverworts, a carabid beetle elytron (*Pterostichus* sp.), a caddis-fly wing (fam. Limnephilidae) and tubes of caddis larvae (probably *Potamoxophylax* spp., fam. Limnephilidae).

4.8. Pollen

4.8.1. Introduction

Pollen was extracted from three samples of tufa clasts (A, C and D), weighing, respectively, 377, 124 and 165 g. The samples were dissolved in 10% HCl, marked with a *Lycopodium* tablet, disaggregated in NaOH, treated three times in HF and subjected to double acetolysis. This severe treatment successfully produced relatively clean and identifiable preparations. Despite the calcareous nature of the deposit, pollen was generally well preserved, with a lack of pollen rather than deterioration causing interpretative difficulties. Concentrations varied from 3.3 to 10.6 pollen grains g^{-1} calcite. Counts for indeterminable pollen were low. The pollen counts are listed in Table 5. Taxonomic nomenclature is that suggested by Bennett et al. (1994).

Table 5
Pollen counts for tufa clasts A, C and D in the Lower Channel deposits[a]

Sample	A	C	D
Betula sp.	14	2	3
Pinus sylvestris	34	7	9
Ulmus sp.	2	5	—
Quercus sp.	14	1	3
Tilia sp.	1	—	—
Alnus glutinosa	7	2	3
Carpinus sp.	14	6	4
Fraxinus excelsior	62	6	2
Corylus avellana	18	7	—
Salix sp.	47	—	3
Sorbus type	—	—	1
Frangula alnus	4	3	—
Hedera helix	1	—	—
Juniperus communis	—	1	—
Euonymus europaeus	1	—	—
Poaceae undiff.	218	45	92
Cyperaceae undiff.	6	—	—
Ericales	1	—	—
Asteroideae	3	1	2
Cardueae	1	—	—
Centaurea nigra	3	—	1
Centaurea scabiosa	—	—	1
Lactuceae	11	2	16
Cerastium type	2	—	—
Caryophyllaceae	4	—	—
Brassicaceae	2	1	3
Plantago lanceolata	16	2	4
Plantago media/major	2	—	—
Potentilla type	—	2	—
Ranunculaceae	7	—	—
Rhinanthus type	3	2	—
Rubiaceae	—	—	1
Rumex undiff.	—	—	1
Saxifraga granulata type	—	3	1
Saxifraga oppositifolia type	—	—	1
Apiaceae	1	—	—
Menyanthes	—	1	—
Potamogeton	7	2	1
Sparganium	1	—	—
Sphagnum sp.	1	1	1
Pteropsida (monolete) indet.	1	—	1
Indeterminable	26	3	16
ΣTLP + aquatics + spores	509	102	154

[a]Above values are expressed as actual counts. Summary details: A - ΣTLP 499 (+ 8 Aquatic, + 2 Spores) + 26 Indeterminable. Concentration 10.6 gr g^{-1} calcite; C - ΣTLP 98 (+ 3 Aquatic, + 1 Spore) + 3 Indeterminable. Concentration not found due to clumping problems with exotic; D - ΣTLP 151 (+ 1 Aquatic, + 2 Spores) + 16 Indeterminable. Concentration 3.3 gr g^{-1} calcite.

Little is known about pollen deposition in tufa. It is assumed that most was trapped in the bryophyte cushions and probably derived aerially from the immediate surrounds of the site, rather than from ground- or running water.

4.8.2. Ecological significance

The general AP suite is interglacial, with high counts for *Fraxinus* and *Pinus sylvestris,* and lower counts of *Quercus*, *Betula*, *Carpinus* and *Corylus*. The local, temperate woodland was probably ash-dominated with oak, hazel and hornbeam, and possibly pine on more exposed or thinner, sandier soils. Such woodland is very difficult to identify in the Quaternary record due to the paucity of pollen records from calcareous sites. However, ash woodland with taxa similar to those at Marsworth occurs today, for example, on the older Palaeozoic limestones of South Devon. Charcoal remains from a Neolithic context at Broken Cavern, Torbryan, South Devon (Cartwright, 1996), comprise woody taxa nearly identical to those in the Marsworth tufa, and parallels have been made with the surviving, local, ash-dominated woodland.

Pollen in clasts C and D is dominated by grass. The high Poaceae (Gramineae) values and wide range of herbs indicate that the area beside the tufa deposit was open, perhaps because of animals browsing beside the small stream, especially given the presence of Ranunculaceae and Lactuceae pollen and species such as *Plantago lanceolata*. Trampling could have broken up the tufa. The range of herb taxa, albeit recorded individually by small counts, probably represents a wide variety of species, as most are referable only to family or genus, and could derive from both grassland and wetland taxa.

4.8.3. Biostratigraphy and correlation

It is difficult to date the tufa from its pollen. The trees represented clearly indicate interglacial rather than interstadial conditions. An Ipswichian age is possible, probably from the IpIIb/III period, given the presence of *Carpinus* (although this taxon also occurs late in OIS 7 (Reille et al., 1998; Turner, 2000)), the low level for *Ulmus*, the overall distribution of taxa, and the absence of *Picea* (and also in effect of *Tilia*). However, the tufa pollen is difficult to correlate with that from other sites because of taphonomic differences and unusually high *Fraxinus* values associated with the calcareous soils near Marsworth. No direct correlates are obvious in the British Quaternary record. The most similarities occur with samples of mid- to late-interglacial age in terms of the co-existence of *Fraxinus* and *Carpinus*. For the best assemblage (A), comparison with Zone III at Wretton is close (Sparks and West, 1970), although the exact age of this site is now considered uncertain. The relative openness of the Marsworth site, while characteristic of some Ipswichian sites (e.g. Barrington et al., 1975), may have featured in more than one interglacial.

An alternative correlation of the pollen is with OIS 7. Although pollen assemblages of unequivocal stage 7 age have not been defined in Britain, several sites have been referred to this period on faunal, amino-acid or stratigraphic grounds, including Ilford (Seven Kings), Essex (West et al., 1964); Aveley, Essex (West, 1969); Strensham,

Worcestershire (de Rouffignac et al., 1995); Stanton Harcourt, Oxfordshire (Buckingham et al., 1996); and Stoke Goldington, Buckinghamshire (Green et al., 1996). Correlation of the Marsworth pollen in terms of the general spread of arboreal taxa with open-ground indicators is good for Aveley, but not for Stoke Goldington, where the assemblage is late interglacial. Correlation with Stanton Harcourt is perhaps reasonable (although *Fagus* is recorded there), but poor with Ilford, where *Fraxinus* is absent and the bedrock London Clay rather than Chalk.

The key palynological criteria distinguishing the Marsworth tufa are the high counts of *Fraxinus*, relatively high *Carpinus*, the evidence for other thermophilous trees, the absence of *Picea* and *Abies*, and the importance of Poaceae and *Plantago lanceolata*. No correlations match all these criteria. Arguments based on absence are inherently weak when the counts are low, as here, and the individuality of the site — its potentially very local signal and calcareous nature, make palynological biostratigraphic correlation uncertain. Thus on the evidence available this approach cannot assign a clear age to the tufa, although correlation with either OISs 5e or OIS 7 is likely. However, correlation with the earlier pollen assemblages of the Hoxnian as defined by West (1956, 1980) or by Turner (1970) is unlikely.

5. Plant remains in the Lower Channel deposits

5.1. Introduction

Pollen and plant macroremains were recovered from the Lower Channel deposits at site P1 (Figs. 2 and 5). A preliminary account of them was given in Green et al. (1984), with Field (1993) providing further detail on the macrofossils. The account below presents further information about the palynology of the Lower Channel sediments, excluding the tufa. Nomenclature of the plant remains follows Clapham et al. (1989).

5.2. Macrofossils

Two samples of the Lower Channel mud (Fig. 5), each weighing 1 kg, were wet-sieved and analysed. Plant remains were picked from the residues using a low-power binocular microscope. Twenty-five taxa were identified (Table 6).

5.3. Pollen and spores

Twenty-five samples for pollen and spore analysis were collected from a 1.5 m-thick continuous sequence at section P1 (Fig. 5). The samples were prepared for analysis using a combination of HCl, KOH and HF digestion (Moore et al., 1991). The palynomorphs recovered were generally in good condition, with few signs of deterioration

Table 6
Plant macrofossils from section P1, Lower Channel[a]

Sample number:		M1	M2
Shady places			
Stellaria cf. *neglecta* Weihe	s	1	—
Viola odorata L./*hirta* L.	s	2	—
Grassland, open and disturbed ground			
Cerastium cf. *fontanum* Baumg.	s	—	2
Draba sp(p).	s	—	155
Erophila verna (L.) Chevall.	s	—	17
Fumaria sp(p).	fr	2	—
Polygonum aviculare L.	fr	1	—
Potentilla tabernaemontani Ascherson/ *crantzii* (Crantz) G. Beck ex Fritsch	a	1	7
Potentilla sp.	a	1	—
Taraxacum Section *Taraxacum*	a	2	—
Stellaria cf. *media* (L.) Vill.	s	1	—
Viola subgenus *Melanium* sp(p).	s	12	7
Waterside, damp ground and shallow water			
Callitriche sp.	fr	1	—
Carex cf. *lepidocarpa* Tausch	tr.n	2	—
Nasturtium officinale R.Br.	s	2	—
Zannichellia palustris L.	fr	1	—
Unclassified			
Carex sp(p).	tr.n	281	1
Caryophyllaceae sp(p).	s	2	6
Cruciferae sp(p).	s	—	524
Gramineae sp(p).	cy	15	—
Ranunculus subgenus *Ranunculus* sp(p).	a	52	—
Rumex subgenus *Rumex* sp(p).	n	—	2
Viola riviniana Reichenb./*canina* L.	s	—	3
Viola sp(p).	s	35	67

[a] Abbreviations: a, achene; cy, caryopsis; fr, fruit; n, nutlet; s, seed; tr.n, trigonous nutlet.

tion and infrequent Pre-Quaternary types, suggesting the sediment was largely in situ. However, the samples analysed contained only small quantities of pollen and spores, the uppermost sample, at the base of the flinty coombe rock, yielding just three microfossils. At this and all other horizons in the mainly inorganic, upper fine gravels and intercalated chalky mud, at least five slides with $22 \times 40 \, \text{mm}^2$ coverslips were counted. In all other counts, a minimum of 100 grains and spores was attained, and thus a 10 cm sampling interval was used at these levels. Below this, in the organic mud and uppermost sand, counts of between 200 and 400 grains were obtained at most levels from five slides, allowing use of a 5 cm sampling interval.

The paucity of pollen could be due to one or more factors. A sparse plant cover, however, seems unlikely because the pollen assemblage, while including taxa that indicate open, treeless areas, suggests that the landscape was well vegetated. Second, a depressed pollen productivity characteristic of cold-climate floras is also unlikely because the botanical and other biological remains from the Lower Channel, described below, indicate temperate

conditions. Many of the plants contributing to the pollen rain in the Lower Channel are not usually represented by high frequencies of pollen in, for example, late Holocene non-forested environments. Third, rapid sedimentation could have diluted the pollen rain, but sedimentation rates are unknown. Fourth, oxidation levels, microbial activity and pH values could have been high enough to destroy many pollen grains and spores, although had this been so, the remaining palynomorphs might exhibit more signs of differential preservation.

Another important taphonomic issue concerns pollen sources and site catchment. Still or slow-flowing water in the Lower Channel, inferred below, indicates that water-borne pollen supplemented air-borne pollen. As the site is small, the model of Jacobson and Bradshaw (1981) suggests that it should receive mainly local pollen. However, as Moore et al. (1991) note, this model applies to forested landscapes rather than the mainly herbaceous vegetation near Marsworth. Moore et al. suggest that at sites in non-forested landscapes with low pollen production, as perhaps near Marsworth, the influence of far-travelled pollen becomes proportionately greater. This issue is discussed below.

The pollen sum chosen was total land pollen and spores (TLPS). Thus, small quantities of pollen from a diverse, local aquatic flora were excluded, whereas a small, mainly extra-local component of terrestrial spores was included. Percentage frequencies were calculated and the pollen diagram (Fig. 13) drawn using the TILIA computer package of E.C. Grimm, Illinois State Museum. The description of pollen taxa follows Birks (1973) and Moore et al. (1991).

5.4. Description and interpretation of the pollen spectra and plant macrofossil assemblages

The highest pollen sample, at the junction of the 'chalky mud and fine chalk gravel' and 'flinty coombe rock' (Fig. 5), contained only single occurrences of Cyperaceae, *Selaginella selaginoides* and *Lycopodium clavatum*. Hence this spectrum is omitted from Fig. 13. The observed restriction of *S. selaginoides* and *L. clavatum* to the top of the pollen profile may reflect the cold climate that triggered coombe-rock formation because these species are today mainly montane in northern Europe, although they do occur on heaths and moors at lower altitudes.

The difference and uniformity of the other pollen spectra militate against their division. Thus a single biozone is designated, characterised by low (usually ca 10% or less of TLPS) frequencies of arboreal and shrub taxa and high (usually ca 90% or more of TLPS) values of herbaceous taxa. In contrast, the frequencies of arboreal and shrub taxa in the tufa are ca 40% of TLPS.

Aquatic plant pollen occurs in low frequencies but represents a diverse flora. Hence, surprisingly few macro-

fossils from water plants were recovered (Table 6). Given the modern habitats of the fossils (Haslam et al., 1975; Haslam, 1978), the channel was probably shallow, still to slow-moving, eutrophic and highly alkaline, with a substrate of mineral and organic material. In the deeper parts floated *Nymphaea* and *Nymphoides*, while *Nuphar* either floated or was submerged; other floating plants were *Hydrocharis* and *Lemna*. Floating or submerged in shallower water were *Callitriche* and *Hottonia*, and *Hippuris* and *Stratiotes* were submerged or emergent in shallower areas at the channel margins. Some Gramineae pollen and macrofossils probably derived from this source.

Wetland fringed the waterbody. Macroremains of *Carex* and substantial quantities of Cyperaceae pollen show that sedges were an important part of marsh vegetation. *Juncus* sp. and *Ranunculus sceleratus* (identified from a bulk sample of the channel mud by Dr C. Turner), and *Sparganium, Typha* spp. and *Butomus* sp. also grew here. Seeds of *Nasturtium officinale* and *Sinapis* type pollen (which includes *Nasturtium*) indicate that this inhabited the water's edge. *Aster*-type pollen includes that of *Eupatorium cannabinum, Bidens cernua, B. tripartita, Pulicaria dysenterica* and *Carduus acanthoides*, all of which occur today in damp grassland and marsh beside streams in lowland England, as do *Filipendula ulmaria, Thalictrum flavum, Valeriana dioica, Lychnis flos-cuculi, Lysimachia vulgaris, Scrophularia auriculata, Teucrium scordium, Dipsacus pilosus* and *Thelypteris palustris*, together with some species of *Epilobium, Myosotis, Apium, Oenanthe* and *Ranunculus*.

On the drier areas the dominant vegetation was herb-rich calcareous grassland. Gramineae pollen dominates all spectra. *Aster*-type pollen includes that of *Bellis perennis* and *Erigeron acer*, characteristic of modern Chalk grassland. *Anthemis*-type pollen includes that of *Leucanthemum vulgare*, and *Centaurea nigra*-type *C. nemoralis*, both of which prefer base-rich soils, as do some *Cirsium* species. There are macroremains of *Taraxacum*, and consistent, substantial frequencies of *Cichorium intybus* type pollen. *C. intybus* is locally common in calcareous grassland today, and its pollen type also includes *Hypochoeris maculata, Leontodon hispidus, L. taraxacoides* and *Picris acioides*, currently more widespread members of such vegetation, as is *Campanula glomerata*. *Campanula*-type pollen includes *Phyteum orbiculare*, also locally abundant now in the Chalk grassland flora of southern England. *Filipendula vulgaris, Saxifraga granulata, Rhinanthus minor, Dianthus deltoides, Plantago media, Rumex acetosa, Linum perenne* (a *L. austriacum* type pollen), *Cynoglossum officinale* (a *Myosotis arvensis* type), *Botrychium lunaria, Knautia, Scabiosa* and most species of *Lotus* could also have been members of this vegetation.

Some open, stony ground probably occurred on the Chalkland, as inferred from macroremains of *Draba* and *Erophila verna* (both taxa included in *Sinapis* type pollen).

Fig. 13. Pollen and spore diagram from section P1 in Lower Channel deposits.

Also present here could have been *Viola arvensis*, *Verbascum* (a *Scrophularia* type pollen) and *Polypodium australe* (included in the *P. vulgare* spore type). *P. australe* is currently found on steep slopes and in open areas on base-rich rocks in lowland Britain (Clapham et al., 1989).

Disturbed sandy or gravelly areas are inferred from macroremains of *Polygonum aviculare* and *Fumaria*, together with pollen of *Spergula* type (including *Spergularia*), *Centaurea cyanus*, *Plantago coronopus*, *P. major* and *Artemisia*. The most likely areas of disturbance were the channel sides, probably trampled by large herbivorous mammals, described below, coming to drink and wallow.

Little botanical evidence exists for tree and tall shrub growth within the pollen catchment of the Lower Channel. No macrofossils of trees or shrubs were found and the pollen values are those usually attributed to a dearth of local and regional woodland. The best represented tree pollen is *Pinus*, but this grain's susceptibility to far dispersion and Moore et al.'s (1991) non-forested landscape model of pollen representation suggest that pine trees may not have been growing then in this part of southern England. The acceptance of a far-travelled pollen component raises the issue of whether the other arboreal taxa had a similar provenance. While this cannot be discounted, it seems more likely that the low, sporadic frequencies of *Betula*, *Alnus*, *Salix*, *Populus* and *Ribes rubrum* pollen came from trees and tall shrubs growing either singly or in small clumps on the channel sides. Similar representation of *Quercus*, *Ulmus*, *Tilia*, *Carpinus* and *Corylus* may reflect scattered trees or small patches of open woodland growing in the best soil. *Fraxinus* prefers calcareous soil and may have been a part then, as now, of scrub on Chalk substrates, together with *Juniperus* and *Cornus sanguinea*.

Acidic conditions, with both wet and dry habitats, are indicated by Ericales pollen, *Lycopodiella inundata* and *Pteridium aquilinum* spores. Heath occurs today on Chiltern slopes covered by clay-with-flints. These weathered remnants of Tertiary strata probably possessed similar vegetation in the past.

5.5. Climatic, biogeographic and biostratigraphic implications of the flora

Many of the plant taxa recorded in the Lower Channel currently tolerate a broad climatic range, temperate to arctic, and are widely distributed in northern Europe. They have also been found in both cold- and temperate-stage Pleistocene sediments (Godwin, 1975). The majority of Lower Channel taxa belong to the modern flora of southern England (Clapham et al., 1989) and suggest the former existence on the Chilterns of some analogous plant communities. Thus there seems little to suggest that the climate was significantly warmer or colder than that today, except for the evidence from the uppermost pollen

sample. The abundant macroremains of *Draba*, which now has a number of species confined to high altitudes and latitudes, and whose seeds are common in cold-stage sediments (Godwin, 1975) could have come from *D. muralis*; this species, although rare, today occurs on calcareous substrates in southern England. Some of the aquatic plants (e.g. *Lemna*, *Hottonia* and *Zannichellia*) have modern ranges which extend no farther north than southern Fennoscandia, and hence are unable to tolerate intense cold. Certain other aquatics (e.g. *Nymphoides* and *Stratiotes*) are now only sparsely distributed in the British Isles, the major extent of their ranges lying further east. This may hint at a more continental climate at the time.

The flora is either of interglacial or interstadial status. If it is interglacial *sensu* Turner and West (1968), then it records only part of one such episode. Low frequencies of tree pollen in spectra with boreal taxa dominant, but thermophilous taxa present, probably indicate a late interglacial substage. *Pinus* and *Picea* have no diagnostic biostratigraphic value in the Middle or Late Pleistocene of Britain, except that *Picea* seems not to have survived beyond the Early Devensian. However, *Abies*, well established during parts of the Cromerian and Hoxnian interglacials, was rare or absent in the Ipswichian (West, 1980). Accordingly, the Marsworth flora could belong to the Post-temperate substage (IV) of the Cromerian, Hoxnian, or a subsequent pre-Ipswichian interglacial. However, *Abies* pollen is sparsely recorded and may, together with that of *Pinus* and *Picea*, have been dispersed to southern England from mainland Europe.

Less is known about interstadial floras in Britain. Most data are from temperate episodes in the Devensian Stage (Jones and Keen, 1993), when boreal forest was characteristic, except in the Middle Devensian Upton Warren Interstadial, whose flora was a mixture of arctic-alpine, boreal and temperate plants, and comprised mainly grassland vegetation (Coope et al., 1961, 1997). Pre-Devensian interstadial floras from Brandon, Warwickshire (Kelly, 1968), and High Lodge, Suffolk (Turner, 1973; West, 1980; Hunt, 1992), both indicate that grassland was part of the vegetation, accompanying *Betula-Salix-Juniperus* scrub at Brandon and boreal forest at High Lodge. While some general similarities exist between these interstadial floras and that from Marsworth, detailed consideration of the floristic evidence militates against their correlation.

Greater similarity occurs between the vegetation in the Marsworth Lower Channel and that at Stoke Goldington (Green et al., 1996), where herb-rich grassland was well developed and open woodland existed with *Pinus*, *Picea*, *Abies*, *Carpinus* and *Corylus*. The plant remains from clay at Upper Strensham (de Rouffignac et al., 1995) are consistent with the patchy occurrence of *Betula*, *Pinus*, *Picea*, *Quercus*, *Alnus*, *Fagus* and *Carpinus* in a species-rich grassland. De Rouffignac et al. equate this temperate

episode with that represented at Stanton Harcourt (Briggs et al., 1985), where the interglacial flora was dominated by herb-rich grassland and disturbed ground species, and included woodland with *Quercus, Fagus, Carpinus, Alnus, Betula* and *Pinus* (Buckingham et al., 1996). Although Stoke Goldington, Upper Strensham and Stanton Harcourt have higher frequencies of arboreal pollen than Marsworth, this does not preclude botanical correlation between them, for the Marsworth pollen may date from a later part of the same interglacial (note pollen in tufa clast A; Table 5).

The uppermost sample at Marsworth has cold-climate pollen quite distinct from that beneath it. The channel fill was sealed by flinty coombe rock during later periglacial conditions. It seems that the fill was truncated at the start of coombe-rock deposition, and that an hiatus exists in the sequence, with the anomalous pollen assemblage providing evidence of a significantly colder climate, either at the end of the interglacial or the start of the ensuing cold stage.

The possibility remains that the Lower Channel fill is of interstadial affinity. A thermophilous plant assemblage, usually diagnostic of an interglacial, could develop during an interstadial were the climate sufficiently warm and refugia sufficiently close. The shorter timespan of an interstadial would prevent the orderly vegetation succession characteristic of an interglacial. The sudden and disorderly appearance of thermophiles in an interstadial probably reflects lower levels of competition than those in an interglacial (Woillard, 1978). Devensian insect faunas indicate that interstadial climates were not always cool (Coope, 1977).

6. Mollusca in the Lower Channel deposits

6.1. Introduction

The Lower Channel deposits were sampled for Mollusca at sections P1 (Fig. 5) and P2 (Fig. 2). In addition, details from sections examined by J.G. Evans and M.P. Kerney in the 1970s are incorporated in the present account. Evans and Kerney's major section, site B (Fig. 2), appears to correlate closely in stratigraphy and molluscan content with sections P1 and P2 of the 1980–1986 investigation. The results of these analyses are shown in Fig. 14 and Table 4. Samples from sections P1 and P2 were taken at approximately 10 cm intervals. The samples were oven dried at 40°C and washed through sieves to 500 μm. Sorting and identification was carried out using a 10–40× binocular microscope. The samples from the Evans and Kerney investigation each weighed ca 1.0 kg (dry weight) and were processed similarly to those in the 1980–1986 work.

Molluscan remains were abundant, a total of 3435 individuals being recovered from section P1. The
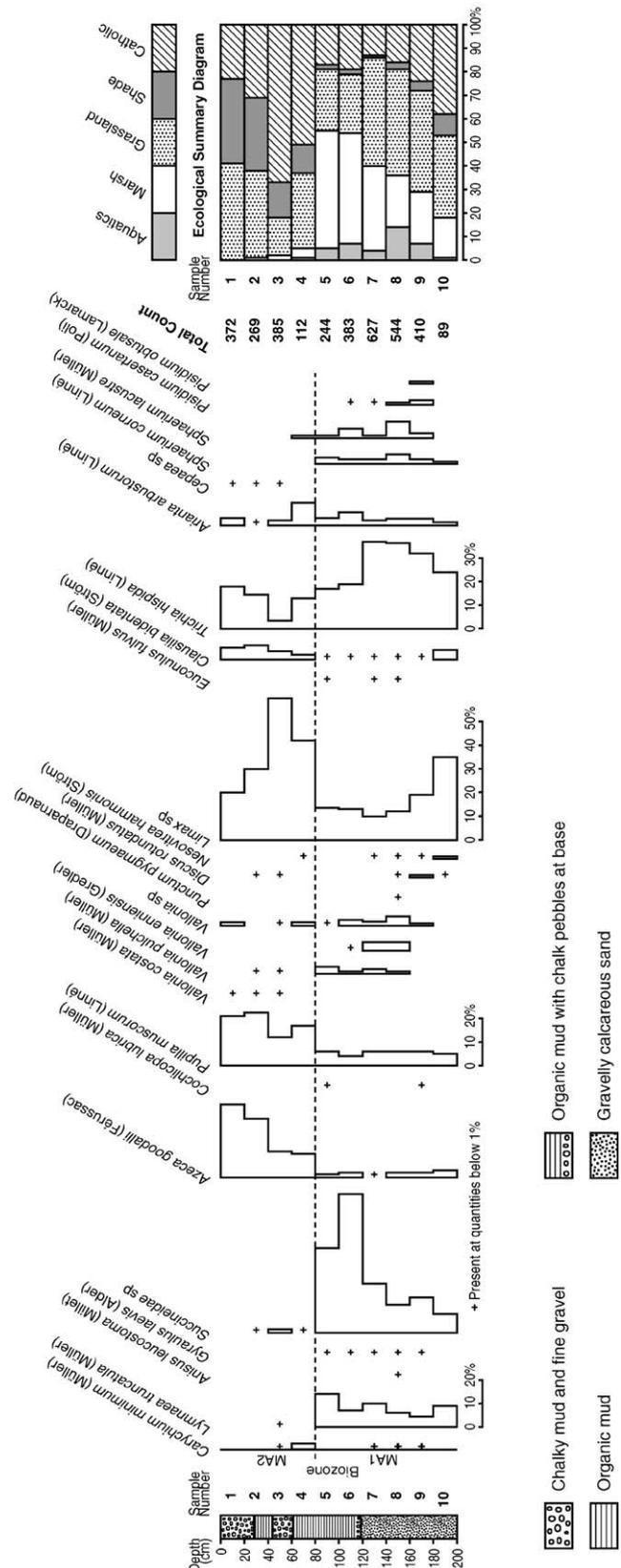

Fig. 14. Mollusc diagram from section P1 in Lower Channel deposits.

nomenclature below follows Kerney (1976) for aquatic species, and Kerney and Cameron (1979) for land species.

6.2. The molluscan fauna

The major section examined, P1, forms the basis of this account, although additional species occur in P2 and Evans and Kerney's site B. The P1 assemblage (Table 4) is divided into two biozones (Fig. 14). Biozone MA1, comprising the basal 1.20 m of the succession, contains numerous marsh and aquatic taxa, although these are accompanied by grassland and catholic species and a few individuals of shade-demanding taxa. The aquatic Mollusca are those of slum conditions (*sensu* Sparks, 1961), that is, of small, still, poorly oxygenated water bodies prone to drying [*Anisus leucostoma*, *Sphaerium lacustre* and *Pisidium casertanum*], although slightly better conditions are indicated by the presence of *Gyraulus laevis* and *Sphaerium corneum*. The majority of the Mollusca in MA1, however, indicate marsh (Succineidae), grassland and bare soil conditions [*Pupilla muscorum*, *Trichia hispida* and limacid slugs]. Shade-demanding taxa [*A. goodalli*, *D. rotundatus* and *Clausilia bidentata*] occur in low numbers.

Biozone MA2, forming the upper 0.80 m of the succession, is characterised by a disappearance of the fully-aquatic species and a great decrease in marsh taxa (Fig. 14). Grassland species such as *P. muscorum* increase, although other grassland inhabitants of the genus *Vallonia* maintain similar values to biozone MA1. Apart from *P. muscorum*, the biozone is dominated by limacid slugs, which inhabit environments varying from grassland to marsh, and shade indicators, of which *A. goodalli* is dominant and *C. bidentata* common. The shaded character of the fauna is also indicated by records from Evans and Kerney's work which are not found in section P1. Six additional taxa are recorded in their layer 8 [within unit B3 of the present investigation] [*Carychium tridentatum*, *Ena obscura*, *A. nitidula*, *Cochlodina laminata*, *Balea perversa* and *Helicigona lapicida*], all of which are typical today of shaded environments such as woods or scrub. Most of the shells of these shade species are broken and could be derived from deeper in the channel, although the ending of any influence of flowing water indicated in MA1 may preclude the most likely reworking mechanism. In addition, the intact specimens of *Arianta arbustorum* in MA2 suggest that little sedimentary disturbance took place, and the restriction of certain taxa to this biozone suggests that no source existed for reworking of some of these species.

Section P1 has 24 molluscan taxa represented (Fig. 14) and similar sediments in section P2 contain three more taxa [*C. tridentatum*, *Vertigo pygmaea* and *A. nitidula*]. The records from Evans and Kerney's work indicate four additional shade-demanding taxa (*E. obscura*, *C. laminata*, *B. perversa* and *H. lapicida*), plus the more

catholic *Vitrina pellucida*, *Aegopinella pura* and *Milax* sp. Thus the total number of species is 31.

6.3. Environmental indications of the molluscan fauna

The molluscan faunas from the Lower Channel sequence at Marsworth can be divided into two biozones, MA1 (plus Evans and Kerney's layer 9 at site B [within unit B3 of the present investigation]), and MA2 (Evans and Kerney's layer 8, site B [within unit B3 of the present investigation]).

Samples from P1 and P2 suggest slight water flow. The Evans and Kerney samples at site B have only one aquatic taxon, *P. casertanum*. It is likely that these samples came from different places in the Lower Channel and reflect the different facies which would occur during infilling of a small stream.

There is little in the fauna to suggest a cold climate, although the indications of open habitats might be thought to indicate cold-climate grassland. The total number of species (31), given the small size of the stream and the restricted number of species in grassland faunas, does not suggest cold conditions. Rather, the occurrence of such relatively southern species as *A. goodalli* and *D. rotundatus* indicates a temperate climate.

In MA2 the fauna suggests that the local environment became drier, with a predominantly grassland and shade or scrub fauna replacing the aquatic and marsh elements in MA1. This change may record sedimentary infilling of the channel or increased climatic dryness reducing spring flow, although rainfall values were clearly still high enough and evapotranspiration low enough to support the damp habitats required for a diverse mollusc fauna. In addition, stable-isotope work with δ^{18}O and δ^{13}C for calcite from *Limax* plates (Leng et al., 1998) indicates a humid climate with temperature and precipitation little different from that today. There is little evidence that the environmental change reflects climate cooling and the continued presence of the thermophile species *A. goodalli*, *E. obscura*, *D. rotundatus*, *A. nitidula*, *C. laminata*, *C. bidentata*, *B. perversa* and *H. lapicida* indicates a continuation of the general climatic conditions of MA1, as all of these species presently have a restricted northern range in Europe (Kerney and Cameron, 1979).

In summary, it is suggested that the faunas in biozones MA1 and MA2 represent the end of an interglacial.

6.4. Age of the fauna

Molluscan biostratigraphy in the Middle and Upper Pleistocene is not well developed for terrestrial faunas, with only large river fluvial assemblages giving any indication of age (Keen, 1990; Preece, 1995). Nothing in the molluscan fauna from the Lower Channel indicates any particular age. End-interglacial faunas are generally not well known, and on molluscan grounds the Marsworth

fauna could be correlated with any late-Middle or Late Pleistocene stage.

7. Coleoptera in the Lower Channel deposits

7.1. Introduction

Samples for coleopteran analysis were taken in 5 cm units through the full thickness (1.5 m) of the organic mud of the Lower Channel in section P2 (Fig. 2). These samples were taken contiguously so that no spaces were left between them. To maintain some degree of sampling consistency throughout the section, each sample was of about 3 l. However, because of varying amounts of inorganic material within the channel, it cannot be assumed that exactly the same quantity of fossiliferous sediment was processed each time.

Twenty-five samples were analysed. The sediment was washed over a sieve with a mesh aperture of 0.3 mm and the insect remains concentrated by oil flotation (Coope, 1986). The Coleoptera species recovered were preserved in tubes of 30% alcohol to prevent fungal attack. They were identified by comparing the fossil material with well-identified modern specimens. No morphological differences were found between the fossils and their modern equivalents. Altogether 92 taxa were recognised, of which 57 could be named to the level of species or species group. These are listed in Table 7, where the nomenclature and taxonomic order follow that of *Die Käfer Mitteleuropas* (Lucht, 1987).

7.2. Environmental interpretation based on the Coleoptera

Very little variation in the assemblages of Coleoptera occurs throughout the organic mud of the Lower Channel (Table 7). There is some indication from the mixture of relatively southern and northern species (compare the southern species *Stomodes gyrosicollis* with the more northern species *Eucnecosum brachypterum*) that the sediment may have been churned then by the large mammals. For the most part, however, the coleopteran sequence presents a consistent picture of the past environment built up as a mosaic from the present-day habitat preferences of all the species present in this fauna.

It is curious that this coleopteran fauna from a channel infilling does not include species indicative of running water: none of the riffle beetles (Helminthidae) that are so characteristic of flowing, well-aerated water. These species require running water to be present year-round, and it is tempting to view their absence here as evidence that the flow within the channel may have been intermittent or even seasonal. The numbers of carnivorous water beetles (the Dytiscidae), which live in both running and still water, were likewise extremely low. Only the abundance of *Helophorus* and some species of Hydrophilidae

indicate the presence of aquatic habitats, but these were probably stagnant ponds choked with rotting vegetation.

The Coleoptera provide ample evidence for the local existence of a marshy habitat with the aquatic grass *Glyceria*, probably growing both within and beside the channel. This grass is the main host plant of the chrysomelid species *Donacia semicuprea* and of the weevil *Notaris acridulus*, both of which were abundant throughout the sequence. It is interesting to note that *Glyceria*, the sweet grass, is very attractive to large herbivorous mammals and may well have drawn them to the vicinity of the marsh to feed. This interpretation is supported by the relative abundance of species of *Aphodius*, most of which are dung beetles. Some of the staphylinid beetles (e.g. *Oxytelus gibbulus*) are also associated with dung, where they prey upon small arthropods and worms.

The carabid species *Agonum thoreyi* lives on the margins of eutrophic ponds where the vegetation comprises tall reedy plants. It even lives on piles of dead reeds partially submerged in the water (Lindroth, 1992, p. 73). Amongst the phytophagous Coleoptera two species are characteristic of these marshy habitats: *Hydrothassa hannoveriana* feeds on *Caltha palustris* and *Prasocuris phellandrii* lives on various aquatic Umbelliferae.

In places this swampy vegetation must have been more open with bare patches of humus-rich soils interspersed between the tall plants. Such habitats would be suitable for *Elaphrus cupreus* and *Loricera pilicornis*. The preferred habitat of *Platynus albipes* is on clayish sandy soil at the water's edge, where there is only very sparse vegetation. *Clivina fossor* lives in open grassy places where the vegetation is short or patchy. It is a fossorial species that excavates tunnels in moist soil provided that it has enough clay or humus to maintain the integrity of the tunnels. It cannot burrow in pure sand. *Bembidion guttula* also lives in wet swampy ground overgrown with tall vegetation of *Carex* and grasses but it also occurs in damp meadows. *Patrobus septentrionis* in northernnmost Europe is very eurytopic but in southern Fennoscandia and the British Isles it is confined to damp places near water with a rich vegetation of *Carex*.

Several other species of Carabidae such as *Patrobus atrorufus*, *Pterostichus niger*, *P. melanarius*, *P. nigrita* indicate open, meadow-like country with a humus-rich soil and shaded by abundant weedy vegetation. *Trechus obtusus* is also a species of damp meadows but *T. quadristriatus* seems to prefer drier ground. Similarly, *Calathus fuscipes*, though not markedly xerophilous, lives amongst tall meadow-like vegetation. *Stomodes gyrosicollis* is a weevil that feeds exclusively on clover and lucerne. Species of *Sitona* feed on the leaves of various species of Papilionaceae and have larvae that live underground on the roots of these plants; in their early growth stages they attack the bacterial nodules on the roots and at later growth stages feed on the roots themselves. Other weevils such as *Otiorhynchus*, *Tropiphorus* and *Alophus* are

polyphagous, feeding on a wide variety of herbaceous plants. It is interesting to note that this assemblage of coleopteran species has, in modern times, been able to take advantage of human agricultural activities which have in many ways mimicked these ancient habitats.

Drier sandy soils are required by *Serica brunnea*, whose subterranean larvae feed on the roots of a wide variety of plants. *Cryptichus quisquilius* is likewise characteristic of well-drained sandy soils, where it probably feeds on fungus. Both species are rare in this assemblage, perhaps because such dry habitats were remote from the channel edge.

Several of the Coleoptera have more specialised requirements. *Thanatophilus dispar* and *Silpha tristis* are carcass beetles. Species of *Hister* are also often found in carrion, where they are predators on fly and beetle larvae. *Phosphuga atrata* is a predator on snails, and *Coccinella undecimpunctata* on aphids.

This coleopteran assemblage completely lacks any obligate tree-dependent species: no leaf-eating weevils, no scolytid bark beetles, no species that burrow into dead wood and no species that feed on fungus infestations of decaying tree trunks. In fossil coleopteran assemblages from forests such species are frequent. It seems reasonable, therefore, to infer that either trees were sparse in this environment or existed at some distance, possibly several kilometres, from the site.

7.3. Climatic implications of the coleopteran fauna

7.3.1. Thermal climate

This assemblage contains no obligate cold-adapted species, i.e. those restricted to localities above modern treeline. Although a number of species are present that can *tolerate* cold conditions, they do not *have to* live under such conditions. Thus there is no evidence that the rarity of trees was due to intolerable cold. Moreover, as the coleopteran assemblage is thoroughly western European, the rarity of trees cannot be attributed to a steppic environment.

The fauna includes only two species with predominantly southern geographical ranges. *Stomoides gyrosicollis* is a southeast European species that reaches as far north as eastern Austria and Czechoslovakia, where it is confined to the plains. There is an isolated population in central France, where it was introduced from Bosnia/Herzegovina in horse fodder during the Franco-Prussian war (Hoffmann, 1950). Although this species is phytophagous, its range can hardly be restricted today by the distribution of its food plant, chiefly clover. It suggests that some climatic factor permitted it to live well to the north of its present-day geographical limit. *Oxytelus gibbulus*, one of the most abundant species in this assemblage, is now almost entirely confined to the Caucasus Mountains.

Some species hint at rather cooler conditions than those of the present day. *Pycnoglypta lurida* is a northern species whose range extends as far south as eastern Prussia. The geographical range of *Eucnecosum brachypterum/norvegicum* is boreo-montane, with a continuous distribution only in northwestern Britain and in Fennoscandia north of about latitude 60°. *Simplocaria metallica* is another north European species that ranges as far south as southern Finland and Norway. The occurrence of these three species in the uppermost samples of this sequence hints at moderate climate cooling near the end of the channel infilling phase.

An assessment of the total assemblage of Coleoptera from Marsworth indicates a temperate climate, with temperatures not much different from those today in central England, i.e. not nearly cold enough to inhibit growth of broad-leafed trees such as *Quercus* or *Ulmus*. Any hint at greater climatic continentality is moderate indeed and probably inadequate to account for the rarity of trees at this site.

Using the Mutual Climatic Range method for reconstructing palaeotemperature (Atkinson et al., 1987), 29 species (carnivores and scavengers only) gave the following figures:

TMAX (mean temperature of the warmest month) 15–17°C
TMIN (mean temperature of the coldest month) −9–1°C

These figures indicate that TMAX and TMIN lay somewhere between these limits and not that it ranged between them. However, sensitivity tests on the MCR procedure, using modern coleopteran faunas living near to meteorological stations, show that there is a minor deviation of the MCR estimates compared with the actual mean monthly temperatures measured at those stations. A correction equation has therefore been calculated to take account of this deviation (Coope et al., 1998). Using this equation, the mean values for TMAX and TMIN are as follows:

TMAX mean (corrected) 15°C.
TMIN mean (corrected) −5°C.

These values give a most likely figure for the mean temperatures of the warmest and coldest months, respectively.

7.3.2. Precipitation

Although it is not yet possible to quantify objectively the levels of past precipitation from fossil coleopteran assemblages, some qualitative estimate of habitat humidity can be made. It is clear from the numerous species of marsh-dependent beetles that the climate was not arid. There are hints from the lack of any running-water

Table 7
Coleoptera remains from section P2, Lower Channel[a]

Samples in cm below top of organic mud:	120–125	115–120	110–115	105–110	100–105	95–100	90–95	85–90	80–85	75–80
Species of Coleoptera in systematic order										
Carabidae										
Carabus sp.										
Leistus rufescens (F.) or *ferrugineus* (L.)										1
Notiophilus sp.										
Elaphrus cupreus Duft.						1				
Loricera pilicornis (F.)										
Clivina fossor (L.)										
Bembidion guttula (F.)										
Bembidion sp.										
Trechus quadristriatus (Schrk.) and/or *obtusus* Er.			1	2				1		
Patrobus septentrionis Dej.										
Patrobus atrorufus (Ström)	1			1		1	2	1		1
Pterostichus nigrita (Payk.)										
Pterostichus niger (Schall.)						1				
Pterostichus melanarius (Ill.)	1	1		1			1	1		
Calathus fuscipes (Goeze)										
Agonum thoreyi Dej.										
Platynus ruficornis (Goeze)										
Dytiscidea										
Hydroporus sp.										
Agabus bipustulatus (L.)				1						
Agabus sp.										
Hydraenidae										
Ochthebius bicolon Germ. type	1	1		6			1	1		
Helophorus nubilus F.	1						1	2	1	1
Helophorus "aquaticus" auct. = *aequalis* Th.	2	1	2	1	1	1	1	3	4	
Helophorus misc. small spp.		1		6	1	2	3	1		2
Hydrophilidae										
Coelostoma orbiculare (F.)							1	1		1
Cercyon melanocepthalus (L.)										
Cercyon tristis (Ill.)		1								
Cercyon convexiusculus Steph.										
Cercyon sp.								2		1
Megasternum bolitophagum (Marsh.)										
Cryptopleurum minutum (F.)										
Hydrobius fuscipes (L.)		1		1		1		1		
Histeridae										
Hister sp. *sensu lato*										
Siphidae										
Thanatophilus dispar (Hbst.)										1
Silpha tristis Ill.										
Silpha sp.						1				
Phosphuga atrata (L.)				1						
Ptiliidae										
Acrotrichis sp.			1		1					
Staphylinidae										
Eusphalerum sp.										
[b]*Pycnoglypta lurida* (Gyll.)										
Olophrum fuscum (Grav.)					1			1		
Eucnecosum brachypterum (Grav.) and/or [b] *norvegicum* Munst.										
Acidota crenata (F.)										
Lesteva longelytrata (Goeze,)	1			1	1			1		

70–75	65–70	60–65	55–60	50–55	45–50	40–45	35–40	30–35	25–30	20–25	15–20	10–15	5–10	0–5
					1									
							1			1				
	1									1				
									1					
								1						
										1				
			1									1	1	
										1				
1		2	1	2	2	1	2			1	2	2	1	
													1	
			1				1	1						
		1		1									1	
										1				
										1				
								1						
			1			1							1	
	1													
				2	2	1	1	1				1		
					2	1				1	1		1	
3	2		3	4	4	5	3	2	4	5	1	2	2	
5				3	5	4	6	1	1	3	1	2	2	1
1										1				
										1				
		1		1										
													1	
1		1	1	1	1		1		1	1	1		1	
						1					1			
					1	1	1	1	1					
										1				
				1	1									
							1			1				
		1	1						1			1		
										1			1	
				1	3	1	2	1	1	5	1	2	2	
	1									1	1		1	1
				1			1							
2			1	2	1	1	1			1		2	1	
		1												

Table 7 (*Continued to next page*)

Table 7 (*Continued*)

Samples in cm below top of organic mud:	120–125	115–120	110–115	105–110	100–105	95–100	90–95	85–90	80–85	75–80
Geodromicus sp.	1									
Antherophagus alpinus (Payk.)										
Trogophloeus sp.										
Oxytelus rugosus (F.)		1	1	1	6		2	4	1	
[b]*Oxytelus gibbulus* Epp.		1	1	1		1	5	2	1	
Oxytelus nitidulus Grav.										
Platystethus arenarius (Fourcr.)										
Platystethus cornutus (Grav.)		2		1		1				
Platystethus nodifrons Mannh.								1		1
Platystethus nitens (Sahlb.)		1			1					
Stenus spp.	1	1	2	3	2	1	3	1	1	1
Euaesthetus laeviusculus Mannh.				1						
Quedius spp.		1								
Tachyporus chrysomelinus (L.)										
Tachyporus sp.									1	
Tachinus sp.				1						
Boletobiinae *Gen. et sp. indet.*										
Gymnusa brevicollis (Payk.)			2		1		2	1	2	
Aleochaninae *Gen. et sp. indet.*	2	8	8	1	4	1	6	8	6	2
Elateridae										
Agriotes sp.		1				1				
Byrrhidae										
[b]*Simplocario metallica* (Stürm)										
Byrrhus sp.							1			
Cryptophagidae										
Atomaria sp.		1				1				1
Lathridiidae										
Lathridius sp.	1	2		1				1	1	
Corticaria sp. or *Melanophthalma* sp.										
Coccinellidae										
Coccinella cf. *undecimpunctata* L.		1								
Tenebrioionidae										
Cryptichus quisquilius (L.)										
Scarabaeidae										
Aphodius spp.	1	2		3	1	1	2	2		2
Heptaulacus sp.										
Serica brunnea (L.)										
Chrysomelidae										
Donacia semicuprea Panz.	2	1	1	1	3	1	12	11	4	1
Phaedon sp.										
Hydrothassa hannoveriana a(F.)			1	1						
Prasocuris glabra (Hbst.)										
Prasocuris phellandrii (L.)										2
Phyllodecta sp.								1		
Curculionidae										
Apion spp.	1			1			2	2	1	
Otiorynchus fuscipes (Ol.) group							1			
Otiorynchus ligneus (Ol.)								1		1
Otiorynchus sp.										
[b]*Stomodes gyrosicollis* (Boh.)		1				1	1	1		2
Trachyphloeus sp.										
Sitona spp.						2	1	2		
Tropiphurus obtusus (Bonsd.)										
Notaris acridulus (L.)	4	3	1	3	1	1	3	7	2	
Alophus triguttatus (F.)				1				1		1
Hypera sp.										
Ceutorhynchiinae *Gen. et sp. indet.*						1		1		

[a]The numbers opposite each species and below each sample indicate the minimum number of individuals of each species in that sample.
[b]Indicates a species that is not now present in the British Isles. The samples were collected in 5 cm units and are measured from the top of the fossiliferous sequence in the Lower Channel.

70–75	65–70	60–65	55–60	50–55	45–50	40–45	35–40	30–35	25–30	20–25	15–20	10–15	5–10	0–5
	1													
		1										1		
1	1		1	2	3	5	2			2		1	1	
	1		2	5	3	3	3	1	1	3		1	2	
1														
				1				1						
									1					
1			1	1	1				1					
							2			1		1		
	3		2	3	1	2	2	1	1	7	2	7	3	1
												1	1	
1														
						1								
												1		
						1			1					
2	2		3	3	3	1	4	2		2	2	1	1	
6	12	2	3	9	3	5	4	3	2	14	3	6	9	
1														
												1		
				1				1		1		1	1	
										1				
			1							1				
							1					1		
2	1	1	3	3	6	3	1	1	4	9	4	6	7	
								1	1					
1			1											
9	12	3	4	13	10	8	7	1	1	5	1	1	1	1
												1		
			1		1									
	1													
	1	2			2	1	1			4		1	2	
1		1	1	1		1			1	2				
1			1			1	1						1	
										1				
	1	2		1	1						1			
		1												
				2	1									
									1					
4	3	1	1	7	2	3	5	1	2	1	1	1	2	
1	2			1			1							
								1	1					
		1				1							1	1

beetles that the channel may not have flowed year-round. Flow may have been seasonal, with summers that were moderately dry, but not dry enough to desiccate the marsh. Snowmelt may have supplied ample spring runoff to replenish the marsh and channel without necessarily implying high precipitation levels.

7.4. Stratigraphical implications of the coleopteran fauna

The Marsworth beetle assemblage is very similar indeed to that from Stoke Goldington (Green et al., 1996) and, though less so, to the faunas from Stanton Harcourt (Briggs et al., 1985) and Strensham (de Rouffignac et al., 1995). Of particular significance is the remarkable abundance in all these sites of the staphylinid beetle *Oxytelus* (= *Anotylus*) *gibbulus*, which today seems to be restricted to the Caucasus Mountains. (For further information on both the fossil and modern distribution of this species, see Hammond et al., 1979.) This species occurred sporadically in Britain at the end of the Ipswichian and during the Upton Warren Interstadial, but always in very small numbers. Only during OIS 7 does it appear in such numbers as to be one of the most abundant species in the coleopteran assemblages. At Marsworth this species clearly fulfills that criterion throughout the whole of the Lower Channel sequence. Since *O. gibbulus* is today associated with dung, it is unlikely that its rarity or absence from other British interglacial sites can be attributed to a lack then of available habitats.

The age of all these sites is demonstrably pre-Ipswichian and there are good grounds for believing in their interglacial status. The stratigraphical context of Strensham leaves no room to doubt that it is pre-Ipswichian because it is at a higher altitude in the Avon terrace staircase than terrace 3 with its Ipswichian vertebrates, including *Hippopotamus*. In addition, the aminostratigraphical context of the Strensham Court Bed suggests that it antedates the Ipswichian (Maddy, 1999). Similarly at Stoke Goldington, the fossil record, amino-acid racemisation ratios and uranium-series dating from the lower channel (Green et al., 1996) suggest a pre-Ipswichian age. Both these sites can be attributed with reasonable certainty to OIS 7. At Stanton Harcourt the fossil-bearing deposits were intimately associated with trunks of oak and with shells of the bivalve *Corbicula fluminalis* in their growth position. Thus on floral and faunal (both coleopteran and molluscan) grounds this episode clearly represents an interglacial.

In contrast to the similar beetle faunas from the three sites above, these coleopteran assemblages are very different from those dating from the Ipswichian (Coope, 1974; Keen et al., 1999), Hoxnian (Coope, 1993; Keen et al., 1997) or Cromerian Interglacials (Maddy et al., 1994; Shotton et al., 1993).

For the above reasons, the Coleoptera provide a strong biostratigraphical case for attributing the Mars-

sworth interglacial deposits infilling the Lower Channel to some part of OIS 7.

8. Vertebrate remains

8.1. Lower Channel

8.1.1. Fauna

Mammalian remains (Figs. 15–17; Table 8) were collected from gravelly calcareous sand and overlying organic mud from the Lower Channel (levels 3 and 2, respectively, in Fig. 6), and from gravelly silty sand (unit B2) and the base of the overlying pebbly silty clay and loam (unit B3) at site B (Fig. 4). The remains comprised bone fragments and many complete, well-preserved bones and teeth. Approximately 11,700 bones and teeth specimens were collected during the controlled excavation in the Lower Channel (P3 in Fig. 2). The number of specimens recovered from levels 3, 2 and 1 were approximately 10,600, 700 and 400, respectively. The recorded bone scatter in level 3 is shown in Fig. 15. Eight hundred and thirty-four specimens belonging to 12 species have been identified (Table 8, Schreve, 1997), including *Mammuthus primigenius* (woolly mammoth) (Fig. 17) and previously unpublished records of an indeterminate leporid (hare or rabbit), *Vulpes vulpes* (fox), *Palaeoloxodon antiquus* (straight-tusked elephant), *Bos primigenius* (aurochs) and cf. *Bison priscus* (bison).

8.1.2. Ecological significance of the mammals

Open grassland indicators are most abundantly represented in the mammalian fauna from the Lower Channel. For example, *Equus ferus* (horse) comprises more than 35% of the assemblage, and *Mammuthus primigenius* more than 23%. The microtine assemblage consists exclusively of *Microtus oeconomus* (northern vole), a species most widely distributed today throughout the northern tundra and taiga of continental Europe, especially in wet, grassy habitats (Miller, 1912; Stuart, 1982). Woodland habitats are inferred from *Palaeoloxodon antiquus*, *Bos primigenius* (aurochs) and *Ursus arctos* (brown bear). The proximity of a slow-flowing water source is suggested by remains of *Neomys fodiens* (water shrew) and *Arvicola terrestris cantiana* (water vole). Temperate conditions are indicated by the occurrence of straight-tusked elephant and aurochs, known in Britain only from warm Pleistocene episodes (Stuart, 1982). As the same species occur at different depths within the Lower Channel, there is no evidence for environmental change during deposition.

8.1.3. Biostratigraphy and correlation

The presence of *Mammuthus primigenius* in a temperate context suggests that the Lower Channel fill dates from OIS 7. Woolly mammoth is unknown from the Hoxnian Interglacial, from sites attributed to OIS 9 (Bridgland,
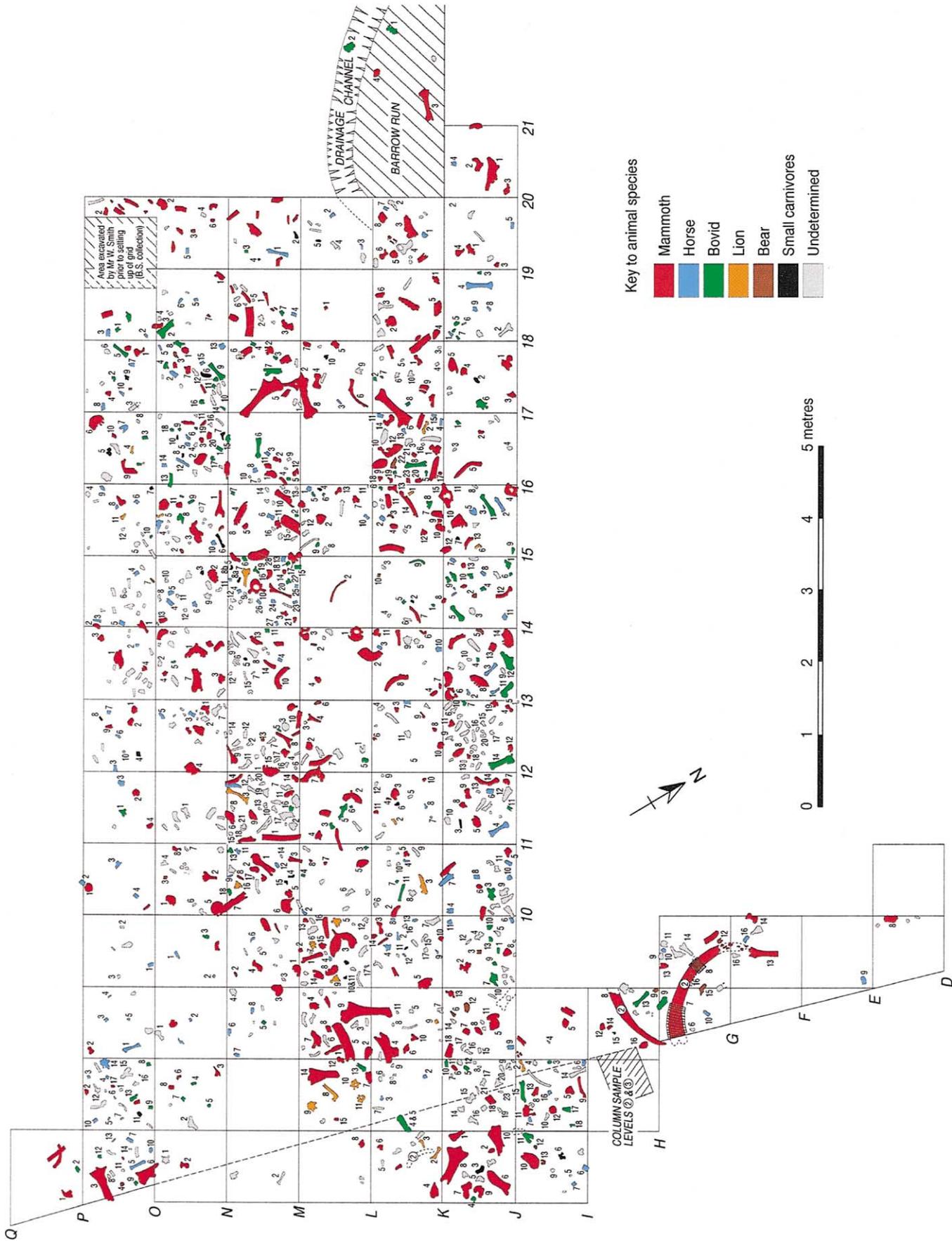
Fig. 15. Detailed plan of bone scatter in level 3 (gravelly calcareous sand; lower fluvial deposits correlated with unit B2 in Table 1) of controlled excavation in Lower Channel. Location corresponds with south-western half of site gridded for excavation (P3 in Fig. 2). Grid line P coincides more or less with south-western side of rectangle P3 in Fig. 2. Dashed line marks location of stratigraphic section in Fig. 6.
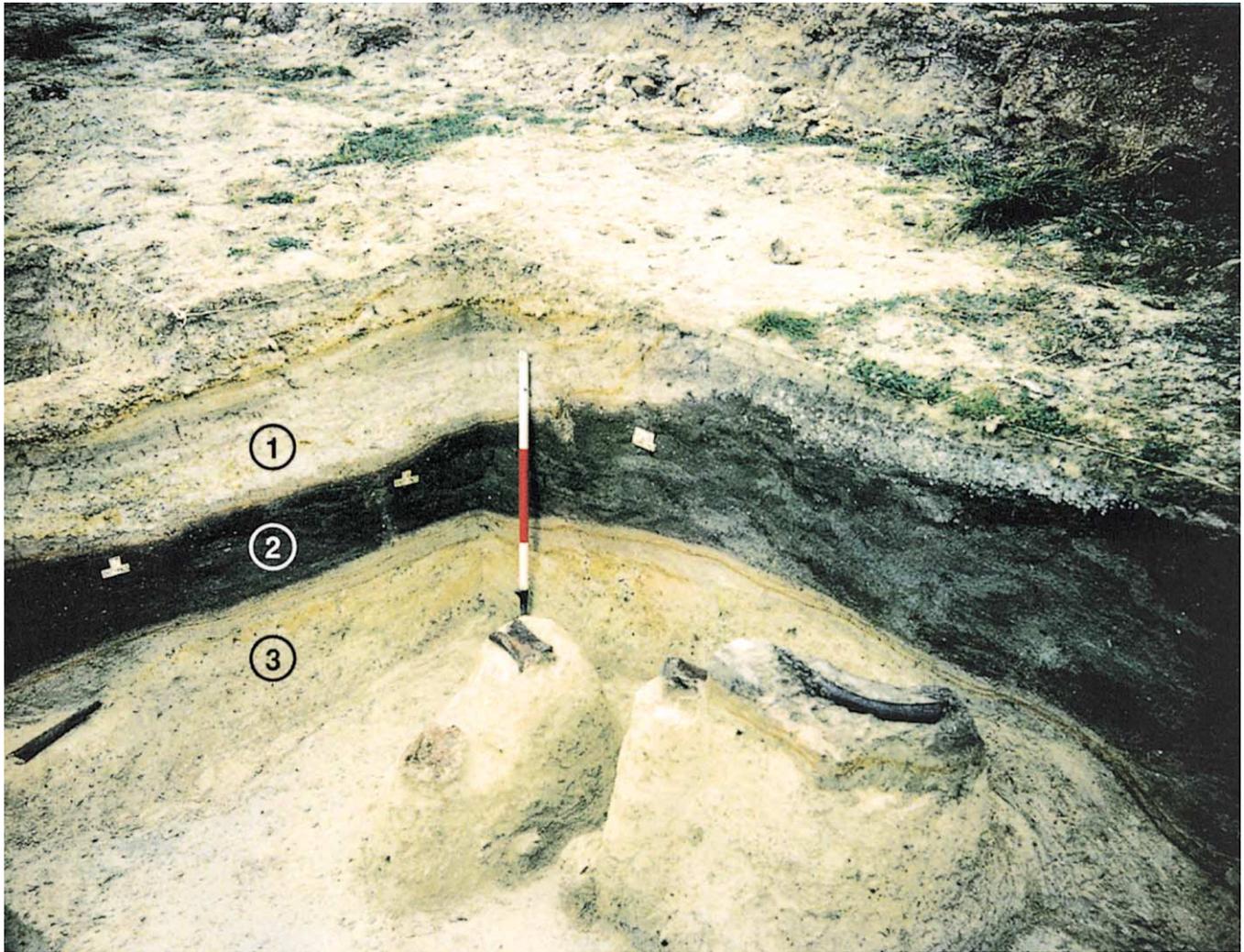
Fig. 16. An assemblage of in situ mammal bones from controlled excavation in Lower Channel, most of which typically underlie organic mud. Same bones shown in square J6 of Fig. 15. (David Parish/Buckinghamshire County Museum).

1994; Schreve, 1997) and from the Ipswichian 'Hippopotamus' fauna (Bridgland, 1994). In contrast, woolly mammoth consistently occurs in faunas now widely assigned to a pre-Ipswichian temperate episode equated with OIS 7, the stratigraphic position of which is well-established within long fluvial sequences such as those of the Lower Thames and Avon (Sutcliffe, 1976, 1995; Wymer, 1985; Bridgland, 1994; de Rouffignac et al., 1995). *M. primigenius* is also known from the warmest part of the Devensian (OIS 3) and from interstadials within the Devensian but with a totally different faunal association to that observed at Marsworth. Furthermore, the Lower Channel *M. primigenius* sample includes molars of the 'Ilford type', a morphotype characterised by both small size and primitively low plate count in the molars (Davies, 1874; Adams, 1877–1881; Lister and Joysey, 1992; Lister, 1996). These features also occur in certain teeth from other sites attributed to OIS 7, including Ilford (Sutcliffe, 1964); Northfleet, Kent (Wenban-Smith,

Fig. 17. Mammoth ulna in situ beneath organic mud in Lower Channel. Proximal end of ulna rests on Chalk bedrock. Ulna corresponds to bone 9 in squares L8 and K8 in Fig. 15. (David Parish/Buckinghamshire County Museum).

1995); Brundon, Suffolk (Moir and Hopwood, 1939); and Stanton Harcourt (Scott and Buckingham, 1997), suggesting that the 'Ilford-type' mammoth may be of biostratigraphic significance in demonstrating an OIS 7 age (Lister and Joysey, 1992; Lister, 1996). To date, the 'Ilford-type' mammoth has been found only in association with evidence for temperate climatic conditions.

At localities such as Ilford and Stanton Harcourt the percentage of *M. primigenius* molars of 'Ilford type' reaches 100%. However, at Marsworth both the 'Ilford type' and more advanced specimens with a higher plate count (similar to typical Devensian *M. primigenius*) co-exist (Lister, 1996). Of 16 complete mammoth last molars from the Lower Channel, eight have a morphology typical of Ilford and other OIS 7 sites, with small crowns and low lamellar counts, and eight have a more advanced morphology typical of *M. primigenius* from later deposits,

especially of cold stages (Lister and Joysey, 1992; Lister, 1996). The co-occurrence of primitive and more advanced types in the undisturbed context of the Lower Channel suggests an age towards the end of the OIS 7 interglacial, since 'advanced' forms appear to have completely replaced the 'Ilford type' by OIS 6 (Lister and Brandon, 1991; see later). A similar pattern is observed at Brundon (A.M. Lister, pers. comm.), possibly also reflecting a date toward the end of this interglacial.

Other elements of the Lower Channel mammal fauna also have biostratigraphic significance. The presence of *Palaeoloxodon antiquus* in combination with the 'Ilford type' *M. primigenius* is considered characteristic of OIS 7 (Schreve, 1997), although remains of the former are always much scarcer, as in the Lower Channel, where *P. antiquus* comprises just over 1% of the identifiable elephant remains.

Table 8
The Mammalian fauna from the Lower and Upper Channels and intervening cold-climate deposits

	Gravelly silty sand (level 3)[a]	Organic mud (level 2)	Unit B3 (level 1 and machine cut)	Upper Channel
Insectivora				
Neomys fodiens (Pennant)	x	—	—	—
Lagomorpha				
Leporidae sp., indeterminate hare or rabbit	x	x	—	—
Rodentia				
Arvicola terrestris cantiana (Hinton), water vole	x	—	—	x
Microtus oeconomus (Pallas), northern vole	x	—	—	—
Microtus sp., indeterminate vole	x	—	—	—
Carnivora				
Panthera leo (L.), lion	x	x	—	—
Ursus arctos L., brown bear	x	x	—	—
Vulpes vulpes (L.), fox	x	x	x	—
Canis lupus L., wolf	x	x	x	—
Proboscidea				
Mammuthus primigenius (Blumenbach), woolly mammoth	x	x	x	—
Palaeoloxodon antiquus (Falconer and Cautley), straight-tusked elephant	x			x
Elephantidae sp., indeterminate elephant	x	x	—	—
Perissodactyla				
Equus ferus Boddaert, horse	x	x	x	—
Stephanorhinus hemitoechus (Falconer), narrow-nosed rhinoceros	—	—	—	x
Artiodactyla				
Hippopotamus amphibius Linné, hippopotamus	—	—	—	x
Cervus elaphus, Linné, red deer	—	—	—	x
Cervus cf. *elaphus* L., red deer	x	—	—	—
Dama dama, (Linné), fallow deer	—	—	—	x
Megaloceros giganteus (Blumenbach), giant deer	—	—	—	x
Cervidae sp., indeterminate deer	x	—	—	—
Bos primigenius Bojanus, aurochs	x	—	—	—
Bison priscus Bojanus, bison	—	—	—	x
cf. *Bison priscus* Bojanus, bison	x	—	—	—
Bovidae sp., indeterminate large bovid (*Bos* or *Bison*)	x	—	x	—

[a]Levels 3, 2 and 1 refer to those in the controlled excavation through the Lower Channel (see Fig. 6).

Equus ferus, abundant in the Lower Channel deposits, also suggests a pre-Ipswichian age on account of its absence from the British Last Interglacial (Sutcliffe, 1995). It may be argued that since most unequivocal Last Interglacial sites represent only pollen zones Ip I and II, it cannot be verified that horse was genuinely absent from the British Isles during zones Ip III and IV. However, the balance of evidence suggests that horses (together with humans) were absent from Britain and from most of north-west Europe for an extensive period encompassing at least the whole of OIS 5 and 4. Horse has never been recovered from any Last Interglacial site yielding hippopotamus (see below), and its absence from Britain during OISs 5e is therefore assured. Nor does horse occur in the few cases where deposits post-dating zone Ip II are present, such as at Swanton Morley, Norfolk (Coxon et al., 1980). The continuing absence of this species during the later parts of OIS 5 is further noted in the deposits of the Gower caves, and horses (and indeed humans) do not appear to have returned to the British Isles until the mid-Devensian, when they are recorded at sites such as Pin Hole, Cresswell (Currant and Jacobi, 1997). To argue that there was a brief re-immigration of horse into the British Isles for a period corresponding to pollen zones III and IV of oxygen isotope substage 5e requires special pleading, and there is no apparent physical mechanism (such as reconnection to the continental mainland) which might have permitted this.

The microtine assemblage from the Lower Channel likewise suggests an age within OIS 7. The northern vole (*Microtus oeconomus*) occurs in deposits ranging from the Cromerian Complex to the early Holocene in the British Isles (Stuart, 1982), but it appears to have dominated the British microtine fauna during OIS 7 and especially 6 (Schreve, 1997). Although the sample size from the Marsworth Lower Channel is relatively small ($n = 11$), the exclusive representation of this species may be significant. The dominance of *M. oeconomus* during this period is apparently associated with increased intraspecific dental morphological variability, a factor which has in the past led to the misattribution of *M. oeconomus* material to *Microtus nivalis* or *Microtus malei* (Hinton, 1907, 1926; Sutcliffe and Kowalski, 1976). It is now recognized that these forms represent a single, morphologically-variable population (Stuart, 1982). The Marsworth material also includes dental morphologies which would previously have been attributed to *M. nivalis* and *M. malei*. A progressive increase in the size of the first lower molars in *M. oeconomus* has also been documented throughout the later Middle Pleistocene, peaking in OIS 6 (Schreve, 1997). The mean length of the first lower molars from Marsworth (2.78 mm ± 0.067, $n = 6$) is slightly smaller but comparable to that from Crayford (2.87 mm ± 0.041, $n = 12$). However, the mean length in the Marsworth sample is significantly smaller than those from sites attributed by Schreve (1997) to OIS 6, thereby implying a pre-OIS 6 age for the Lower Channel.

An age towards the end of the OIS 7 interglacial is suggested for the Lower Channel mammal fauna based upon the presence of morphologically advanced specimens of *M. primigenius* and comparison with the fauna at Aveley (Bridgland, 1994), where a long sequence spans most of OIS 7 (Schreve et al., in prep.). The earliest temperate deposits at Aveley record an episode of very warm conditions at the beginning of this interglacial, characterised exclusively by species favouring fully-temperate woodland. This woodland fauna is replaced higher up the sequence by a 'mammoth-horse' assemblage and other species characteristic of more open grassland conditions, although apparently the climate remained warm. The mammalian assemblage from the Lower Channel at Marsworth most closely resembles the later temperate faunal grouping at Aveley. No evidence was found at Marsworth of the earlier woodland fauna, although the leaf impressions of thermophilous woodland trees in the tufa clasts may date from this early phase.

8.2. Pebbly silty clay and loam [unit B3]

8.2.1. Fauna

Five mammal species (97 specimens) were identified from level 1 of the controlled excavation and in an adjacent machine-cut through it parallel to the vertical section shown in Fig. 6. Level 1 comprised pebbly silty clay and loam [correlated with unit B3 of sections B1–B3] that overlay the fluvial sediments of the Lower Channel (Table 8). The sediment from the machine-cut is believed to derive mainly from level 1, based on the distinctive preservation condition of the bones (see below) and the sediment attached to them. The mammalian assemblage from level 1 and the machine-cut is typically quite different to that from the Lower Channel, both in its character and preservation, the specimens being a creamy yellow colour (rather than brown or dark-stained) and frequently broken and abraded; however, not all of the bone from level 1 is so poorly preserved. Specimens attributed to the extinct 'ass', *Equus hydruntinus* by Green et al. (1984) on the basis of very small dental and postcranial material, have been re-identified as a small-bodied form of *Equus ferus* (Schreve, 1997).

8.2.2. Ecological significance

The mammalian remains from the pebbly silty clay and loam are characteristic of open environments. This is suggested by the predominance of *Equus ferus* in the assemblage and the presence of other large grazing or part-grazing herbivores, *Mammuthus primigenius* and large bovids. No indication of climate is given by the mammalian assemblage, since all species are known from temperate and cold stages alike.

8.2.3. Biostratigraphy and correlation

The large horse of the Marsworth Lower Channel is replaced in the overlying deposits by a small-bodied form (the origin of the misidentification of *Equus hydruntinus* by Green et al., 1984) whose occurrence precludes both an Ipswichian and an Early Devensian age — periods when this species was apparently absent from Britain (Sutcliffe, 1995; Currant and Jacobi, 1997). An OIS 6 age for the pebbly silty clay and loam is inferred from the small form of *Equus ferus*, in conjunction with the stratigraphic position of the deposits, post-dating the fluvial sediments in the Lower Channel and pre-dating the Upper Channel deposits. The distinctive small-bodied horse has been recovered from cold-climate deposits at sites which include Bacon Hole, S. Wales (Stringer, 1975, 1977; Stringer et al., 1986); Norton Farm, W. Sussex (Bates, 1998; Bates et al., 1998; Bates et al., 2000); Black Rock, Brighton, E. Sussex (Mantell, 1833); and Clevedon Cave, Somerset (Reynolds, 1907). At Norton Farm and in the Black Rock raised beach, the small horse first appears in conjunction with micropalaeontological evidence for the onset of cold-climate conditions during a period of high sea-level, thought to represent the transition from OIS 7 to 6 (Parfitt et al., 1998). At Bacon Hole, Clevedon Cave and in the coombe rock overlying the raised beach at Black Rock, there is evidence to suggest that small horses persisted well into OIS 6 (Schreve, 1997). The decrease in body size of *E. ferus* remains from Marsworth may reflect the adaptation of horses to stressful climatic and vegetational conditions (cf. Forstén, 1996) following climatic deterioration at the end of an interglacial.

A post-OIS 7 age is also consistent with the occurrence of distinctive *M. primigenius* molars within deposits from the machine-cut. As far as the small sample allows ($n = 3$), the molars observed in the pebbly silty clay and loam comprise solely a more derived form, unlike those in the underlying Lower Channel deposits, of which 50% of the diagnostic ones are of the primitive 'Ilford-type'.

8.3. Upper Channel

8.3.1. Introduction

A 1976 rescue excavation in the Upper Channel by the Pitstone Local History Society recovered abundant bone concentrated in irregular patches over an area of at least $100\,m^2$. The largest concentration was ca 12 m across, the bones lying horizontally but with no particular orientation in a discrete layer of coarse, poorly-sorted gravel. The fossils in the Upper Channel are definitely in primary context. Several small groups of bones occur which apparently belonged to single skeletons, for example, parts of the right humerus, radius and ulna (bones of the forelimb) of a narrow-nosed rhinoceros and the associated upper left and right cheek dentition of a hip-

popotamus. Many of the bones had been shattered in situ and most had been heavily etched by plant roots. Their condition reflects burial of no more than a few centimetres below the base of the modern soil of the Tring Series (Avery, 1964).

Over the following 18 months APC regularly visited the site to collect further material and examine the stratigraphy of the fossil-bearing deposits as the site was developed. A section close to the largest bone concentration showed faunal remains to occur throughout the stratified silt, sand and gravel fill of a shallow fluviatile channel and in associated pond-like depressions. These features were cut into involuted loams and Chalky gravels overlying heavily disturbed Chalk, sharply truncating the involutions (Fig. 8; Worsley, 1987). Except for the restricted area with the fossiliferous deposits, the cold-stage deposits formed the local subsoil geology. The remarkable survival of so much bone so close to the modern ground surface is probably due to the sealing of the fossils under a layer of very tenacious pale blue marly clay which capped the channel fill and filled the associated shallow pond-like depressions.

8.3.2. Ecological significance

The Upper Channel fauna is a temperate assemblage which appears to reflect a mosaic of woodland and grassland habitats. Hippopotamus is closely associated with a wide range of freshwater aquatic environments. Its grazing activities, along with those of other megaherbivores such as *P. antiquus* and *S. hemitoechus*, are likely to have led to local or even regional habitat modification and would have maintained large expanses of open ground.

8.3.3. Biostratigraphy and correlation

The mammal fauna from the Marsworth Upper Channel (Table 8) is a slightly restricted version of a highly characteristic assemblage known from many sites in England and Wales (Currant and Jacobi, 1997). The biostratigraphic importance of this assemblage as a marker for the climatic optimum of the Last Interglacial was first recognized by Sutcliffe (1960) in his description of material from Joint Mitnor Cave, Devon. At Victoria Cave, North Yorkshire, U-series dating of clean stalagmite enclosing key elements of this fauna indicated an age of ca 125 ka BP, the warmest part of the Last Interglacial complex (OISs 5e) (Gascoyne et al., 1981). A very consistent association exists between this mammalian faunal assemblage and other evidence for fully-interglacial conditions as inferred from pollen, beetles and molluscs at sites such as Trafalgar Square, Central London; Barrington, Cambridgeshire; and Swanton Morley (Stuart, 1995). Pollen samples from the Upper Channel (examined by Dr P.L. Gibbard) yielded no identifiable plant remains.

9. Ostracoda in the Lower Channel deposits

9.1. Introduction

Ostracods were recovered from the washed residues prepared for molluscan analysis from section P1 (Fig. 5). Substantial numbers of ostracods, both adults and pre-adult instars, were observed in gravelly calcareous sand of the lower part of the sequence (samples 7–10; Fig. 5). The 11 species identified are listed in Table 9. No ostracods were observed in samples from above the gravelly calcareous sand.

9.2. Environmental indications of the ostracod fauna

Prionocypris zenkeri (Chyser), a relatively large form in its adult valves, dominates three of the four samples. This swimming ostracod is today associated with year-round streamflow, and dwells amidst long strands of green plants in typical chalk streams. Second in abundance is either *Candona neglecta* Sars or *Ilyocypris bradii* Sars. *C. neglecta* is a cold-temperature species that burrows in soft substrates, often quite common in Pleistocene assemblages but now relatively rare in Britain. *I. bradii* is a non-swimming species that clambers on aquatic vegetation and prefers stable, cool temperatures. *Herpetocypris reptans*, has similar preferences to *Candona*, usually occurring in still or stagnant water bodies with rich plant growth. At section P1, however, the delicate valves of this species are mostly fragmented and may have been washed into the present association.

These dominant species point to a stream with perennial flow, probably quite shallow and rich in aquatic plant growth. However, also present in the assemblage are elements from habitats nearby, including species associated with spring issues (*Potamocypris wolfi* Brehm, *P. zschokkei* (Kaufmann) and *Cypridopsis subterranea* Wolf) and calc-tufa formation ((*Eucypris pigra* (Fischer)).

Ostracod assemblages comparable to those at Marsworth are known from the Holocene travertines of Bad Langensalza, Saxony (Diebel and Peitrzeniuk, 1975), and from interglacial calcareous sands in rivers of the same region. *Prionocypris*-dominated levels also occur in channel deposits within Thames terrace sediments of Upton Warren Interstadial age at the Ismaeli site in South Kensington, Central London (Coope et al., 1997), and at Isleworth, Middlesex (Kerney et al., 1982). No species represented in the ostracod fauna indicate regional temperatures unlike those of the Marsworth area today.

10. Geochronology

10.1. U–Th dating

Previous age determinations on the Marsworth tufa were of limited success. Five samples were analysed, of which two gave isotope ratios signifying the occurrence of post-depositional leaching (Green et al., 1984). Of the other three samples, detritally corrected ages of 171^{+28}_{-24}, 165^{+34}_{-27} and 149^{+16}_{-14} ka were obtained, which with 1 sigma errors suggest that the tufa could have formed at any time from 199 to 138 ka BP.

Five new analyses were carried out in the present study to improve the age constraints on the time of tufa deposition. Four samples were chosen which visually appeared to lack recrystallised calcite or Chalk clasts, and which were laminated. Five 30–100 g subsamples were prepared, including one top and bottom pair on a single sample and, as far as possible, avoiding inclusion of detrital Chalk clasts. The samples were dissolved, uranium and thorium extracted and counted using standard techniques (Gascoyne, 1977).

These five new U–Th age estimates and the previous ones are listed in Table 10. The new analyses have ages with errors reported at 1σ, and thus the range of ages of all the analyses is best represented as $> 350–156$ ka BP, which does not improve the dating of the deposit. Most of the samples suffered from detrital thorium contamination, although none appeared to be leached, and all fall within the 'permitted zone' of uranium and thorium isotopes. The one clast analysed in top and bottom sections yielded mean ages which differed by 120 ka (although they do agree within 1σ errors), despite the counting of less than 50 laminae from top to bottom in the clast. This suggests that the errors associated with the tufa clasts represent errors in counting statistics or a breakdown in the assumptions of U–Th dating rather than long periods of tufa deposition.

Assuming that tufa deposition occurred during a single interglacial (as indicated by pollen and stable-isotope evidence) and that all the reworked clasts are from this deposition phase, then an isochron plot can be used to correct for the presence of any non-radiogenic ^{230}Th

Table 9
Ostracoda from the Lower Channel deposits, section P1

Sample number	7	8	9	10
Candona candida Müller	2	3	—	1
Candona neglecta Sars	4	14	2	26
Cypridopsis subterranea Wolf	—	—	—	1
Cyprinotus salinus (Brady)	—	2	—	—
Eucypris pigra (Fischer)	—	7	—	1 + ?1
Herpetocypris reptans (Baird)	12	12	—	—
Ilyocypris bradii Sars	6	9	7	7
Potamocypris cf *maculata* Alm	—	—	1	—
Potamocypris wolfi Brehm	4	2	—	9
Potamocypris zschokkei (Kaufmann)	—	—	—	12
Prionocypris zenkeri (Chyzer)	1	96	98	132
Total	29	145	108	190

Table 10
U–Th analyses on tufa clasts from the Lower Channel deposits[a]

Sample ID	Laboratory ID	^{238}U (ppm)	^{234}U/^{238}U	^{230}Th/^{234}U	^{230}Th/^{232}Th	Age (corrected)
	HUTH1359	0.14 ± 0.02	0.81 ± 0.16	1.91 ± 0.347	5	Leached
	HUTH1360	0.12 ± 0.02	4.41 ± 0.83	1.033 ± 0.107	17	Leached
	HUTH1539	0.06 ± 0.01	2.16 ± 0.19	0.88 ± 0.065	12	$171 + 28 - 24$
	HUTH2215	0.08 ± 0.01	1.48 ± 0.13	0.833 ± 0.071	15	$165 + 34 - 27$
	HUTH2237	0.10 ± 0.01	1.55 ± 0.08	0.795 ± 0.041	37	$149 + 16 - 14$
Mar-96-1	BRIS7049	0.075 ± 0.002	1.413 ± 0.039	1.056 ± 0.057	29 ± 6	> 274
Mar-96-2	BRIS7054	0.122 ± 0.003	1.336 ± 0.025	0.870 ± 0.066	9 ± 2	$188 + 45 - 32$
Mar-96-3	BRIS7055	0.147 ± 0.003	1.268 ± 0.023	1.103 ± 0.039	4.5 ± 0.2	> 400
Mar-96-4t	BRIS7056	0.103 ± 0.002	1.339 ± 0.027	0.894 ± 0.040	14 ± 2	$201 + 30 - 24$
Mar-96-4b	BRIS7050	0.120 ± 0.002	1.453 ± 0.019	1.046 ± 0.034	41 ± 6	$321 + 70 - 46$

[a] Analyses HUTH1359-2237 from Green et al. (1984). BRIS7056 and 7050 are top and bottom analyses on one clast. Chalk groundwater ($n = 40$) ^{234}U/^{238}U $= 1.50 \pm 0.38$. Chalk bedrock ^{234}U/^{238}U $= 1.00$; U-238 (ppm) $= 0.36$–1.02 (Norfolk), 0.052–0.180 (Lincolnshire).

(e.g. from detritus) or of other phases within the tufa (e.g. Chalk clasts and acid insoluble residue). Isochron age determinations are only valid if there is one source of detritus. A test for this is to plot ^{230}Th/^{232}Th vs. ^{234}U/^{232}Th and ^{234}U/^{232}Th vs. ^{238}U/^{232}Th; the intercepts give the values of ^{230}Th/^{232}Th and ^{234}U/^{232}Th in the detritus, which can be compared to the global mean detritus values (Szabo and Roshalt, 1982). The eight non-leached analyses were used to construct isochron plots, which give gradients of ^{230}Th/^{234}U of 0.90 ± 0.019 ($r = 0.97$) and ^{234}U/^{238}U of 1.48 ± 0.085 ($r = 0.99$); and intercepts of ^{230}Th/^{232}Th and ^{234}U/^{232}Th fall at 0.5 ± 2.3 and -0.53 ± 2.35, respectively. The values of the latter fall outside the 1σ global range of ^{230}Th/^{232}Th $= 0.5$–1.5 and ^{234}U/^{232}Th $= 0.7$–1.4, although they do agree within 1σ errors of the isochron, which are very large. The isochron age for the deposit yields a date of 197^{+71}_{-44} ka, or a 1σ range of 268–153 ka BP, which does not improve on the individual analyses.

The poor time constraint of the Marsworth tufa from the analyses in Table 10 can be better understood by considering the potential source of the detritus. One obvious source of contamination within the tufa is that of Chalk clasts and sediment particles derived from the bedrock. This Chalk in turn has detrital components (clays and silicates) which comprise 1–4% of the total and probably have a different isotopic value. The Chalk, being acid soluble, is dissolved during the chemical preparations for U–Th analysis and thus provides an unknown proportion of U and Th. Uranium–thorium isotope results from solid Chalk samples demonstrate that ^{238}U concentration ranges from 0.05 to 1.0 ppm. ^{234}U/^{238}U range from 0.94 to 1.19 and ^{230}Th/^{234}U from 0.94 to 1.13, both equal to the secular equilibrium value of ca 1; ^{234}U/^{232}Th varies from 0.9 to 4.5 (Cuttell et al., 1986; Smart, unpub. data). Thus the bedrock has an uranium concentration 1–10 times higher than that of the

tufa, and variable and potentially high activities of ^{232}Th. Both factors, together with the unknown amount of contamination, and the fact that the U–Th preparations revealed acid-insoluble detritus of between 1 and 6% of the total tufa mass, suggest that (1) the isochron age is not reliable as it is only appropriate for mixing between two end-members, and (2) U–Th analyses for individual analyses cannot be considered reliable.

In summary, the tufa is badly contaminated with Chalk debris and bedrock silicate or soil detritus. Both of these will probably cause overestimation of the true age of the tufa, due to the addition of detrital ^{230}Th, although some ^{234}U is also probably contributed. For Chalk, the ^{230}Th/^{234}U should be 1 (as complete dissolution occurs), but for the insoluble detritus ^{230}Th/^{234}U will be > 1, overestimating the age. Some samples appear to have been leached (although careful sample selection in this study should have avoided this problem), thus disobeying the closed-system requirement for U–Th dating. Overall, these problems are insurmountable. Table 10 demonstrates that the U–Th analyses generally yield ca 180–160 ka BP best age estimates, although with high ^{230}Th/^{232}Th ratios. However, the ^{232}Th is essentially monitoring acid insoluble residue contamination, not Chalk contamination. The ages are thus corrected for acid insoluble residue mixing, but the carbonate phase includes a diluting old Chalk component, that cannot be measured, and which leads to age overestimation. Thus the true ages, based on the U-series analyses, must be younger than 180–160 ka BP.

10.2. Amino-acid geochronology

Alloisoleucine/Isoleucine (Aile/Ile) amino-acid ratios were measured on Mollusca collected from the stratigraphical units shown on Table 11, using standard procedures described in Bowen et al. (1985). All of the ratios were measured in 1996–97 at the Cardiff Laboratory

Table 11
Alloisoleucine/isoleucine (Aile/Ile) ratios measured on *Trichia hispida*, *Succinea* sp. and *Arianta arbustorum* from the Lower Channel and Site B. Comparative aminostratigraphy at Beckford, Cassington (where *Bithynia* sp. is representative of *Trichia* sp.) and Trafalgar Square

Laboratory number	Unit/site	Genus/species	AIle/Ile	Correlation (δ^{18}O stage)
UKAL 157A	Stony sandy silt[a]	*Trichia hispida*	0.09	5e
UKAL 157B	Stony sandy silt[a]	*Trichia hispida*	0.08	5a
UKAL 158A	Stony sandy silt[a]	*Succinea* sp.	0.09	5
UKAL 148A	Unit B3[b]	*Arianta arbustorum*	0.09	5
UKAL 156A	Unit B3[b]	*Arianta arbustorum*	0.08	5
UKAL 156B	Unit B3[b]	*Arianta arbustorum*	0.09	5
UKAL 156C	Unit B3[b]	*Arianta arbustorum*	0.07	5
ABER 360A	Unit B3[c]	*Arianta arbustorum*	0.09	5
ABER 360B	Unit B3[c]	*Arianta arbustorum*	0.10	5
		Arianta arbustorum	0.09 $\pm$ 0.01(6)	5
UKAL 142A	Organic mud[d]	*Succinea* sp.	0.10	5
UKAL 142B	Organic mud[d]	*Trichia hispida*	0.12	5e
ABER 482 A-D	Beckford	*Arianta* sp.	0.11 $\pm$ 0.10 (40)	5a-4
ABER 1119 A-F	Cassington	*Bithynia tentaculata*	0.08 $\pm$ 0.01 (6)	5a
ABER 466 A-C	Trafalgar Square	*Trichia hispida*	0.10 $\pm$ 0.01 (3)	5e

[a] In involution above flinty coombe rock, 1 m depth, site B.
[b] Base of pebbly silty clay loam [unit B3], 6.25–6.50 m depth, Section B1. Location shown in Fig. 4.
[c] From gravelly calcareous sand in Lower Channel at section P2.
[d] From Lower Channel near section P2.

(UKAL) except for those measured in 1984 (ABER), when the laboratory was in Aberystwyth. Thus the ratios are reproducible. No samples were available for analysis from the Upper Channel deposits.

The Aile/Ile ratios afford comparison with the standard aminostratigraphy proposed for southern Britain (Bowen et al., 1989; Bowen, 1999; Bowen, 2000, in press). Aile/Ile ratios for standard aminozones (revised from Bowen et al., 1989) here and correlated with OISs 5e are 0.1 $\pm$ 0.01 (11) for the Trafalgar Square Aminozone, including ratios from *T. hispida* of 0.1 $\pm$ 0.01 (3). Characteristic ratios of the Cassington Aminozone of 0.08 $\pm$ 0.01 (6) are correlated with OISs 5a (Bowen, 1999, 2000, in press).

Aile/Ile ratios on *Arianta* at Beckford, Worcestershire, of 0.11 $\pm$ 0.1 (4) (ABER 482A–D) (Hughes, 1987) are on samples from silt beds within the Wasperton Member of the Warwickshire Avon Valley Formation at Beckford (Briggs et al., 1975), which is correlated with the Devensian (Maddy, 1999). This is the only direct comparison with *Arianta* from the Lower Channel at Marsworth.

Other comparisons are with Aile/Ile ratios for *Succinea* sp., *Trichia* sp. and *Arianta* sp. from samples of central Europe loess deposits, which show that the rate of epimerisation is quickest for *Succinea* sp., intermediate for *Trichia* sp. and slowest for *Arianta* sp. (Oches and McCoy, 1995). Direct comparison is not possible because of differences in mean annual temperature, lack of an

independent geochronology and provenance of the samples from cold-climate loess deposits. But after allowing for these factors they suggest that the Aile/Ile ratios from Marsworth indicate an early last glacial cycle age: that is, OIS 5 and/or younger.

Thus the Aile/Ile ratios indicate that the age of the molluscs from Marsworth are time equivalent to OISs 5e and younger. This conflicts with the stratigraphical (Fig. 3) and palaeontological evidence (Tables 7 and 8), or interpretations of taphonomy, but not with the uranium-series age estimate. It poses questions about the inferred relative ages of the Lower and Upper Channel deposits that are some 97 m apart. If, however, the inferred age relationship between the deposits infilling the two channels is correct, then another explanation is required. It is possible that the diagenetic history of the samples from the Lower Channel at Marsworth has influenced the extent of epimerization, but this is thought unlikely to have occurred for three different species.

11. Discussion

From the above palaeontological evidence, an Ipswichian (OISs 5e) age for the Upper Channel deposits is well established. However, the age for the Lower Channel deposits suggested by the U–Th geochronology and aminostratigraphy differs from that inferred from the

biostratigraphy. This age discrepancy can be interpreted in four ways.

First, both the tufa and Lower Channel deposits also date from OISs 5e. This interpretation is consistent with both the U–Th geochronology and aminostratigraphy but inconsistent with both the mammalian and coleopteran biostratigraphy (see interpretation four, below). Of these four lines of evidence, only mammalian biostratigraphy can be applied to both the Upper and Lower Channels, and in this case, the mammalian assemblages from the channels are remarkably different (Table 8), with only that from the Upper Channel resembling assemblages from sites attributed to the Ipswichian.

The key to arbitrate between the different ages inferred for the Lower Channel from geochronology and biostratigraphy is the periglacial stratigraphy between the channels. This stratigraphy strongly suggests that the Upper Channel is both stratigraphically and altitudinally above the Lower Channel, separated from it by a single sedimentary sequence capped by coombe rock and involutions (Figs. 3, 8 and 9). This stratigraphic relationship has been established, beyond all reasonable doubt, from the recorded position and elevations of the channels and the intervening periglacial features.

To accommodate the U–Th age estimates and aminostratigraphy from the Lower Channel, the above stratigraphic interpretation of a single involuted coombe rock layer dating from one periglacial episode (Worsley, 1987) must be rejected, and instead, two similar layers dating from two different periglacial episodes must be inferred: (1) a post-Ipswichian layer above the Lower Channel, observed along hundreds of metres of quarry face that show it to be relatively uniform in thickness (e.g. between *x* and *y* in Fig. 3), must disappear to the northwest of the Lower Channel before reaching the Upper Channel; and, coincidentally, (2) a pre-Ipswichian layer at a similar elevation to layer 1 must disappear to the southeast of the Upper Channel before reaching the Lower Channel. Although this interpretation cannot be rejected definitively, the complete lack of reported evidence for a bipartite periglacial stratigraphy (despite numerous, well-exposed quarry sections examined over many years) and the extraordinary coincidences required suggest that this interpretation is unlikely.

The second interpretation is that both the tufa and the Lower Channel deposits date from an interstadial during OIS 6. This interpretation is discounted, because the pollen, leaf impressions and Mollusca within the tufa indicate that it formed during temperate woodland and warm (i.e. interglacial) conditions.

Third, the tufa dates from OIS 7, and the Lower Channel deposits from an interstadial in stage 6. This interpretation fails to account for the very close similarities between the mammal assemblage from the Lower Channel and those from numerous sites assigned to OIS 7, in particular the upper part of the sequence at

Aveley, Ilford (Uphall Pit) and Stanton Harcourt (Stanton Harcourt Bed; Gibbard, 1999). Key mammalian biostratigraphic indicators of OIS 7 include the primitive 'Ilford-type' mammoth, in association with *P. antiquus*, *E. ferus* and a large form of *M. oeconomus*. Furthermore, the mammalian assemblage from the periglacial deposits *above* the Lower Channel is wholly consistent with an OIS 6 age, inferred from the presence of a particularly small caballine horse and fully evolved *M. primigenius*. The Coleoptera also show that the palaeoclimate during the time of infilling of the Lower Channel was sufficiently warm to support mixed oak forest. Indeed, the coleopteran fauna from the Lower Channel closely resembles that from the deposits at Stanton Harcourt, which include numerous prostrate trunks of oak. There can thus be little doubt that the Lower Channel deposits accumulated under fully interglacial conditions.

Finally, both the tufa and the Lower Channel deposits date from OIS 7. This interpretation is consistent with the observed periglacial stratigraphy (Figs. 3, 8 and 9) and is the simplest in palaeoecological terms, but appears to contradict the geochronological data. Comparison of the pollen in the tufa with the pollen and macroscopic plant remains in the Lower Channel deposits shows evidence of moderate climatic cooling, as does the coleopteran evidence from the top of these deposits. But in spite of this cooling the Lower Channel deposits still should be credited with interglacial status. The open ground and grassland conditions, and sparseness of trees at this time, indicated by both the fossil plants and Coleoptera, probably resulted from the intense grazing pressure by the large herbivorous mammals whose bones were so abundant in this horizon. However, if the fourth interpretation is correct, then the ages inferred from the U–Th geochronology and aminostratigraphy remain a puzzle.

In conclusion, the case for inferring an OIS 7 age for the tufa and Lower Channel deposits is, on the evidence of biostratigraphy and periglacial stratigraphy (Figs. 3, 8 and 9; Tables 7 and 8), stronger than that for an OISs 5e age. The latter is based on geochronological data (Tables 10 and 11) of which some are strongly affected by contamination and which would require a bipartite periglacial stratigraphy for which no evidence has been observed.

12. Conclusions and summary

The preferred palaeoenvironmental history of the Marsworth sedimentary sequences described above is summarised thus:

1. During full interglacial temperate stage conditions of OIS 7, tufa formed at the outlet of a small limestone spring similar to those emerging today near the foot of the Chiltern scarp. Ash-dominated woodland with oak, hazel and hornbeam probably grew locally.

However, the area beside the spring supported grass and wide range of other herbs, and was probably kept open by grazing animals.

2. Later during the same temperate stage, the tufa was redeposited as clasts in a small river channel. Near the channel banks were disturbed sandy or gravelly areas, perhaps from trampling by large mammals. The Lower Channel was fringed with wetlands containing abundant sweet-grass *Glyceria*, a favourite food for large herbivores. In drier areas the dominant vegetation was herb-rich calcareous grassland. Trees, including birch, alder, willow and poplar, probably grew on the channel banks, and oak, elm, lime, hornbeam and hazel may have grown as scattered trees or small patches of open woodland on the best soil. An age towards the end of OIS 7 is inferred from the occurrence of mammoths with both the 'Ilford-type' dentition together with others having more morphologically-advanced tooth structure. Coleopteran evidence also suggests correlation with other sites which have been attributed to OIS 7.

3. During the early stages of the infilling of the Lower Channel, the plant and animal fossils indicate that the climate was about as warm as that of central England at the present day. However, both the coleopteran and pollen evidence suggests that a slight cooling set in during the later stages of infilling.

4. Colluvial processes infilled and buried the Lower Channel with pebbly silty clay and loam (unit B3). Intense periglacial conditions followed, with solifluction depositing a sheet of flinty coombe rock (unit B4), and permafrost aggrading. Thermal contraction cracking permitted ice-wedge growth (Worsley, 1987), and ice segregation and frost heave brecciated near-surface Chalk. Windblown sand accumulated above the flinty coombe rock and was later deformed into involutions. An OIS 6 age for this periglacial episode is inferred from remains of a small-bodied horse.

5. River-channel cutting and filling above the periglacial features (Fig. 8) recurred during a later interglacial. This period is correlated with OISs 5e on the basis of the mammalian fauna from the Upper Channel deposits, which includes hippopotamus and narrow-nosed rhinoceros.

13. Uncited Reference

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