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# CHANGING ENVIRONMENT AT THE LATE UPPER PALAEOLITHIC SITE OF LYNX CAVE, NORTH WALES

*Abstract*

Lynx Cave is one of a handful of locations in North Wales that provide evidence of Late Upper Palaeolithic hunter-gatherers at the end of the last ice-age. With the region being recolonized at a time of rapid environmental change there is a need to develop on-site palaeoenvironmental records that are directly linked to the archaeology in order to further understanding of the environments and landscapes that these hunter-gatherer groups experienced. Through carbon ($\delta^{13}C$), nitrogen ($\delta^{15}N$) and sulphur ($\delta^{34}S$) stable isotope analysis of animal bones we explore the environmental conditions during the human occupation of Lynx Cave. Analysis of the data indicates the faunal isotope results cluster into three distinct groupings, which when considered in light of the species composition, radiocarbon dates, sample layer provenance and known temporal patterns in herbivore isotope data from Northern Europe, are likely to relate to GI-1cba (the Allerød period) around 13,700-13,000 cal BP, GI-1cba/GS-1 (the Late Allerød / early Younger Dryas period) around 13,100-12,800 cal BP, and the Bronze Age. The isotope data indicates that the Late Upper Palaeolithic or Late Palaeolithic occupations occurred in an open landscape in which soils were undergoing changing hydrological conditions linked to ice sheet melt and permafrost thaw process and subsequent recovery. The evidence of butchery marks on the faunal remains from both Late Glacial isotope clusters, along with the disparate radiocarbon dates and the presence of three hearths, support the idea of very short-term episodic use of the cave over an extended time period.

*Keywords*

Bone, collagen, stable isotopes, permafrost thaw, sulphur, Creswellian

## INTRODUCTION

The repopulation of the British Isles after the retreat of the Last Glacial Maximum ice sheets occurred immediately prior to, or at the very onset of, the Late Glacial Interstadial (i. e., GS-2 to GI-1 boundary on the NGRIP GICC05 time scale: Rasmussen et al., 2014) (Jacobi and Higham, 2011). These Late Upper Palaeolithic occupations are mostly associated with Final Magdalenian style lithic artefacts, known locally as the Creswellian, although some shouldered and large bi-points from the region are of Hamburgian form (Jacobi and Higham, 2011; Pettitt and White, 2012). The earliest Late Upper Palaeolithic archaeological assemblages are found at King Arthur's Cave (Wye Valley) and in Cheddar Gorge, Somerset (Gough's Cave and Sun Hole Cave), while reoccupation of other areas, such as Devon (Kent's Cavern) and the east Midlands (Creswell Crags), appears to have been somewhat delayed (Jacobi and Higham, 2009a, 2009b, 2011). Later in the Late Glacial Interstadial (Greenland Interstadial GI-1), the Late Upper Palaeolithic was replaced by Final Palaeolithic technologies, including *Federmesser* technologies including penknife points (Pettitt and White, 2012). This broadly coincided with a shift towards the woodland phase of the Late Glacial Interstadial (GI-1d/1c), greater use of open air locations, and a diversification in fauna targeted as prey, with evidence of reindeer, red deer, large bovids and hares being hunted alongside horse (Jacobi and Higham,

**Fig. 1** Position of Lynx Cave in North Wales (red square), shown alongside location of other archaeological sites mentioned in the text (red circles): **1** Kendrick's Cave; **2** Raven Scar Cave; **3** Fox Hole Cave; **4** Dead Man's Cave; **5** Creswell Crags; **6** King Arthur's Cave; **7** Priory Farm; **8** Aveline's Hole; **9** Gough's Cave; **10** Kent's Cavern; **11** Bob's Cave.

2009a, 2009b, 2011; Pettitt and White, 2012). Although the broad relationship between the British Late Upper and Final Palaeolithic human presence and climate change is known, with such rapid rates of climatic and environmental change occurring across the Late Glacial Interstadial, the landscapes that these hunter-gatherer groups experienced are likely to have varied considerably across the region. Obtaining detailed on-site palaeoenvironmental and palaeoecological information directly from archaeological material allows the reconstruction of local conditions experienced by these populations and complements regional and global records. Here we explore the archaeological record at Lynx Cave in Denbighshire, North Wales (**Fig. 1**) through carbon, nitrogen and sulphur isotope analysis of animal bones, with the aim of reconstructing the environmental conditions during the Late Upper Palaeolithic (hereafter LUP) occupation of the cave and furthering understanding of the archaeological sequence represented at the site.

The stable isotope composition of herbivore bones reflects the local environment and ecology at the time the animal lived. After death the *in vivo* isotope compositions are preserved and through analysis of the archaeological bone remains these records can be used to reconstruct dietary ecology, animal behaviour and local environmental conditions during periods when humans were active within the landscape. Herbivore carbon ($\delta^{13}C$), nitrogen ($\delta^{15}N$), and sulphur ($\delta^{34}S$) isotope ratios reflect those of the plants they consume (Gannes et al., 1998). Plant $\delta^{13}C$ and $\delta^{15}N$ values are determined by underlying environmental conditions

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(Kohn, 2010; Amundson et al., 2003; Craine et al., 2015). Thus, faunal δ¹³C and δ¹⁵N values represent an environmental signal, mediated by species-specific dietary behaviours. Environmental parameters that have been shown to influence herbivore δ¹³C values include temperature, water availability, relative humidity, atmospheric carbon dioxide concentrations and the canopy effect (Heaton, 1999; Kohn, 2010). For herbivore δ¹⁵N values, parameters include temperature and precipitation, mediated through soil processes (Stevens and Hedges, 2004; Stevens et al., 2008). Of particular relevance to this study is the observation that the δ¹⁵N values of herbivores in Northwest Europe were likely strongly influenced by permafrost thaw processes during the Pleniglacial – Late Glacial (Stevens and Hedges, 2004; Stevens et al., 2008; Drucker et al., 2011b, 2012; Reade et al., 2020b, 2021). Herbivore δ³⁴S values are influenced by underlying lithology, soil-bedrock interactions, mineral weathering and soil environment (e.g., microbial activity, water and oxygen content) (Thode, 1991; Nehlich, 2015; Nitsch et al., 2019; Reade et al., 2020a, 2020b). It has been suggested that across the Pleniglacial – Late Glacial transition environmentally driven parameters potentially linked to soil and permafrost conditions may have had a greater influence on animal bone δ³⁴S values than underlying lithology (Reade et al., 2020b, 2021).

## SITE BACKGROUND

Located close to Llanarmon-yn-Ial in Denbighshire, North Wales, Lynx Cave is situated between the twin peaks of Bryn Alyn, at the base of a small limestone outcrop, on the south side of a small valley (**Fig. 1**; Blore, 2012). Discovered in 1962 by J. Blore and B. Nuttall, the small cave was excavated primarily by Blore over the subsequent 50 years. The cave is one of a handful in North Wales that provide evidence of LUP hunter-gatherers at the end of the last ice-age. The LUP lithic assemblage solely contains abruptly modified blades and bladelets, some of which have been described as resembling Creswellian or Hamburgian types (Blore, 2012; Pettitt and White, 2012). Similar cave assemblages that also do not contain any other retouched tool forms such as burins or scrapers have been found at Aveline's Hole in Somerset, Bob's Cave in Devon, Priory Farm Cave in Pembrokeshire, Fox Hole in Derbyshire, and Dead Man's Cave and Raven Scar Cave in Yorkshire (Jacobi, 2005). The shoulder-backed points are likely to be later examples of their forms which, when found in association with straight-backed blades and bladelets and curve-backed points, suggest a late Hamburgian tradition (Pettitt and White, 2012). When found in the British Isles such assemblages have been called 'Hengistbury-type' assemblages (Conneller and Ellis, 2007). The suggested age of such assemblages is typically considered to be around the interface between the Older Dryas (GI-1d) and the start of the Allerød (GI-1cba) (Conneller and Ellis, 2007; Jacobi and Higham, 2011; Pettitt and White, 2012). Conneller and Ellis (2007) and Jacobi and Higham (2011) use a different terminology from Pettitt and White, calling this an early variant of the *Federmesser*. The later part of the *Federmesser* industries were dominated by the penknife point; a mono-point with curve-backing, leading edge retouch with a proximal oblique termination resulting in the tool having an off-set tang (Jacobi and Higham, 2011). The absence of penknife points amongst the Lynx Cave assemblage would therefore suggest that the Lynx Cave assemblage may be contemporaneous with the earlier variant of the *Federmesser* in the British Isles, as defined by Conneller and Ellis (2007) and Jacobi and Higham (2011). A further observation of the Lynx Cave lithic assemblage relates to the use of the tools. The two shoulder-backed points and one of the curve-backed bi-points display impact fractures. All the straight-backed blades and bladelets are also fragmentary with fractures consistent with their use. This small assemblage would fit a task-site where a limited range of activities, dominated by hunting, were taking place.

| Sample number | Layer | Lab Code | ¹⁴C age [BP] | Age [cal BP]* | Late Glacial climatic phase | Species | Element | Comment | Reference |
|---|---|---|---|---|---|---|---|---|---|
| 940 | D | OxA-16854 | 11,015±50 | 13,090-12,820 | GI-1cba/GS-1 | *Rangifer tarandus* | Humerus | Smashed when fresh for marrow extraction | Blore, 2012 |
| 621 | C/D | OxA-7993 | 11,145±80 | 13,230-12,840 | GI-1cba/GS-1 | *Rangifer tarandus* | Humerus | Smashed when fresh for marrow extraction | Blore, 2012 |
| 620 | C/D | OxA-12884 | 11,245±65 | 13,300-13,075 | GI-1cba | *Bos primigenius* | Left femur | Smashed when fresh for marrow extraction | Currant and Jacobi, 2011 |
| 622 | C/D | OxA-19206 | 11,640±45 | 13,600-13,370 | GI-1cba | *Cervus elaphus* | Left astragalus | | Jacobi and Higham, 2011 |
| 704 | D | OxA-19207 | 11,680±45 | 13,735-13,445 | GI-1cba | *Cervus elaphus* | Left tibia | | Jacobi and Higham, 2011 |
| NW2 Artefact 6 | C? | OxA-8164 | 11,700±90 | 13,770-13,355 | GI-1cba | most likely *Cervus elaphus* | Bone point | Magdalenian in style | Bronk Ramsey et al., 2002 |

**Tab. 1** Late Glacial radiocarbon dates from Lynx Cave.
* Calibrated age range in cal BP at 95 % confidence (INTCAL20), using OxCal v4.4.2 (Bronk Ramsey, 2020).

At Lynx Cave, radiocarbon (¹⁴C) dates from butchered mammal bones from the same sedimentary context as the LUP lithic assemblage date this occupation to the second part of the Late Glacial Interstadial (Allerød, i. e., GI-1cba) (**Tab. 1**; **Fig. 2**). Occupations at the site appear to have occurred throughout GI-1cba, co-inciding with some of the dated LUP human remains and cultural artefacts recovered at Kendrick's Cave, some 50 km away on the Creuddyn peninsula on the North Wales coast (Richards et al., 2005; Jacobi et al., 2009; cf. https://www.britishmuseum.org/collection/object/H_Palart-900). Therefore, although the LUP assemblages in North Wales are small in size and few in number, the radiocarbon dates suggest human presence in the region was sustained over a significant period of time, even if visits to the area were fleeting.

The deposits at Lynx Cave have suffered from some disturbance particularly in the upper layers, but some LUP archaeology was recovered from undisturbed levels. Layers A and B contained disturbed deposits and artefacts from the Late Bronze Age, Romano-British and historic periods, along with fauna typical of both late Pleistocene and Holocene environments. Layer C was also disturbed but to much less extent than Layers A and B. Layer C contained human remains, some of which were located within a burial mound, together with a range of artefacts including a worked antler, horse cheek piece and a shale bracelet, which are likely to date to either the Bronze or the early Iron Age. Fauna from this layer included typical Holocene domesticates, such as sheep, goat, bovids, and horse in addition to roe deer and a single red deer, the latter of which may have been disturbed from its original context (Blore, 2012). Unlike the other animals, some bovid bones show evidence of cut-marks, but these are few in number. A radiocarbon age of 2,945 ± 35 uncal BP (OxA-8070) from a black stork (*Ciconia nigra*) humerus found in Layer C confirms attribution of these deposits to the British Bronze Age. The few lithic artefacts found in this layer are likely to have been disturbed from the layers below. Two non-conjoining mesial fragments of what is considered to be a single bone point were recovered from the perimeter of the burial mound in Layer C in an area of disturbed sediments (Blore, 2012: Fig. 26, p58). These point fragments have been described as resembling fluted spear-points

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typical of the Magdalenian (Wymer in Blore, 2012). Both fragments have one ancient and one recent break and both have a groove that may represent the remnant of the medullary cavity. On one piece this runs the whole length of the dorsal face, whereas on the other it is only partial. Both are fragments close to each end, as both pieces taper towards a point. They may originate from a long bone of red deer. The pieces are both clearly worked, except within the groove. One of these point fragments (Specimen A6 AC-NMW acc. no. 83.98H/1) has produced a direct radiocarbon age of 11,700 ± 90 uncal BP (OxA-8164) confirming its LUP origin (Aldhouse-Green, 2000; Blore, 2012). Carbon isotope measurements made on the sample during
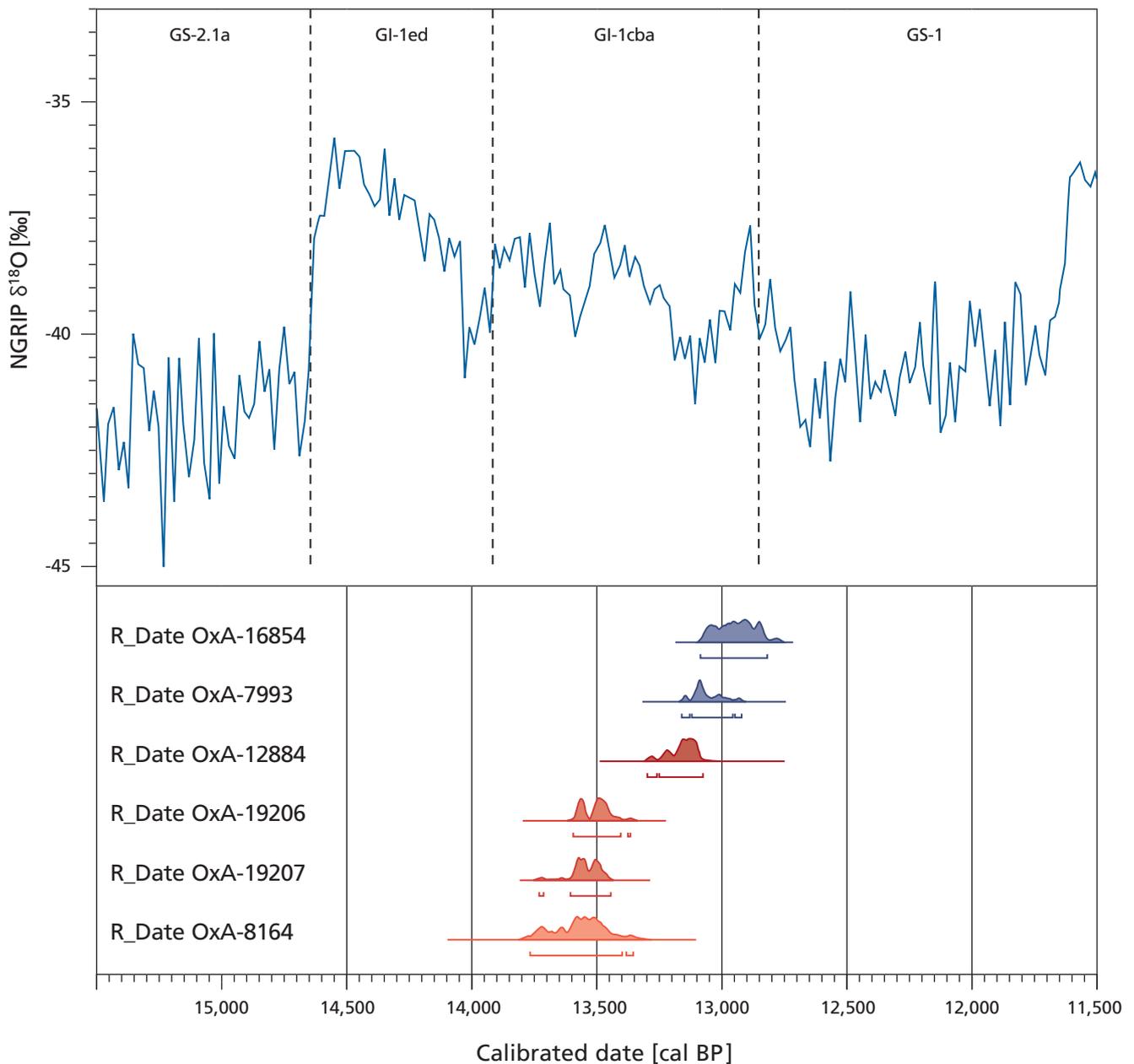


**Fig. 2** Calibrated radiocarbon dates for Late Upper Palaeolithic occupation of Lynx Cave (cf. **Tab. 1**) plotted against the NGRIP isotope record. *Rangifer tarandus* = blue (OxA-16854, OxA-7993); *Bos primigenius* = dark red (OxA-12884); *Cervus elaphus* = medium red (OxA-19206, OxA-19207); Bone point (most likely of *Cervus elaphus*) = light red (OxA-8164); Calibration using OxCal v4.4.2 (Bronk Ramsey, 2020); NGRIP atmospheric data from Reimer et al. (2020).

radiocarbon dating gave isotope values consistent with the red deer analysed in this study, thus supporting the potential species identification (Bronk Ramsey et al., 2002). A comparable point, dated to 11,210 ± 90 uncal BP (OxA-2847) was found at Coniston Dib, Derbyshire (Hedges et al., 1992; Blore, 2012). The lack of Mesolithic and Neolithic deposits in the cave is thought to be due to a huge rock-fall event that inundated the cave entrance at the end of the Pleistocene.

Layer D contained relatively undisturbed deposits which extended throughout the cave and was underlain by Layer D1 in the back section of the cave only. Within Layer D three hearths were found near the entrance to the cave, along with LUP lithic artefacts spread throughout the cave, bone artefacts and butchered animal remains. The lithic assemblage contained nine abruptly modified blades and bladelets; comprising six straight-backed blades, two curve-backed blades and one shoulder-backed point (Jacobi, 2005; Blore, 2012). One bone point was recovered from the lower levels of Layer D, this is undated and is not of a form that would enable its dating on stylistic grounds alone. An antler point was also recovered from a small void within the back of the chamber, attached to the side wall 10 cm above layer D1. The position of recovery of these points and the complexity of cave deposits suggest they may have found their way from layer C as despite their recorded findspots they are unlikely to be older than those described from the layer C/D interface. The faunal assemblage recovered from Layer D was small but included elk (*Alces alces*), aurochs (*Bos primigenius*) red deer (*Cervus elaphus*) and reindeer *(Rangifer tarandus)* (Blore, 2012). Most of the large herbivores display evidence of butchery, including for marrow extraction. Five radiocarbon dates from fauna from Layers D and C/D securely place their formation into GI-1cba and to the GI-1a/GS-1 transition (**Tab. 1**; **Fig. 2**). The red deer $^{14}$C dates (likely to be from a single individual) are similar to that of the bone point recovered from the perimeter of the burial mound in Layer C in a disturbed area (**Tab. 1**; **Fig. 2**). The aurochs and reindeer $^{14}$C dates are younger, towards the end of GI-1cba, and for the reindeer, potentially the start of GS-1 (Younger Dryas) (**Tab. 1**; **Fig. 2**). Analysis of charcoal from the hearths showed the wood for fuel was sourced from Scots pine (*Pinus sylvestris*), willow (*Salix* sp.) or birch (*Betula* sp.) and oak (*Quercus sp.*) (P. Thomas in: Blore, 2012). A single left humerus of a child aged around 10-years-old was also recovered from Layer D. However, this bone is assumed to be out of context, as it is similar in colour and preservation to the human bones found in the upper layers, and dissimilar to the faunal bones recovered from Layer D. Furthermore, it is of similar developmental stage as the child mandible found higher in the cave stratigraphy, however, the specimen has not been radiocarbon dated.

Layer E is thought to contain Late Glacial aeolian deposits, although no radiocarbon dating has been undertaken from this layer. The layer was devoid of archaeology except for a small number of bones that were found at the top of the layer. They are thought to have originated from Layer D and became compressed into the uppermost part of Layer E as people and animals used the cave (Blore, 2012).

## METHODOLOGY

A total of 35 bone samples were selected for stable isotope analysis (**Tab. 2**). Three reindeer bones from Layers A/B were sampled despite being from a mixed deposit. This was because their physical appearance and condition was comparable to the reindeer assemblage from Layer D and two of the bones had been fractured when fresh, and therefore could provide environmental information linked to human activity at the site.

Four *Bos* and one horse bones were sampled from the burial mound in Layer C, with three of the former displaying cut-marks, two of which were described as being "*by a heavy instrument*" and one having

| Sample No. | Museum/ Excavation Sample No. | W/mark | Spit No. | Additional excav. info | Layer Group | Layer | Bone (Humanly modified?) | Species |
|---|---|---|---|---|---|---|---|---|
| UPN-804 | 83.98H/9 | 7 | 2M | 150 | Disturbed (Layer A/B) | A/B | Metacarpal (1) | *Rangifer tarandus* |
| UPN-824 | 83.98H/11 | 14 | 1M | 401 | Disturbed (Layer A/B) | A/B | Phalanx 1st | *Rangifer tarandus* |
| UPN-805 | 83.98H/10 | 23 | 2M | 427 | Disturbed (Layer A/B) | A/B | Metacarpal (2) | *Rangifer tarandus* |
| UPN-786 | 2015.11H/88.1 | -5 | 5 | 831 | Holocene (Layer C) | C | Rib | *Bos primigenius* |
| UPN-785 | 2015.11H/88.2 | -5 | 5 | 832 | Holocene (Layer C) | C | Vertebra | *Bos primigenius* |
| UPN-794 | 2015.11H/88.6 | -4 | 6 | 759 | Holocene (Layer C) | C | Vertebra | *Bos primigenius* |
| UPN-835 | 2015.11H/79 | -4 | 5 | 803 | Holocene (Layer C) | C | Tibia | *Equus* |
| UPN-797 | 83.98H/12 | 23 | 4 | 702 | Holocene (Layer C) | C (burial mound) | Rib (3) | *Bos primigenius* |
| UPN-803 | 2015.11H/88.3 | 27 | 4 | 639 | Holocene (Layer C) | C (burial mound) | Rib (4) | *Bos primigenius* |
| UPN-795 | 2015.11H/88.4 | 27 | 4 | 640 | Holocene (Layer C) | C (burial mound) | Rib (5) | *Bos primigenius* |
| UPN-791 | 2015.11H/88.5 | 27 | 4 | 635 | Holocene (Layer C) | C (burial mound) | Cuboid tarsal | *Bos primigenius* |
| UPN-798 | 2015.11H/101 | 27 | 4 | 641 | Holocene (Layer C) | C (burial mound) | Axis Vertebra | *Equus* |
| UPN-829 | 83.98H/13/B | 28 | 6 | 620 | Pleistocene (Layer D/D1/E) | C/D | Femur | *Bos primigenius* |
| UPN-808 | 2015.11H/126 | 28 | 6 | 621 | Pleistocene (Layer D/D1/E) | D | Humerus (6) | *Rangifer tarandus* |
| UPN-807 | 2015.11H/103.2 | -14 | 10 | 944 | Pleistocene (Layer D/D1/E) | D | Radius | *Rangifer tarandus* |
| UPN-833 | 2015.11H/106.7 | 1 | 7 | 925 | Pleistocene (Layer D/D1/E) | D | Phalanx | *Alces* |
| UPN-790 | 2015.11H/89.1 | 4 | 5 | 623 | Pleistocene (Layer D/D1/E) | D | Humerus | *Bos primigenius* |
| UPN-827 | 2015.11H/106.5 | 4 | 4 | 622 | Pleistocene (Layer D/D1/E) | D | Astragalus | *Cervus elaphus* |
| UPN-801 | 2015.11H/103.4 | 5 | 5 | 633 | Pleistocene (Layer D/D1/E) | D | Metacarpal | *Rangifer tarandus* |
| UPN-796 | 2015.11H/103.6 | 8 | 4 | 626B | Pleistocene (Layer D/D1/E) | D | Metacarpal | *Rangifer tarandus* |
| UPN-800 | 2015.11H/103.1 | 8 | 4 | 626A | Pleistocene (Layer D/D1/E) | D | Metacarpal | *Rangifer tarandus* |
| UPN-830 | 2015.11H/106.3 | 21 | 6 | 704 | Pleistocene (Layer D/D1/E) | D | Tibia | *Cervus elaphus* |
| UPN-906 | OxA-16854 | 24 | 11 | 940 | Pleistocene (Layer D/D1/E) | D | Humerus | *Rangifer tarandus* |
| UPN-792 | 2015.11H/106.2 | 25 | 9 | 630 | Pleistocene (Layer D/D1/E) | D | Tibia | *Cervus elaphus* |
| UPN-784 | 2015.11H/106.4 | 29 | 9 | 631 | Pleistocene (Layer D/D1/E) | D | Radius | *Rangifer tarandus* |
| UPN-799 | 2015.11H/103.3 | 29 | 5 | 632 | Pleistocene (Layer D/D1/E) | D | Radius | *Rangifer tarandus* |
| UPN-802 | 2015.11H/103.5 | spoil B/C | | 936 | Pleistocene (Layer D/D1/E) | D | Ulna | *Rangifer tarandus* |
| UPN-793 | 2015.11H/106.8 | -15 | 17 | 951 | Pleistocene (Layer D/D1/E) | D (presumed) | Antler burr (7) | *Cervus elaphus* |
| UPN-806 | 2015.11H/106.6 | 3 | 5 | 656 | Pleistocene (Layer D/D1/E) | D-E | Metatarsal | *Cervus elaphus* |
| UPN-783 | 2015.11H/106.1 | 8 | 6 | 629 | Pleistocene (Layer D/D1/E) | D-E | Tibia, shaft | *Cervus elaphus* |
| UPN-825 | 2015.11H/104.1 | 19 | 11 | 1045 | Pleistocene (Layer D/D1/E) | D1 | 2nd phalange | *Rangifer tarandus* |
| UPN-789 | 2015.11H/107.2 | 27 | 12 | 1059 | Pleistocene (Layer D/D1/E) | D1 | premolar | *Rangifer tarandus* |
| UPN-832 | 2015.11H/89.2 | 29 | 12 | 1047 | Pleistocene (Layer D/D1/E) | D1 | Phalanx | *Bos primigenius* |
| UPN-787 | 2015.11H/107.3 | 30 | 12 | 1053 | Pleistocene (Layer D/D1/E) | D1 | molar | *Rangifer tarandus* |
| UPN-788 | 2015.11H/107.1 | 30 | 12 | 1054 | Pleistocene (Layer D/D1/E) | D1 | premolar | *Rangifer tarandus* |

**Tab. 2** Details of sample provenance and species identification. (1) Proximal end broken when fresh; (2) Proximal end broken when fresh, charcoal end; (3) Cut-marked; (4) Cut with heavy tool; (5) Cut with heavy tool, plus some marks made with flint?; (6) Shattered when fresh; (7) Found away from main passage in layer assumed to be continuation of Layer D.

| Sample No. | Species | ¹⁴C Lab Code* | N [%] | C [%] | S [%] | C:N | C:S | N:S | δ¹³C [‰] | δ¹⁵N [‰] | δ³⁴S [‰] | Inferred age |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| UPN-804 | *Rangifer tarandus* | | 14.4 | 40.3 | 0.2 | 3.3 | 682 | 209 | -19.8 | 2.0 | 14.7 | intrusive (likely Late Glacial) |
| UPN-824 | *Rangifer tarandus* | | 15.6 | 44.5 | 0.2 | 3.3 | 738 | 222 | -19.4 | 1.5 | 15.8 | intrusive (likely Late Glacial) |
| UPN-805 | *Rangifer tarandus* | | 15.0 | 43.4 | 0.2 | 3.4 | 687 | 204 | -19.1 | 1.3 | 13.1 | intrusive (likely Late Glacial) |
| UPN-786 | *Bos primigenius* | | 14.9 | 43.8 | 0.2 | 3.4 | 686 | 200 | -21.8 | 4.7 | 13.7 | Late Holocene |
| UPN-785 | *Bos primigenius* | | 15.4 | 44.8 | 0.2 | 3.4 | 713 | 210 | -23.2 | 6.4 | 16.8 | Late Holocene |
| UPN-794 | *Bos primigenius* | | 15.6 | 44.3 | 0.2 | 3.3 | 691 | 209 | -23.2 | 7.0 | 17.1 | Late Holocene |
| UPN-835 | *Equus* | | 15.8 | 44.6 | 0.2 | 3.3 | 722 | 219 | -22.1 | 2.9 | 14.0 | Late Holocene |
| UPN-797 | *Bos primigenius* | | 15.2 | 42.9 | 0.2 | 3.3 | 698 | 212 | -22.0 | 5.4 | 13.7 | Late Holocene |
| UPN-803 | *Bos primigenius* | | 14.6 | 41.7 | 0.2 | 3.3 | 679 | 204 | -22.4 | 5.9 | 14.0 | Late Holocene |
| UPN-795 | *Bos primigenius* | | 15.1 | 43.2 | 0.2 | 3.3 | 716 | 215 | -22.0 | 5.2 | 14.1 | Late Holocene |
| UPN-791 | *Bos primigenius* | | 14.6 | 42.0 | 0.2 | 3.4 | 683 | 204 | -23.3 | 6.5 | 16.7 | Late Holocene |
| UPN-798 | *Equus* | | 14.8 | 42.0 | 0.2 | 3.3 | 671 | 203 | -22.4 | 5.2 | 13.7 | Late Holocene |
| UPN-829 | *Bos primigenius* | OxA-12884 | 14.8 | 42.5 | 0.2 | 3.4 | 654 | 195 | -20.3 | 3.4 | 7.4 | Allerød |
| UPN-808 | *Rangifer tarandus* | OxA-7993 | 13.2 | 38.3 | 0.2 | 3.4 | 665 | 197 | -19.0 | 1.5 | 13.7 | late Allerød/Younger Dryas |
| UPN-807 | *Rangifer tarandus* | | 13.9 | 40.3 | 0.1 | 3.4 | 716 | 213 | -20.0 | 2.0 | 14.6 | late Allerød/Younger Dryas |
| UPN-833 | *Alces* | | 15.0 | 44.0 | 0.2 | 3.4 | 653 | 191 | -20.4 | 2.2 | 10.0 | late Allerød/Younger Dryas |
| UPN-790 | *Bos primigenius* | | 15.2 | 44.1 | 0.2 | 3.4 | 674 | 200 | -22.3 | 5.7 | 13.6 | intrusive (likely Late Holocene) |
| UPN-827 | *Cervus elaphus* | OxA-19206 | 14.1 | 40.0 | 0.2 | 3.3 | 695 | 210 | -20.5 | 2.2 | 8.1 | Allerød |
| UPN-801 | *Rangifer tarandus* | | 14.4 | 40.6 | 0.2 | 3.3 | 673 | 205 | -19.6 | 1.6 | 14.3 | late Allerød/Younger Dryas |
| UPN-796 | *Rangifer tarandus* | | 16.0 | 44.9 | 0.2 | 3.3 | 723 | 221 | -19.6 | 1.5 | 13.5 | late Allerød/Younger Dryas |
| UPN-800 | *Rangifer tarandus* | | 15.7 | 44.3 | 0.2 | 3.3 | 698 | 212 | -19.5 | 1.3 | 13.9 | late Allerød/Younger Dryas |
| UPN-830 | *Cervus elaphus* | OxA-19207 | 15.3 | 43.8 | 0.2 | 3.3 | 692 | 208 | -20.8 | 2.7 | 7.5 | Allerød |
| UPN-906 | *Rangifer tarandus* | OxA-16854 | 14.3 | 41.0 | 0.2 | 3.4 | 657 | 196 | -19.6 | 2.5 | 13.8 | late Allerød/Younger Dryas |
| UPN-792 | *Cervus elaphus* | | 13.3 | 39.0 | 0.2 | 3.4 | 663 | 194 | -21.3 | 2.9 | 8.6 | Allerød |
| UPN-784 | *Rangifer tarandus* | | 13.8 | 40.1 | 0.2 | 3.4 | 668 | 197 | -18.9 | 1.3 | 15.3 | late Allerød/Younger Dryas |
| UPN-799 | *Rangifer tarandus* | | 13.8 | 39.8 | 0.2 | 3.4 | 688 | 205 | -19.1 | 1.8 | 15.3 | late Allerød/Younger Dryas |
| UPN-802 | *Rangifer tarandus* | | 14.1 | 40.0 | 0.2 | 3.3 | 695 | 211 | -19.0 | 1.3 | 14.2 | late Allerød/Younger Dryas |
| UPN-793 | *Cervus elaphus* | | 13.9 | 40.1 | 0.2 | 3.4 | 675 | 200 | -23.1 | 6.5 | 16.6 | intrusive (likely Late Holocene) |
| UPN-806 | *Cervus elaphus* | | 13.5 | 38.9 | 0.1 | 3.3 | 694 | 207 | -21.1 | 1.8 | 8.4 | Allerød |
| UPN-783 | *Cervus elaphus* | | 15.0 | 42.3 | 0.2 | 3.3 | 731 | 222 | -20.7 | 1.3 | 8.5 | Allerød |
| UPN-825 | *Rangifer tarandus* | | 15.4 | 44.0 | 0.2 | 3.3 | 762 | 229 | -18.9 | 1.5 | 14.0 | late Allerød/Younger Dryas |
| UPN-789 | *Rangifer tarandus* | | 14.8 | 43.1 | 0.2 | 3.4 | 721 | 212 | -17.9 | 2.8 | 16.3 | late Allerød/Younger Dryas |
| UPN-832 | *Bos primigenius* | | 14.6 | 42.7 | 0.2 | 3.4 | 703 | 207 | -20.7 | 4.3 | 11.5 | late Allerød/Younger Dryas |
| UPN-787 | *Rangifer tarandus* | | 15.4 | 45.3 | 0.2 | 3.4 | 674 | 197 | -18.4 | 3.5 | 15.0 | late Allerød/Younger Dryas |
| UPN-788 | *Rangifer tarandus* | | 15.4 | 45.6 | 0.2 | 3.5 | 662 | 192 | -18.5 | 3.0 | 15.7 | late Allerød/Younger Dryas |

**Tab. 3**  Results of stable isotope analysis. * cf. **Tab. 1**.

"*some marks made with flint*" (Blore, 2012). A further three Bos and one horse bones were sampled from Layer C. Due to the presence of the LUP bone point in the Layer C disturbed deposits, we sampled fauna from this level to explore whether any might represent Late Glacial specimens disturbed from their original context.

From the interface of Layer C/D two specimens that had been previously radiocarbon dated to the later part of the GI-1cba were sampled; the aurochs radiocarbon dated to 11,245 ± 65 uncal BP (OxA-12884) and

the reindeer, which was fractured when fresh, to 11,145 ± 45 uncal BP (OxA-7993) (**Tab. 1**; **Tab. 3**; **Fig. 2**) (Currant and Jacobi, 2011; Blore, 2012).

From layer D, one elk, one Bos, four red deer and eight reindeer were sampled for analysis. Of these, two of the red deer bones are thought to belong to the same individual as they were a tibia and astragalus that had similar preservation and when put together articulated well. Both bones had been previously radiocarbon dated to 11,680 ± 45 uncal BP (OxA-19207) and 11,640 ± 45 uncal BP (OxA-19206) (**Tab. 1**; **Tab. 3**; **Fig. 2**) (Jacobi and Higham, 2011). A further aurochs was sampled from layer D1 along with four reindeer, and two red deer from layer D/E.

Samples were taken at the National Museum of Wales. A dental drill with either a small cutting wheel or tungsten burr drill bit was used to take a small sample of bone or tooth dentine (0.2 to 1.1 g) from each specimen. Samples were prepared at University College London (UCL) using a modified version of the Oxford Radiocarbon Accelerator Unit (ORAU) collagen extraction procedures (AG method; Brock et al., 2010), which is based on a modified version of the Longin (1971) method. All samples were treated with 0.5 M hydrochloric acid (HCl) at 4 °C until fully demineralised and then thoroughly rinsed with ultrapure
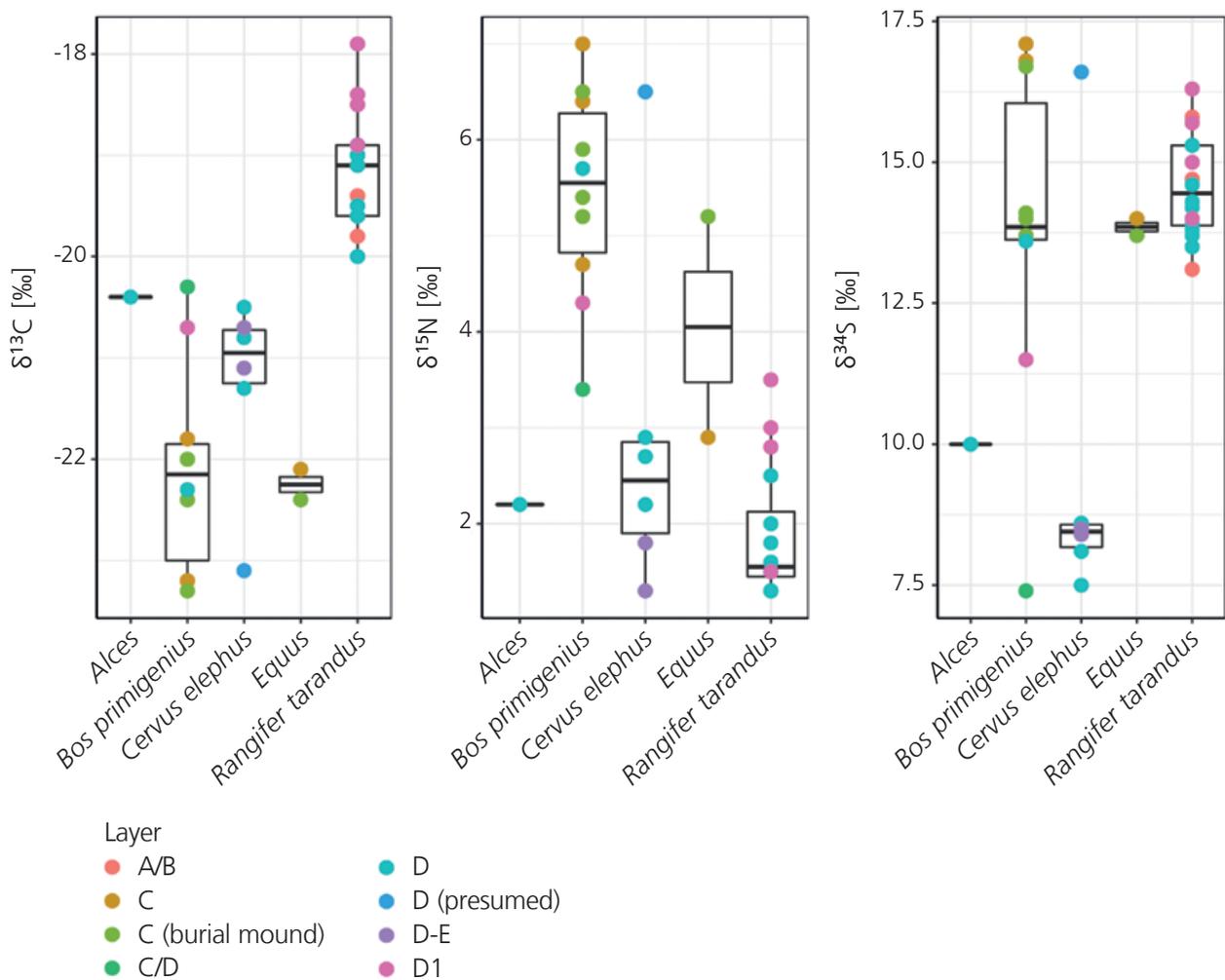


**Fig. 3** Box plot of faunal collagen carbon, nitrogen and sulphur isotope data (with all data points shown) plotted by species with sample layer provenance shown in different colours.
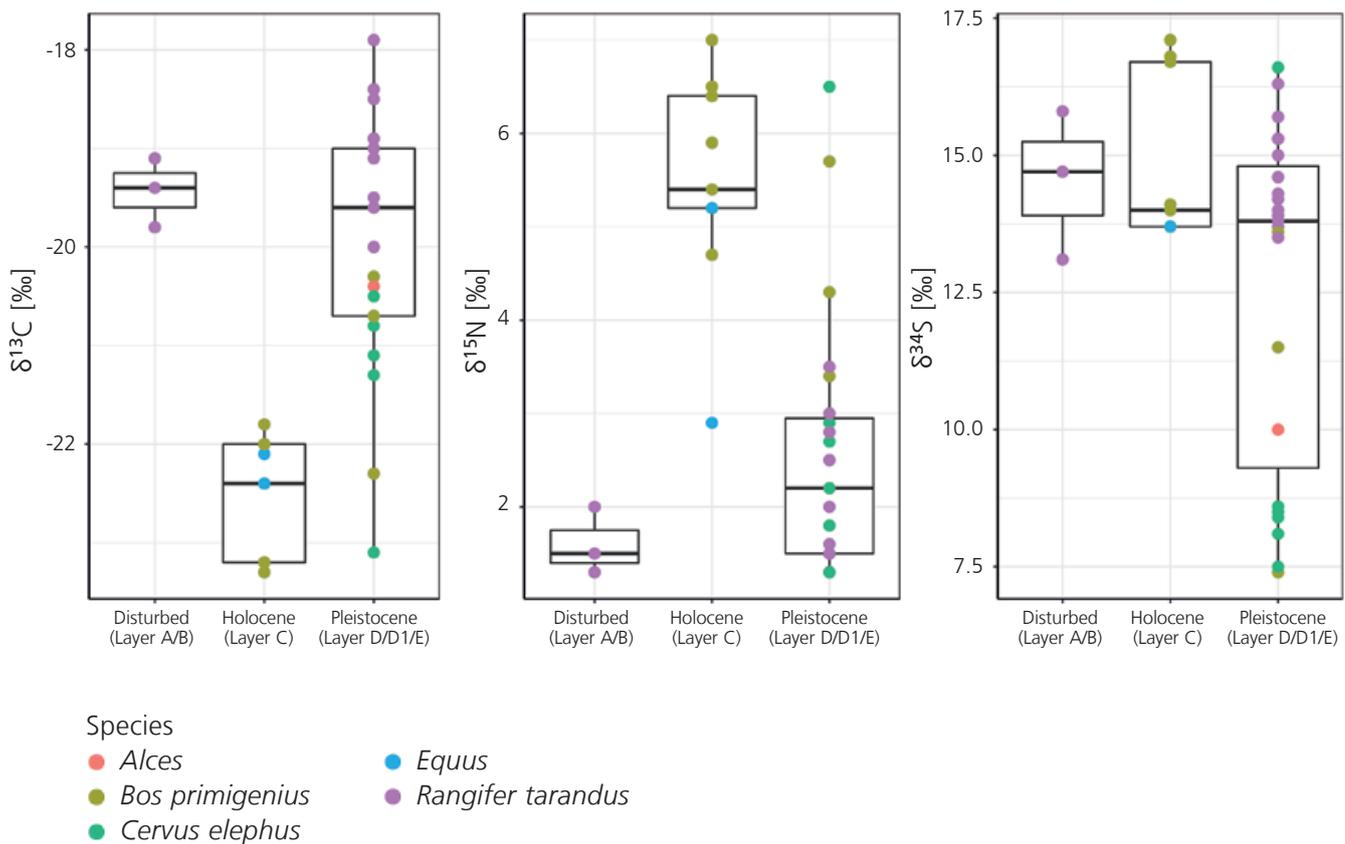
**Fig. 4** Box plot of faunal collagen carbon, nitrogen and sulphur isotope data (with all data points shown) plotted by layers with species shown in different colours.

water. Samples were then treated with 0.1 M sodium hydroxide (30 mins), and 0.5 M HCl (1 hr) to remove humic contaminants (Szpak et al., 2017), again being thoroughly rinsed with ultrapure water between reagents. Samples were then heated in pH3 HCl solution at 75°C for 48 hrs and filtered using a pre-cleaned Ezee-filter, with the supernatant being retained and freeze dried. Between 1.2 and 1.5 mg aliquots of freeze-dried collagen were weighed into tin capsules and analysed using a Delta V Advantage continuous-flow isotope ratio mass spectrometer coupled via a ConfloIV to an EA IsoLink elemental analyser (Thermo Fisher Scientific, Bremen) at the Scottish Universities Environmental Research Centre (SUERC). For every ten unknown samples, three in-house standards that are calibrated to the International Atomic Energy Agency (IAEA) reference materials USGS40 (L-glutamic acid, $\delta^{13}C_{VPDB}$ = -26.4‰, $\delta^{15}N_{AIR}$ = -4.5‰), USGS41 (L-glutamic acid, $\delta^{13}C_{VPDB}$ = +37.6‰, $\delta^{15}N_{AIR}$ = -47.6‰), USGS43 (Indian Human hair: $\delta^{15}N_{AIR}$ = +8.44‰, $\delta^{13}C_{VPDB}$ = -21.28‰, $\delta^{34}S_{VCDT}$ = +10.46‰), IAEA-S-2 (silver sulfide, $\delta^{34}S_{VCDT}$ = +22.7‰), and IAEA-S-3 (silver sulfide, $\delta^{34}S_{VCDT}$ = -32.3‰) were analysed (Sayle et al., 2019). Results are reported as per mil (‰) relative to the internationally accepted standards VPDB, AIR and VCDT. Measurement uncertainty was determined to be ±0.1‰ for $\delta^{13}C$, ±0.2‰ for $\delta^{15}N$, and ±0.3‰ for $\delta^{34}S$ on the basis of repeated measurements of an in-house bone collagen standard and a certified fish gelatin standard (Elemental Microanalysis, UK). Each sample was analysed in duplicate with the exception of two samples (UPN-802 and UPN-804) and reproducibility was better than ±0.1‰ for $\delta^{13}C$, ±0.2‰ for $\delta^{15}N$ and ±0.3‰ for $\delta^{34}S$.

## RESULTS

All samples (n = 35) produced sufficient collagen for isotopic analysis (collagen yields ranged from 3.1 to 16.3 %, 12.6 to 138.4 mg) (**Tab. 3**). All analysed samples returned C:N, C:S and N:S atomic ratios in the range of 3.2-3.5, 590-798 and 172-243, respectively, and %C, %N and %S in the range of 36-45 %, 12-16 %, 0.13-0.20 %, indicating good bone collagen preservation (**Tab. 3**) (DeNiro, 1985; Ambrose, 1990; Nehlich and Richards, 2009). Across the analysed samples $\delta^{13}C$ values ranged from -23.3 to -17.9‰ (mean = -20.6 ± 1.6‰), $\delta^{15}N$ values ranged from 1.3 to 7.0‰ (mean = 3.2 ± 1.9‰), and $\delta^{34}S$
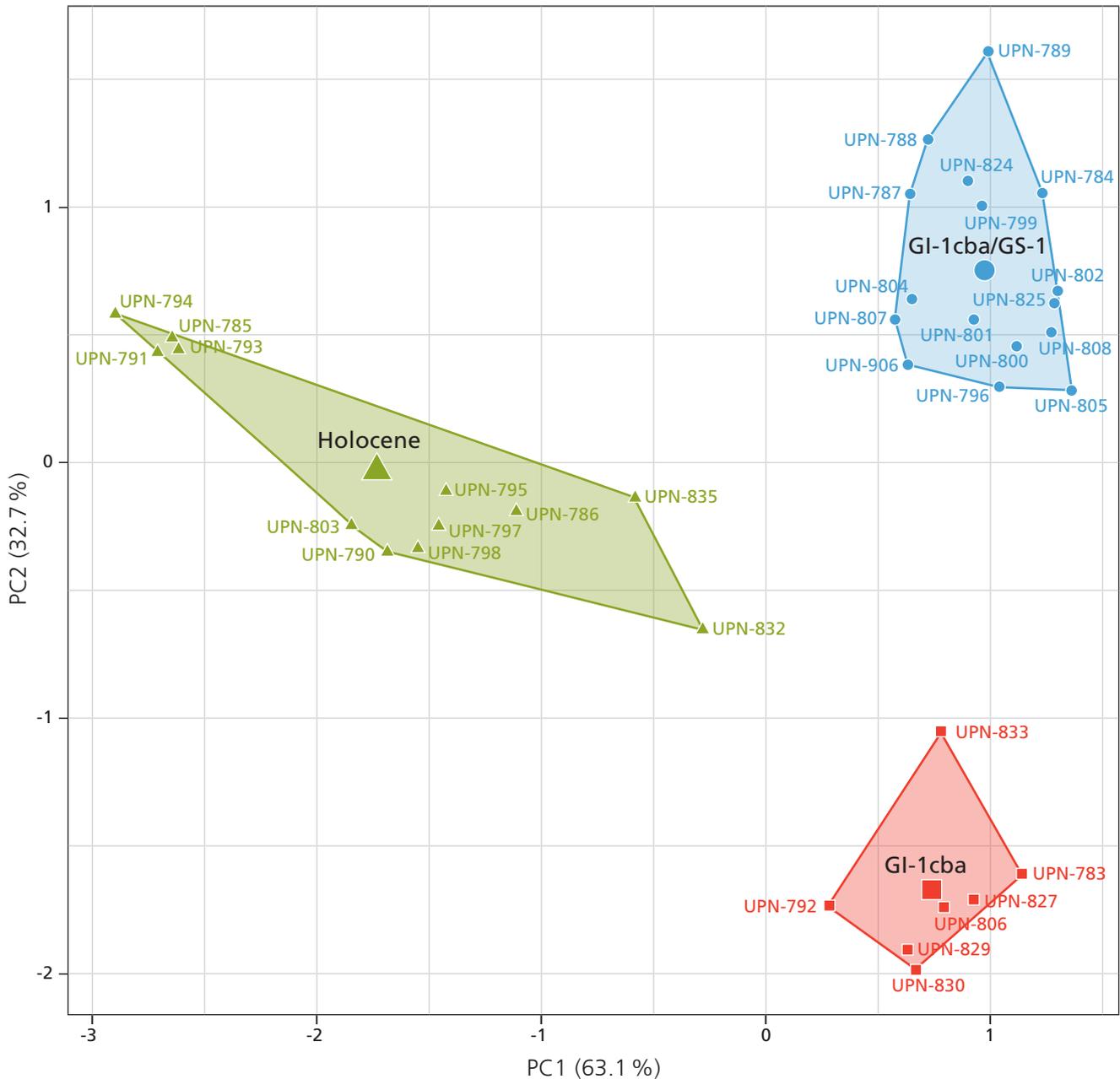


**Fig. 5** Results of cluster analysis. Cluster 1 (red) = GI-1cba (Allerød), Cluster 2 (green) = Holocene, Cluster 3 (blue) = GI1cba/GS1 (Allerød/early Younger Dryas).

values ranged from 7.4 to 17.1‰ (mean = 13.4 ± 2.8‰) (**Fig. 3**). Significant species-based differences are identified in the $\delta^{13}C$ and $\delta^{15}N$ values (Kruskall-Wallis rank sum test, $\chi^2(4) = 26.84 \, p < 0.05$ for $\delta^{13}C$ and $\chi^2(4) = 20.80 \, p < 0.05$ for $\delta^{15}N$), but not in $\delta^{34}S$ values ($\chi^2(4) = 8.53 \, p = 0.07$). Significant differences also occur between samples associated with Holocene (Layer C/burial mound) sediments and those excavated from Pleistocene contexts (Layer D/D-E/D1) for $\delta^{13}C$ (Mann-Whitney U test, $U = 10 \, p < 0.05$) and $\delta^{15}N$ ($U = 190 \, p < 0.05$), but not for $\delta^{34}S$ ($U = 141 \, p = 0.12$) (**Fig. 4**).

Hierarchal cluster analysis of combined $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ values identify 3 distinct groups in the data (**Fig. 5**; Ward's minimum variance, coefficient = 0.963). The first cluster contains all but one red deer sample (n = 5), one aurochs and the elk sample. The cluster is characterised by intermediary $\delta^{13}C$ values, and comparatively low $\delta^{15}N$ and $\delta^{34}S$ values (**Tab. 4**). All samples in this cluster come from Layer D, or the interface of Layer C/D or D/E. Three samples in this cluster have been radiocarbon dated, producing a combined date range of ca. 13,735 to 13,000 cal BP (OxA-12884, OxA-19206, OxA-19207), placing this cluster within GI-1cba.

The second cluster is composed of all reindeer samples (n = 16) and contains no other species. It is characterised by comparatively high $\delta^{13}C$, low $\delta^{15}N$, and high $\delta^{34}S$ values (**Tab. 4**). Within this cluster, the reindeer samples from the Layer A/B disturbed sediments fall within the range of $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ values obtained from the Layer D samples. Samples from Layer D1 display higher $\delta^{13}C$ values (-18.9 to -17.9‰) compared to the other reindeer samples (-20.0 to -18.9‰), but all samples overlap in $\delta^{15}N$ and $\delta^{34}S$ values (**Fig. 5**) Samples in this cluster have been radiocarbon dated to ca. 13,230 to 12,820 cal BP (OxA-7993 and OxA-16854), situating this group within late GI-1cba and early GS-1.

The third cluster of results consists of all but one aurochs samples (n = 9), both horse samples and one red deer sample. It is characterised by comparatively low $\delta^{13}C$, high $\delta^{15}N$ and high $\delta^{34}S$ values (**Tab. 4**). All samples from Layer C and the Layer C burial mound are contained in this cluster, as well as one sample from Layer D, one from D1, and one that was found away from the main passage and area of excavation but presumed to be associated with Layer D. No samples analysed in this cluster have been radiocarbon dated, but a different bone from Layer C was dated between 3,215 and 2,965 cal BP (OxA-8070), placing this group in the Holocene.

## DISCUSSION

Previous work on faunal $\delta^{13}C$, $\delta^{15}N$ and $\delta^{34}S$ values across the Pleniglacial, Late Glacial and Holocene period in Northern Europe have recorded broadly consistent trends, albeit with species specific and regional variation in absolute values, and the timing and magnitude of changes. During the transition from the late Pleniglacial to the Late Glacial, herbivore $\delta^{15}N$ and $\delta^{34}S$ values are particularly low, and $\delta^{13}C$ values are consistent with previous periods (Stevens and Hedges, 2004; Stevens et al., 2008; Drucker et al., 2003, 2009, 2011a, 2011b, 2012; Reade et al., 2020b, 2021). $\delta^{34}S$ values appear to increase rapidly early in the Late Glacial interstadial, whilst an increase in herbivore $\delta^{15}N$ values occurs more gradually through the Late Glacial interstadial, with higher values generally observed in the Holocene (Stevens and Hedges, 2004; Stevens et al., 2008; Drucker et al., 2009, 2011a, 2011b, 2012; Reade et al., 2020b, 2021). $\delta^{13}C$ values initially begin to fall during the latter half of the Late Glacial interstadial (GI-1cba) and more significantly at the start of the Holocene due to changes in atmospheric $CO_2$ concentrations and potentially also due to expansion of woodlands (Drucker et al., 2003, 2008, 2011a; Stevens et al., 2014). Given the range of radiocarbon dates available from the different layers in Lynx Cave and the species found within these layers it seems

| Cluster | δ13C [‰] | | | δ15N [‰] | | | δ34S [‰] | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean ± std | Min. | Max. | Mean ± std | Min. | Max. | Mean ± std | Min. | Max. |
| 1 (GI-1cba) | -20.7 ± 0.4 | -21.3 | -20.3 | 2.4 ± 0.7 | 1.3 | 2.3 | 8.4 ± 0.9 | 7.4 | 10.0 |
| 2 (GI-1cba/GS-1) | -19.1 ± 0.6 | -20.0 | -17.9 | 1.9 ± 0.7 | 1.3 | 1.5 | 14.6 ± 0.9 | 13.1 | 16.3 |
| 3 (Holocene) | -22.4 ± 0.8 | -23.3 | -20.7 | 5.5 ± 0.8 | 2.9 | 7.0 | 14.6 ± 0.8 | 11.5 | 17.1 |

**Tab. 4**   Mean and standard deviation (std) of isotope data from each cluster identified with cluster analysis.

likely that the samples taken for isotope analysis represent a chronological sequence through time, with material sampled from the Late Glacial and the Holocene. Thus, we might expect the broad isotope trends seen in the wider regions to be detected through the layers at Lynx Cave, but some noise may be present in the signal due to some disturbance particularly in the upper layers. Cluster analysis has identified 3 clear groups in the data which when considered in light of the species composition, radiocarbon dates, sample layer provenance and known temporal patterns in herbivore isotope data from Northern Europe, are likely to relate to distinct chronological groupings. However, it is clear that some of the sampled material in certain layers is likely intrusive.

### Layer A/B

Layer A/B is reported to be a highly disturbed deposit potentially containing material of varying ages from the Late Pleistocene to the Holocene (Blore, 2012). Three reindeer were analysed from this layer. Although not directly radiocarbon dated, it is highly unlikely that these are of Holocene age, as the species became extinct in the British Isles either at the end of the Pleistocene or very early in the Holocene (Coard and Chamberlain, 1999). Furthermore, the reindeer have δ15N values that are lower than other wild cervids from Holocene contexts in the British Isles (Stevens et al., 2014). The reindeer δ13C, δ15N and δ34S values are entirely consistent with those of reindeer from Layer D (**Figs. 3-4**) and cluster analysis groups them together (Cluster 1, **Fig. 5**). Taken together, these lines of evidence suggest that the reindeer sampled from layer A/B were intrusive material from (an) older deposit(s) and are likely to be of the same age as the reindeer recovered from Layer D (**Fig. 6**).

### Layer C

Layer C has been attributed mainly to the Bronze Age, although there is some evidence of disturbance and intrusive material (Blore, 2012). Seven aurochs and two horses were analysed from Layer C. All but one sample have relatively high δ15N, high δ34S and low δ13C values (**Figs. 3-4**), and cluster together away from all samples in layers A/B and the majority of samples from layers D/D1/D-E (Cluster 2, **Fig. 5**). One horse (UPN-835) had a relatively low δ15N value, but its δ13C and δ34S values were comparable to those of the other horse (UPN-798) and the rest of the Cluster 2 fauna (**Fig. 5**). The Cluster 2 δ13C and δ15N isotope data are comparable to those of the same species from Holocene site in the British Isles (Lynch et al., 2008; Stevens and Hedges, 2004). Interestingly the Cluster 2 data appear to separate into two groups due to
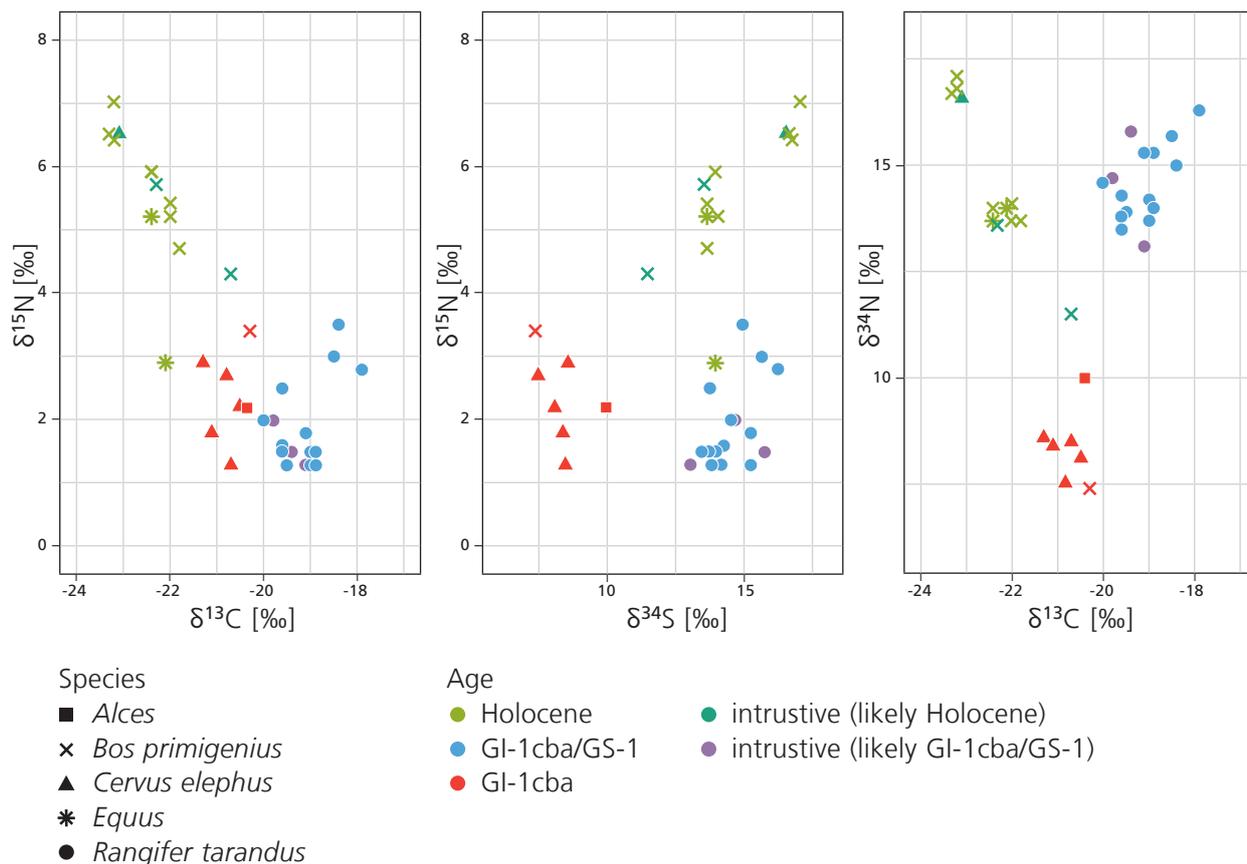
**Fig. 6** Faunal collagen carbon, nitrogen and sulphur isotope data plotted by species and inferred chronological age.

their δ¹³C values, however, this is based on visual inspection of the data and the cluster analysis views the data as a single group (**Fig. 5**). The low δ¹³C values seen for two of the aurochs potentially indicate these individuals lived in a woodland environment, where their δ¹³C values were affected by the canopy effect. By contrast, the aurochs and horse with slightly higher δ¹³C values likely indicate an open environment. These differences could represent animals using different parts of the landscape. Alternatively, they could be linked to chronology, with some animals living in the area at a time when the landscape was more forested and other living in the area when the environment was more open. Without applying direct ¹⁴C dating it is not possible to say which scenario is more likely.

### Layers D/D1/D-E

The majority of the Lynx Cave LUP archaeology was recovered from Layer D/D1 and as the bones found in the top of sterile layer E are thought to have originated from Layer D, the analyses from these layers are considered collectively. A total of 23 samples (elk: n = 1; aurochs: n = 3; red deer: n = 6, reindeer: n = 13) were analysed from layers D/D1/D-E (**Fig. 3**).

A group of seven samples (red deer: n = 5; aurochs: n = 1; elk: n = 1) clearly cluster on their δ³⁴S values (Cluster 3), which are low (7.4‰ to 8.6‰) relative to the range of values in layers D/D1/D-E (7.4‰ to 16‰) and layers A/B/C (13.1‰ to 17.1‰) (**Figs. 3-4**). Three of these samples (UPN-829, UPN-827, UPN-

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830) have been radiocarbon dated (two on the same individual) giving GI-1cba dates of ca. 13,735-13,075 cal BP. Notably none of these samples are reindeer. The $\delta^{13}C$ values are comparable to those seen in other European archaeological sites that date to GI-1cba and indicate an open environment (Drucker et al., 2003; Mannino et al., 2011; Stevens et al., 2014). Yet the identification of charcoal from birch, willow, oak and pine species in the hearths from layers D/D1/D-E show that even if the environment was open, wooded areas must have existed in the vicinity of the site during this period (Blore, 2012). The low $\delta^{15}N$ and low $\delta^{34}S$ values are typical of Late Glacial environments and the isotope data does not suggest significantly warm conditions or mature soils. This data along with the evidence that some of the bones were shattered when fresh indicates the presence of an early phase of human occupation associated with 'temperate' species during GI-1cba (**Fig. 6**).

A second group of 13 samples, all reindeer, group together (Cluster 1, **Fig. 5**), with relatively low $\delta^{15}N$, high $\delta^{34}S$ and high $\delta^{13}C$ values (**Figs. 3-4**). Two species from this group (UPN-808, UPN-906) are radiocarbon dated to ca. 13,170-12,820 cal BP, corresponding to the latter part of GI1-cba/early part of GS-1. Three of the four reindeer samples (UPN-787, -788, and -789) from layer D1 have slightly higher $\delta^{13}C$ and $\delta^{15}N$ values than the reindeer from Layer D (**Fig. 3**), but it should be noted that these samples were taken from teeth whereas the fourth sample and all others from layer D were taken from bones. This difference may be due to the tooth sample representing a shorter time snapshot of diet in early life which is likely for at least two of the specimens and corresponds with the consumption of milk as a calf. Reindeer are typically considered a cold climate species whose presence indicates cool environmental conditions. The reindeer $\delta^{13}C$ values are substantially higher than those of all other species at the site (**Fig. 4**; **Fig. 6**), which is a pattern often observed in Late Pleistocene contexts (e. g., Fizet et al., 1995; Drucker et al., 2003; Stevens et al., 2009). This is because reindeer eat lichen which exhibit higher $\delta^{13}C$ values than sympatric $C_3$ plants (Park and Epstein, 1960; Maguas and Brugnoli, 1996; Drucker et al., 2001). The reindeer's specific diet largely explains the difference in $\delta^{13}C$ values between GI-1cba and GI-1cba/GS-1 groups (Clusters 1 and 3, **Fig. 5**). The low reindeer $\delta^{15}N$ values, comparable to those in Cluster 3, are typical of Late Glacial environments, and suggest soil maturity and nitrogen cycling was similar during the GI-1cba and the late GI-1cba to early GS-1 periods. By contrast, substantially higher $\delta^{34}S$ values are seen for individuals in Cluster 1 relative to those in Cluster 3. Given the species composition disparities between the two clusters, one argument could be that the differing $\delta^{34}S$ values are linked to the species-based differences in landscape use due to ecological preference. This argument is unsatisfactory as it would rely on the late GI-1cba/GS-1 reindeer and the Holocene aurochs and horses using lithologically similar landscapes that are distinct to those being used by the GI-1cba aurochs, red deer and elk. The radiocarbon dates do, however, indicate the reindeer are slightly later in date than the other GI-1cba species, and a similar transition from lower to higher faunal $\delta^{34}S$ values at approximately this time has been observed in other areas of Northern Europe (Drucker et al., 2012; Reade et al., 2020b, 2021). In these contexts, it has been argued that herbivore $\delta^{34}S$ values track changes in soil redox conditions (that control microorganism-mediated isotopic fractionations), which are responding to ice sheet melt and permafrost thaw (Reade et al., 2020b). Another possibility is the higher $\delta^{34}S$ values could be linked to increased input of sulphur from the sea as proximity to the coast reduced due to sea level rise. Yet the amount of sea level rise along the North Wales coastline during the Late Glacial was nowhere near as great as between GS-1 and the mid-Holocene (Roberts et al., 2011), thus it seems unlikely that sea level change is driving the shift in $\delta^{34}S$ values. Furthermore, a similar trend in herbivore $\delta^{34}S$ values is seen in archaeological sites in eastern France, Switzerland and the Czech Republic (Drucker et al., 2012; Reade et al., 2020b, 2021), which are too far from the coast for sea level change to have had an impact. Thus, soil redox and hydrological changes linked to ice sheet melt and/or permafrost thaw offer a more parsimonious explanation for the observed change in herbivore $\delta^{34}S$ values.

Finally, three samples (red deer: n = 1, i.e., UPN-793, aurochs: n = 2, i.e., UPN-790, UPN-832) from Layer D/D1/D-E are clear outliers from the rest of the data from Layer D/D1/D-E, but cluster with the isotope data from Layer C (Cluster 2, **Fig. 5**), which is thought to relate to the Bronze Age/Holocene. Furthermore, their results are consistent with isotope values observed for the same species at Holocene archaeological sites in the British Isles (Lynch et al., 2008; Stevens et al., 2014). The red deer (UPN-793) $\delta^{13}C$ value potentially indicates the animal lived in a wooded environment. This specimen was found away from the main passage in a layer assumed to be continuation of Layer D, but this assumption appears to be speculative. It seems likely that all three specimens represent Holocene intrusive material (**Fig. 6**), although for the aurochs samples, the excavation records do not provide more conclusive support for this.

## CONCLUSIONS

Analysis of the data from Lynx Cave indicates the faunal isotope results clusters into three, or potentially four, distinct groupings, which when considered in light of the species composition, radiocarbon dates, sample layer provenance and known temporal patterns in herbivore isotope data from Northern Europe, are likely to relate to distinct chronological periods. One group (Cluster 2) has rather different isotope values compared to the clusters attributed to the Late Glacial, and when combined with the archaeological and radiocarbon evidence appears to relate to the Bronze Age (Holocene). However, the possibility of two distinct groups within Cluster 2, one indicating an open environment and the other indicating a woodland environment could potentially suggest that the material belongs two time periods (e.g., Early Holocene and Late Holocene) when woodland development within the region likely differed. Alternatively, the potentially distinct groups could indicate contemporary animals using different parts of the landscape.

The second grouping (Cluster 1) seems to relate to GI-1cba (the Allerød period) ~13,700-13,000 cal BP. The temperate species composition (red deer, elk and aurochs) and isotope data indicate an open environment and not particularly mature soil conditions that are likely being impacted by permafrost thaw processes or affected by conditions created as a legacy of ice sheet melt and permafrost thaw. The second grouping seems to relate to GI-1cba/GS-1 (the Late Allerød/early Younger Dryas period) ~13,100-12,800 cal BP, when the presence of tundra-steppe species (reindeer) and isotope data indicate cool environmental conditions with relatively immature soil conditions, but which appear to be recovering from the impact of changing soil and hydrological conditions linked to ice sheet melt and permafrost thaw. The evidence of butchery on the faunal remains from both isotope Cluster 1 (Allerød) and Cluster 2 (Late Allerød/early Younger Dryas), along with the disparate radiocarbon dates and the presence of three hearths support the idea of very short-term episodic use of the cave over an extended time period (Blore, 2012). The Late Upper Palaeolithic lithic assemblage from Lynx Cave is small, but does contain elements typically found at continental Late Magdalenian, Hamburgian and Azilian/*Federmesser* archaeological sites (Blore, 2012; Pettitt and White, 2012). It is not possible from the current evidence to link any particular technocomplex to the radiocarbon dated material at the site. However, from the Lynx Cave data, together with the evidence from Kendrick's Cave (Richards et al., 2005; Jacobi et al., 2009; Cook, 2013), it is clear that people were present in North Wales during the early, middle and Late Allerød and early Younger Dryas periods, even if visits to the area were fleeting. Given that ancient DNA indicates this time period witnessed a major population turnover, and archaeological evidence from across Northern Europe indicate changes in mobility patterns, settlement structure, subsistence economy, technology and social organisation, further work is needed to establish which human groups were present in North Wales at this time (Posth et al., 2016; Amkreutz et al.,

2018). The numerous small caves of similar size to Lynx Cave present through the whole limestone region of North Wales provide the opportunity for such work, along with the human remains from Kendrick's Cave which could be targeted for ancient DNA analysis.

## Acknowledgements

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