Quaternary Science Reviews 339 (2024) 108827

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

New insights on the fauna of Ireland's Younger Dryas and Early Holocene from Alice & Gwendoline Cave

Marion Dowd[a,*], Chris Stimpson[b], Rory Connolly[c], James Bonsall[d], Thorsten Kahlert[e], Rowan McLaughlin[f]

[a] Faculty of Science, Atlantic Technological University, Sligo, Ireland
[b] Oxford University Museum of Natural History, Oxford, UK
[c] Trinity Centre for Environmental Humanities, Trinity College Dublin, Ireland
[d] Fourth Dimension Prospection Ltd., Sligo, Ireland
[e] School of Natural and Built Environment, Queen's University Belfast, Northern Ireland
[f] Hamilton Institute, National University of Ireland Maynooth, Ireland

ARTICLE INFO

Handling Editor: Mira Matthews

Keywords:
Younger Dryas
Ireland
Late Pleistocene
Early Holocene
Alice and Gwendoline Cave

ABSTRACT

The nature of the mechanisms that have shaped the animal communities of the island of Ireland remains a pervasive question in the study of the Quaternary of north-western Europe. Archived Quaternary faunal bone assemblages from antiquarian excavations of cave sites are a direct line of evidence with demonstrable potential to shed light on this issue, but are currently constrained by limited publication, understanding of early excavation protocols, and a lack of chronological reference. Alice and Gwendoline Cave in the west of Ireland was the subject of extensive excavations in 1902, which yielded a substantial faunal assemblage and the first evidence of an Upper Palaeolithic human presence on the island during the terminal Pleistocene. Here, we report further results from this important site. Archaeological excavations and a radiocarbon dating programme in 2019-2020 have shed light on the environmental context of the faunal assemblage, the cave taphonomy and site chronology. Nineteen radiocarbon dates are now available, including new direct dates for brown bear (*Ursus arctos*), giant deer (*Megaloceros giganteus*) and reindeer (*Rangifer tarandus*). The archaeological excavations and the analysis of sedimentary lipids – the first of its kind for an Irish cave site, both suggest that the sediments are primarily of exogenous origin, likely carried into the cave through fissures and openings by runoff or colluvial movements. Our analyses indicate that there were at least three main 'pulses' of bone-bearing sediment accumulation: at the beginning of the Younger Dryas (*c.* 12,700 cal. BP), in the aftermath of the Younger Dryas (11,300 cal. BP) and in the Early Holocene (*c.* 10,000 cal. BP), with a hiatus in sediment deposition after 9700 cal. BP.

1. Introduction

The timing and mechanisms that have shaped the fauna of Ireland remain pervasive questions in studies of Quaternary north-western Europe (Woodman et al., 1997; Searle, 2008; Carden et al., 2012; Montgomery et al., 2014; Sleeman, 2014; Monaghan, 2017; Stimpson, 2024). While Ireland's fauna is unique and distinct, it continues to pose many questions for zoologists, archaeologists and biogeographers, not least due to a relatively limited taxonomic breadth and sparse chronological records (e.g. Woodman, 2014; Monaghan, 2017).

A direct line of evidence for the investigation of the origins and nature of the animal communities of Ireland are bone assemblages recovered from cave excavations. While investigations began in the late nineteenth century (e.g. Adams et al., 1881), and in earnest in the early twentieth century (e.g. Scharff et al., 1903, 1906), the Quaternary vertebrate record of Ireland remains relatively sparse and poorly understood (e.g. Woodman, 2014; Monaghan, 2017). Indeed, the most comprehensive review in taxonomic and chronological scope remains that of the *Irish Quaternary Fauna Project*, which was published in the 1990s (Woodman et al., 1997). Since then, improvements and refinements in radiocarbon dating protocols (e.g. Jacobi and Higham, 2008; Higham, 2011) have revealed that dates in this benchmark work must be viewed with caution. More recent dating programmes have yielded insights into glacial fauna (Carden et al., 2020). The post-glacial

---

* Corresponding author.
E-mail address: marion.dowd@atu.ie (M. Dowd).

https://doi.org/10.1016/j.quascirev.2024.108827
Received 23 May 2024; Received in revised form 5 July 2024; Accepted 6 July 2024

Fig. 1. Alice and Gwendoline Cave – site location and images taken during the 2019 excavation (Thorsten Kahlert).

period is the formative period for Ireland's fauna and is also when Ireland became, and has remained, an island since *c*. 16,000 cal. BP (cal. BP = calibrated years before present, where convention holds the 'present' to be 1950) (Clark et al., 2012; Edwards and Craven, 2017). Data for the post-glacial period are still very poorly represented, especially for studies utilising the latest dating protocols (but see Dowd et al., 2021; Power et al., 2023). As such, archives of bones from the post-glacial period that were recovered from caves in the early twentieth century remain an important source of primary data. One such site is Alice and Gwendoline Cave in County Clare (Fig. 1).

2. Antiquarian investigation

Alice and Gwendoline Cave, located in County Clare in the west of Ireland,[1] penetrates a low-lying Lower Carboniferous limestone outcrop 260 m north of Edenvale Lake. The two principal cave passages (Alice Passage and Gwendoline Passage) have developed along fissures that run parallel to the south-to-north oriented major faults in the limestone. Between the main passages is a third parallel passage with a relatively

---

[1] Cahircalla Beg townland; ITM 532144 674833; SMR CL041-060——

large entrance that quickly narrows to a tight crawl. Two east-west running passages connect the system; the southernmost comprises a tight crawl but the northern passage can be traversed. There are five openings into the cave: three to the south, a small opening to the west, and a roof opening at the end of the largest passage (Fig. 2).

A four-week excavation in 1902, under the auspices of the *Committee Appointed to Explore Irish Caves*, led to the recovery of *c*. 10,000–15,000 animal bone fragments in the cave (Scharff et al., 1906; Dowd et al., 2021). Most of the assemblage was recovered from Alice Passage (25 m long, 2.7 m wide). Two main strata were identified, though significant evidence of stratigraphic disturbance, particularly due to badger activities, was noted. The 'Upper Stratum' comprised 'brown earth, with calcareous tufa' and contained bones of extinct and domesticated fauna. The lower 'Second Stratum' was a 'very tenacious clay … often containing black patches'; it produced extinct faunal remains with some human bones present in the upper portion of the unit (Scharff et al., 1906). The level of the cave floor in the Alice Passage was reduced by up to 0.75 m with the removal of deposits (Fig. 3). A talus of material that had entered the cave via an opening in the roof occurred at the terminus of this passage; this was also largely removed in 1902.

The antiquarian team identified the remains of extinct and extant mammals (including domesticates), fish and birds in the Alice and Gwendoline assemblage (Scharff et al., 1906). Thousands of bones of rat (*Rattus norvegicus*) and rabbit (*Oryctolagus cuniculus*) were (reasonably) deemed recent and intrusive and were not retained. The remainder were deposited in the Natural History Division (NHD) of the National Museum of Ireland (NMI) in Dublin. Ten human bones were also recovered but only two have been located in recent years (Fibiger, 2016; Dowd et al., 2021). Over twenty archaeological artefacts were retrieved, including a flint scraper and chert scraper of likely Neolithic and/or Bronze Age date (both now lost), and two Hiberno-Scandinavian arm-rings (copper alloy and gold) dating to the late ninth or early tenth century CE.

Six bones from the antiquarian excavations had been radiocarbon dated prior to the current project. Three Arctic lemming (*Dicrostonyx torquatus*) mandibles indicated a terminal Pleistocene horizon (Woodman et al., 1997). The date is of limited value, however, as it was obtained on bones using a sample of mixed powder from three different individuals and the samples were processed without ultrafiltration pre-treatment. A butchered brown bear patella and an unmodified brown bear calcaneum also returned terminal Pleistocene dates (12,890–12,678 cal. BP and 12,680–12,252 cal. BP respectively) from the beginning of the Younger Dryas, equivalent to the Late Upper Palaeolithic (Dowd and Carden, 2016; Edwards et al., 2011). A brown bear metatarsal and a human (*Homo sapiens*) clavicle were dated to the Early Holocene (10,227–9778 cal. BP and 10,146–9700 cal. BP respectively), equivalent to the Early Mesolithic (Dowd and Carden, 2016; Dowd et al., 2021) (Table 1). From the Late Holocene, a Great Spotted woodpecker (*Dendrocopos major*) femur was dated to 4235–3985 cal. BP, equivalent

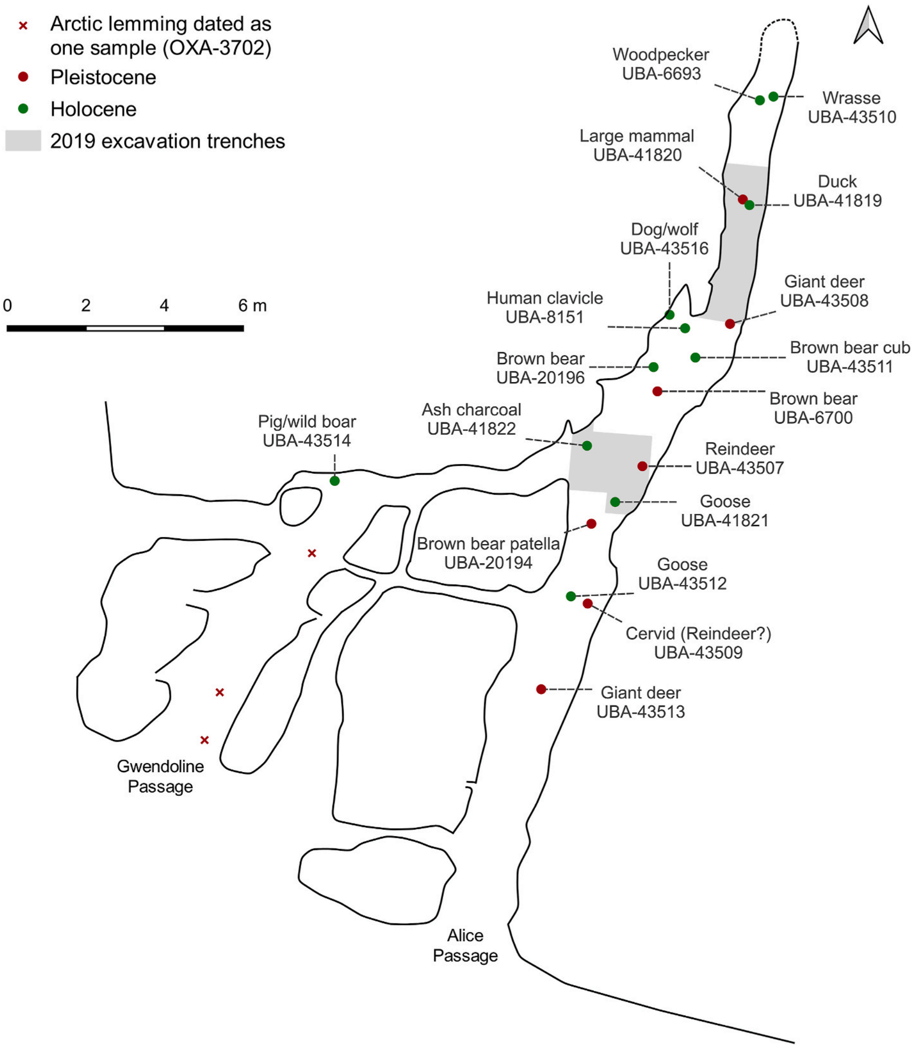

Fig. 2. Plan of Alice and Gwendoline Cave with locations of 2019 excavation trenches and findspots of radiocarbon dated bones (Thorsten Kahlert and James Bonsall).

Table 1

Lab code	Date discovered Trench, Grid Context	Species, element, ID[a]	$\delta^{13}C$	$\delta^{15}N$	C:N ratio	Collagen yield %	Radiocarbon age (BP)	Calibrated radiocarbon date (2 δ) cal BP (years before present, where present is 1950)[b]	Calibrated radiocarbon date (2 δ) cal BCE[b]
PLEISTOCENE									
UBA-41820	12.08.2019 Alice Passage Tr. 1, G.F C.1003	Large mammal Long bone shaft fragment 19E381:95	−19.4	8.8	3.19	4.90	11,061 ± 41	13,093-12891 (93.8%) 12,859-12848 (1.6%)	11,144-10942 (93.8%) 10,910-10899 (1.6%)
UBA-20194 OxA-29358	09.06.1902 Alice Passage (EA131) Second Stratum	Brown bear (*Ursus arctos*) Right patella NMIAD: 2020:12 NMIAD: E1028:1 NMING: F23919 (Dowd and Carden, 2016)	−19.97	6.51	3.28	7.30	10,798 ± 71 10,850 ± 50	12,890-12860 (3.2%) 12,847-12678 (92.3%) 12,884-12865 (3.1%) 12,843-12727 (92.3%)	10,941-10911 (3.2%) 10,898-10729 (92.3%) 10,935-10916 (3.1%) 10,894-10778 (92.3%)
UBA-43509	09.06.1902 Alice Passage (EA125) Second Stratum	Cervid, most likely reindeer (*Rangifer tarandus*) Metapodial fragment NMIAD: E1028:6	−19.6	6.0	3.26	4.00	10,646 ± 72	12,745-12590 (79.7%) 12,546-12487 (15.8%)	10,796-10641 (79.7%) 10,597-10538 (15.8%)
UBA-43513	06.06.1902 Alice Passage (EA94) Second Stratum	Giant deer (*Megaloceros giganteus*) Rib fragment NMIAD: E1028:11	−19.9	7.1	3.19	5.50	10,571 ± 54	12,709-12481 (95.4%)	10,760-10532 (95.4%)
UBA-6700	12.06.1902 Alice Passage (EA150) Second Stratum	Brown bear (*Ursus arctos*) Right calcaneum NMING: F21750 (Edwards et al., 2011)	−19.91	6.15			10,495 ± 51	12,680-12434 (76.2%) 12,392-12374 (0.8%) 12,358-12322 (4.9%) 12,309-12252 (6.7%) 12,236-12175 (6.4%) 12,115-12107 (0.4%)	10,731-10485 (76.2%) 10,443-10425 (0.8%) 10,409-10373 (4.9%) 10,360-10303 (6.7%) 10,287-10226 (6.4%) 10,166-10158 (0.4%)
UBA-43507	11.06.1902 Alice Passage (EA61) 'in calc tufa of great thickness'	Reindeer (*Rangifer tarandus*) Left metacarpal NMIAD: E1028:3	−18.4	5.5	3.26	4.90	10,394 ± 96	12,620-11931 (94.7%) 11,904-11885 (0.7%)	10,671-9982 (94.7%) 9955-9936 (0.7%)
UBA-43508	13.06.1902 Alice Passage (EA167) Second Stratum	Giant deer (*Megaloceros giganteus*) Proximal phalanx NMIAD: E1028:5	−20.7	5.0	3.23	2.60	10,204 ± 91	12,460-12349 (6.0%) 12,329-12300 (1.4%) 12,271-12226 (2.0%) 12,196-11599 (79.4%) 11,582-11474 (4.7%) 11,444-11403 (1.8%)	10,511-10400 (6.0%) 10,380-10351 (1.4%) 10,322-10277 (2.0%) 10,247-9650 (79.4%) 9633-9525 (4.7%) 9495-9454 (1.8%)
OXA-3702	21 + 26.06.1902 Gwendoline Passage (EA14 + EA41) Upper Stratum & (EA101) Second Stratum	Arctic lemming (*Dicrostonyx torquatus*) Three different mandibles NMING: F21138.1–3 (Woodman et al., 1997)	−19.8				10,000 ± 80	11,808-11786 (1.7%) 11,756-11250 (93.7%)	9859-9837 (1.7%) 9807-9301 (93.7%)
HOLOCENE									
UBA-43511	13.06.1902 (EA163) Second Stratum	Brown bear (*Ursus arctos*), juvenile Zygomatic fragment NMIAD: E1028:8	−20.8	5.7	3.17	5.80	9909 ± 53	11,608-11533 (6.8%) 11,502-11426 (8.2%) 11,408-11210 (80.5%)	9659-9584 (6.8%) 9553-9477 (8.2%) 9459-9261 (80.5%)
UBA-43512	09.06.1902 Alice Passage (EA125) Second Stratum	Goose (Anser sp.) Right coracoid NMIAD: E1028:10	−22.6	6.9	3.22	5.40	9836 ± 51	11,393-11375 (2.8%) 11,346-11180 (92.7%)	9444-9426 (2.8%) 9397-9231 (92.7%)
UBA-41821	14.08.2019 Tr. 2, G.2D C.2011	Goose (*Anser* sp.) Sternum fragment 19E381:99	−21.9	4.6	3.20	3.80	9728 ± 40	11,240-11079 (90.6%) 10,925-10887 (4.9%)	9291-9130 (90.6%) 8976-8938 (4.9%)
UBA-20196	12.06.1902 Alice Passage (EA64) Upper Stratum	Brown bear (*Ursus arctos*) Metatarsal IV NMING: F23920 NMIAD: 2020:13 NMIAD: E1028:2 (Dowd and Carden, 2016)	−21.35	0.63	3.27	2.60	8919 ± 64	10,227-9886 (89.1%) 9860-9778 (6.4%)	8278-7937 (89.1%) 7911-7829 (6.4%)
UBA-8151	14.06.1902 Alice Passage (EA166) Second Stratum	Human (*Homo sapiens*) Left clavicle, adult No NMI ID (Dowd et al., 2021; Fibiger, 2016, 17)					8828 ± 34	10,146-10060 (19.2%) 10,043-10020 (3.2%) 10,015-9986 (5.0%) 9964-9700 (68.0%)	8197-8111 (19.2%) 8094-8071 (3.2%) 8066-8037 (5.0%) 8015-7751 (68.0%)
UB-6693	03.06.1902 Terminus of Alice Passage (EA87) Talus material	Great Spotted woodpecker (*Dendrocopos major*) Femur					3750 ± 35	4235-4196 (11.1%) 4185-4059 (59.6%) 4054-3985 (24.8%)	2286-2247 (11.1%) 2236-2110 (59.6%) 2105-2036 (24.8%)

(*continued on next page*)

Table 1 (*continued*)

Lab code	Date discovered Trench, Grid Context	Species, element, ID[a]	$\delta^{13}C$	$\delta^{15}N$	C:N ratio	Collagen yield %	Radiocarbon age (BP)	Calibrated radiocarbon date (2 δ) cal BP (years before present, where present is 1950)[b]	Calibrated radiocarbon date (2 δ) cal BCE[b]
		NMING: F21520 (Monaghan, 2016)							
UBA-43510	03.06.1902 Terminus of Alice Passage (EA87) Talus material	Wrasse (Labrus sp.) Pharyngeal plate NMIAD: E1028:7	−14.1	11.8	3.16	2.40	2295 ± 35	2130–1987 (59.9%) 1979–1833 (34.7%)	181-37 (34.0%) 29 cal. BCE-116 cal. CE (60.5%)
UBA-41819	13.08.2019 Tr.1, G.F C.1006	Duck (*Anas platyrhynchos*) Left coracoid 19E381:97	−22.4	10.0	3.17	4.70	2079 ± 31	2124-1974 (88.8%) 1969–1942 (6.7%)	175-25 (88.8%) 20 cal. BCE-8 cal. CE (6.7%)
UBA-43514	26.06.1902 Gwendoline Passage (EA121) Second Stratum	Pig/wild boar (*Sus* sp.) Calcaneus fragment NMIAD: E1028:14	−21.1	5.1	3.15	4.60	1921 ± 31	1925-1741 (95.4%)	25–210 cal. CE (95.4%)
UBA-43516	13.06.1902 Alice Passage (EA68) ‘pocket in left wall’	Dog/wolf (*Canis* sp.) Calcaneus NMIAD: E1028:12	−21.6	8.7	3.15	7.80	1519 ± 26	1512-1489 (3.7%) 1474-1452 (4.9%) 1418-1344 (86.0%) 1323-1316 (0.8%)	438–462 cal. CE (3.7%) 477–498 cal. CE (4.9%) 532–606 cal. CE (86.0%) 627–634 cal. CE (0.8%)
UBA-41822	14.08.2019 Tr. 2, G.6C C.2009	Ash twig (6 yrs old) charcoal 19E381:S1					18 ± 18	248-229 (26.0%) 136-116 (25.4%) 60-41 (44.1%)	1703–1722 cal. CE (26.0%) 1815–1835 cal. CE (25.4%) 1890–1909 cal. CE (44.1%)
UBA-43515	03.06.1902 Alice Passage? (EA3) Upper Stratum	Equid (Equus sp.) Proximal phalanx, fragment of distal articulation NMIAD: E1028:9	Failed due to insufficient collagen						

[a] Identification numbers for bones discovered in 1902 were attributed by the National Museum of Ireland, some of which relate to sequencing in the Natural History Division (NMING) and others to the Irish Antiquities Division (NMIAD). During their history within the NMI, some bones were given more than one registration number, all of which are presented here to prevent confusion with numbering in previous publications. Dated bones with the ID prefix ‘19E’ were recovered during the 2019 excavations directed by M. Dowd.

[b] Conventional radiocarbon ages were calibrated using OxCal v4.4.4 (Bronk Ramsey 2021).

to the Early Bronze Age (Monaghan, 2016).

3. Methodology

The 2019–2020 project involved a 3D digital survey (supplementary data), geophysical surveys (metal detection, magnetometry, magnetic susceptibility and earth resistance) (SI), a two-week archaeological excavation, sedimentary lipid extraction and analysis (SI) and thirteen new radiocarbon dates on bones recovered in 1902 and 2019. The photogrammetry and 3D laser scan models created in 2019 now allow ‘access’ to the cave: https://skfb.ly/oYpyQ and https://skfb.ly/oYpzR.

Prior to the excavation, a full terrestrial LiDAR scan of the cave was conducted with a Leica P40 and a supplemental structure-from-motion (SFM) survey using a hand-held Canon 6D digital SLR camera equipped with a Speedlite flashgun. Given that the focus of the research excavation was on Alice Passage, priority was given to this section in terms of overall accuracy and detail. Control points were set out along the passage in the form of spheres that were anchored into the cave wall. An Ashtech ProMark 500 L1 GNSS receiver was used to set out basepoints outside the cave. The control points inside the cave were georeferenced by traversing a topo-survey from the basepoints into the cave with a Sokkia TS610 total station. A total of 31 scan stations spaced at 2 m intervals were required to conduct the LiDAR scan. While the P40 is capable of providing RGB data for the point cloud via its built-in camera, light conditions inside the cave were too dark to effectively avail of this option. The terrestrial LiDAR scan (TLS) data was registered in Leica Register 360 and Autodesk Recap. The SFM survey provided data where cave sections were too restrictive to allow for the terrestrial LiDAR scanner to operate and complemented the LiDAR scan with a textured mesh. A total of 844 photographs were processed in Agisoft Metashape to create a dense point cloud and mesh. The point clouds from the SFM and TLS were aligned in Cloud Compare and filtered to reduce point density. The final model was modified to extract data for sections, profiles and a floor plan, which were further processed in ArcGIS Pro and Adobe Illustrator (Fig. 2).

Metal detection, magnetometry, magnetic susceptibility and earth resistance surveys were all conducted along the length of Alice Passage immediately prior to the 2019 excavations (SI). This was the first instance where geophysical techniques were employed inside an Irish cave system. These had the potential to identify the presence of anthropogenic deposits, features associated with the 1902 excavation, modern disturbance and/or faunal burrowing.

The 1902 excavation (Dowd et al., 2021) demonstrated the presence of metal artefacts in the cave, including Hiberno-Scandinavian arm-rings (copper alloy and gold), a James II coin, a lead bullet, and various pieces of iron (an animal trap, nails and fragments). The metal detection survey was used to identify any post-Bronze Age deposits, and particularly to determine areas of later disturbance. An XP Dēus discriminating metal detector with a 9-inch coil was used along the length of the cave passages, sweeping left and right of a central transect across the full width of the cave. The locations of metal hits were recorded and marked but were not excavated.

The magnetometer survey was used to determine potential areas of burning and disturbance. A Geoscan Research FM256 was used at a spatial resolution of 0.25 m × 0.25 m. The morphology of the cave walls, low ceiling height and dark interior meant that safe working was only possible whilst wearing a caving helmet with a magnetic headlamp mounted on it. Following experiments with the headlamp positioning to remove unwanted magnetic interference, good results were obtained, resulting in only a negligible interference response of <1 nT. The magnetic susceptibility surveys were carried out to identify contrasts that might indicate burnt deposits. Two magnetic susceptibility surveys

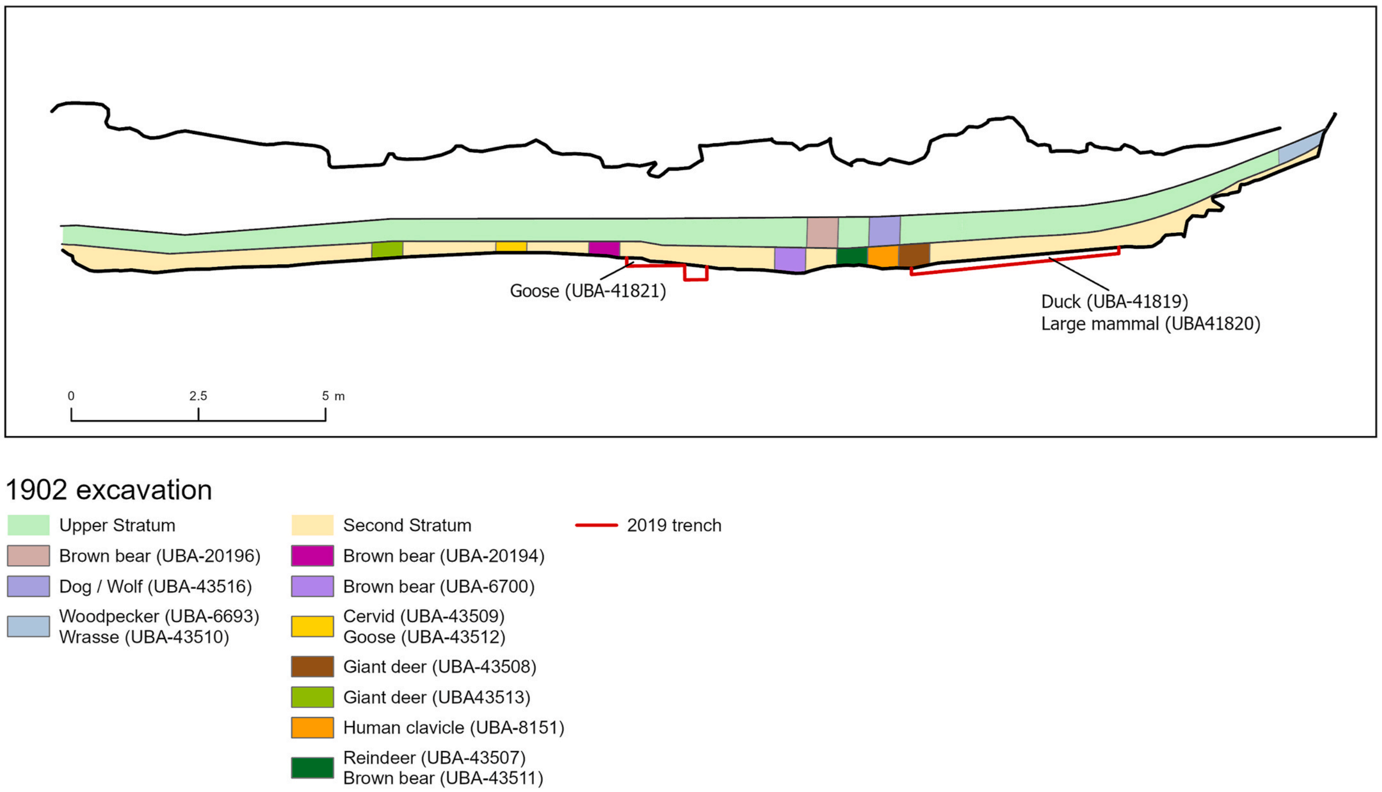

Fig. 3. Schematic longitudinal section of Alice Passage illustrating the 1902 stratigraphy (approximately, as stratigraphic records were minimal); the antiquarian grids from which the radiocarbon dated bones were recovered; and the locations of the 2019 excavation trenches (Thorsten Kahlert).

were carried out at different depths of investigation (DoI). A Bartington Instruments MS2 meter obtained volume specific magnetic susceptibility at the surface with a 1 cm DoI (20 cm sample resolution along a single central transect, using a Bartington MS2F probe). A second survey obtained data at 15 cm DoI (20 cm × 10 cm resolution across the entire cave, using a Bartington MS2D probe).

The earth resistance survey was carried out to determine changes in sediment moisture that might indicate near surface rock indicative of the natural cave floor, bulk sediments above the cave floor and burrowing activities. A Geoscan Research RM15 resistance meter and a Wenner array were used. The array measured 1.6 m in width, wider than the majority of Alice Passage. The array was therefore rotated 90° into orthogonal mode, to collect data along the passage at 0.5 m intervals, along lines spaced 0.25 m apart.

The archaeological excavation involved opening two trenches along Alice Passage (Fig. 2). These were excavated stratigraphically in 0.5 × 0.5 m grids and recorded by single context. Excavated deposits were dry sieved through a 2 mm mesh. Deposits in Trench 1 (4 m N–S x 0.8 m E-W) were removed to a maximum depth of 0.34 m. Two of the seven strata recorded occurred beneath the level of the 1902 excavation. Deposits in Trench 2 (2 m^2) were excavated to a maximum depth of 0.30 m. Of the ten contexts identified, five were beneath the level of the 1902 excavation.

Fifteen sediment samples (~10 g) were collected in vertical sequence from a south profile in Trench 1 for lipid biomarker characterisation and compound specific isotope analysis. Samples were oven-dried at a temperature of 60 °C for 24 h prior to extraction. Extraction of the target alkanes was carried out following the optimised QuEChERS method set out by Herrera-Herrera et al. (2020) based on the original methodology proposed by Anastassiades et al. (2003). 5 g of sediment was transferred to a 50 mL PTFE tube and one spherical glass ball was included. 10 mL of DCM as extraction solvent was added and the mixture was manually shaken for 1 min. IS was added (1 μL 400 mg/L) and the tube was again manually agitated for 30 s; 4 g of MgSO4 and 1 g of NaCl were subsequently added. Manual agitation was again carried out for a duration of 1 min and the mixture was centrifuged at 4700 r.p.m. for 5 min using a Mega Star 1.6 from VWR International (Barcelona, Spain). The supernatant (approx. 6 mL) was then transferred to another 50 mL PTFE tube containing 150 mg of MgSO4 and 25 mg of PSA (clean-up sorbent). This was manually agitated for 30 s and centrifuged at 4700 r.p.m. for 5 min. The supernatant was collected and evaporated under a nitrogen flow using an Organomation evaporator (Massachusetts, USA). The residue was reconstituted in 50 μL of hexane prior to injection in the GC-MS system.

Identification of individual compounds was carried out by comparison of retention times and mass spectra to those of reference compounds (mix C_8–C_{40} and 5α-androstane, Supelco) and mass spectral library databases (NIST). Quantification of concentrations was achieved using calibration curves obtained which plot the ratio $\text{Area}/\text{Area}_{\text{IS}}$ versus the concentration of reference compounds. Correlation coefficients for each sample was higher than 0.995. Concentration is expressed here in terms of μg of individual compound per gram of dry sample ($\mu g\ gds^{-1}$). The average chain length (ACL) was calculated following Poynter et al. (1989) and Freeman and Pancost (2013) using the C_{18}–C_{35} interval: $ACL_{17\text{-}35} = \Sigma(Ci \times [Ci])/\Sigma[Ci]; 18 \leq i \leq 35$. Carbon preference index (CPI) values (C_{25} to C_{33}) were calculated following Bray and Evans (1961): $CPI_{25\text{–}33} = [(\Sigma C_{25\text{–}33odd}/\Sigma C_{26\text{–}34even}) + (\Sigma C_{25\text{-}33odd}/\Sigma C_{26\text{–}34even})] \times 0.5$. Values > 1 denote an OEP (odd over even preference) while values < 1 are indicative of an EOP (even over odd preference). The proportion of aquatic plants (P_{aq}) index was calculated following Ficken et al. (2000): $Paq = (C_{23} + C_{25})/(C_{23} + C_{25} + C_{29} + C_{31})$. The relative contribution of *n*-alkanes C_{29} and C_{31} through the sequence was assessed using long-chain *n*-alkane ratios (LAR): $C_{29}/(C_{29} + C_{31})$.

In 2020, ten bones from the 1902 exploration and four bones from the 2019 excavation were selected for radiocarbon dating with

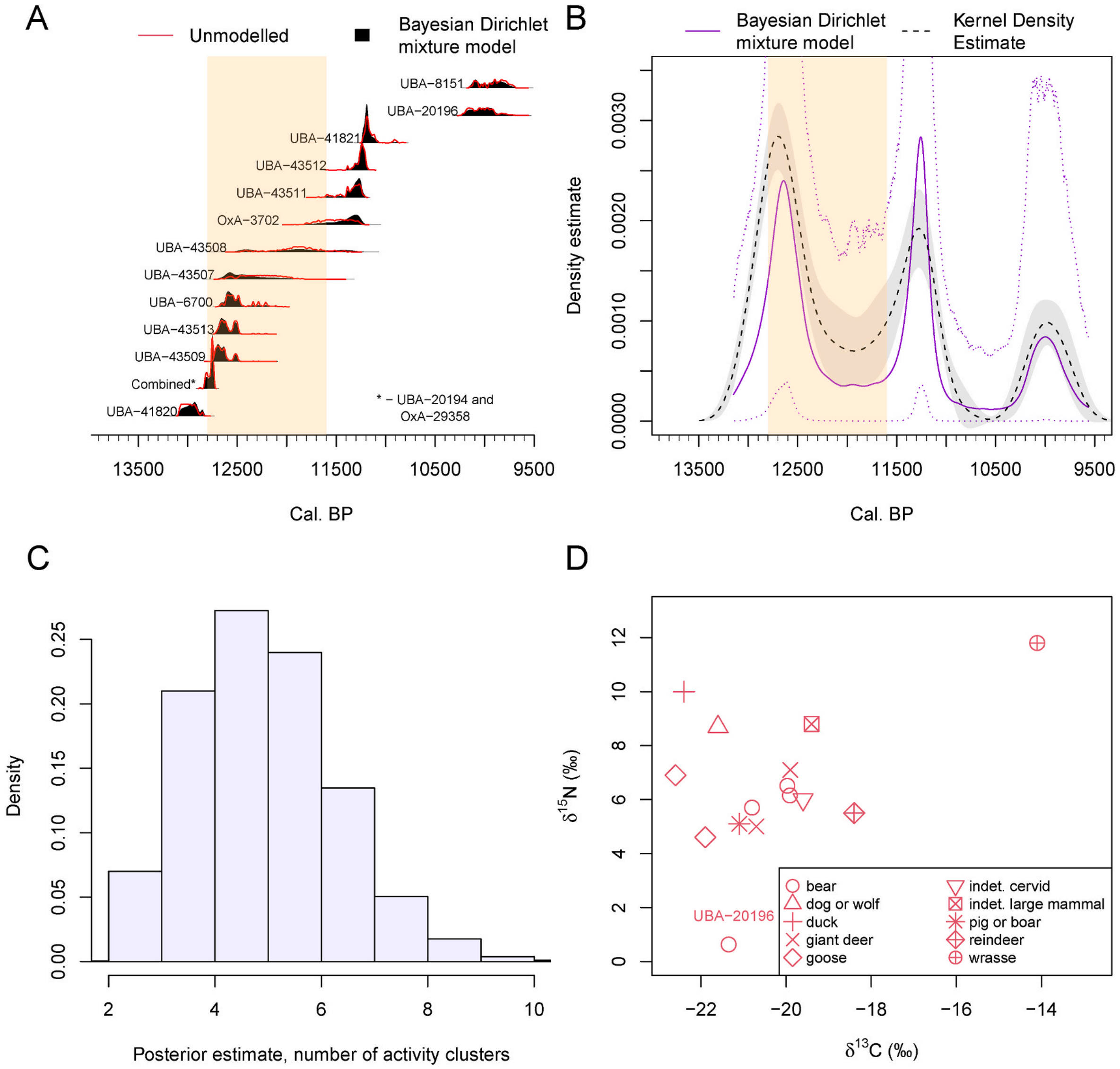

Fig. 4. A) calibrated and modelled Terminal Pleistocene and Early Holocene radiocarbon dates from Alice and Gwendoline Cave; B) temporal density estimates for these data; C) posterior probability number of clusters in the Direchet process mixture model; D) stable isotope results (Rowan McLaughlin).

permission of the NMI (Table 1). Samples were chosen based on a GIS of bone distribution vertically and horizontally across the cave (Dowd et al., 2021), with the objective of analysing samples from different locations as well as from various depths (Figs. 3 and 4). Bones of extinct species were targeted (brown bear, reindeer, giant deer). Bones of duck and goose were selected, though there was nothing to indicate whether these were wild or domesticated. Known domesticates (cattle, sheep) were not included, though they offer great potential for understanding the later Holocene history of the site. Radiocarbon dates were measured by the ^{14}Chrono Centre at Queen's University Belfast using AMS, with stable isotope measurements of bone collagen extracts taken on a separate line using IRMS and two replicates. The dates were calibrated using the IntCal20 calibration curve (Reimer et al., 2020) using *OxCal 4.4* (Bronk Ramsey, 2009) for chi-squared analysis, *MCdensity* for classical kernel density estimation (McLaughlin, 2019) and *WalkerBivarDirichlet* (Heaton, 2022) for Bayesian density estimation. Marine dates were calibrated using Marine20 (Heaton et al., 2020) with a deltaR of −208 ± 35 ^{14}C yrs (Cage et al., 2006).

4. Results

4.1. Formation processes, stratigraphy and pulses of sediment accumulation

The 2019 archaeological excavations have illuminated the natural formation processes that led to the accumulation of bone-bearing deposits in Alice and Gwendoline Cave. The lowest stratum encountered in Trench 1 was an orange-yellow coarse sand that had not been investigated in 1902 (Fig. 3). This stratum was truncated by an irregular natural channel created by water entering through the roof opening overhead. In the terminal Pleistocene and Early Holocene, bone-bearing sediments entered Alice Passage via this route. In support of this, several anomalies in the earth resistance survey can be attributed to drainage and sediment aggradation. The magnetic susceptibility and earth resistance responses towards the end of the passage reflect the extreme mixing of exogenous sediments. The earth resistance survey revealed alternating bands of low, moderate, high and low resistance data reflecting the mixture of sediments (clayey silts, silty clay, silt, sandy and gravelly clay, sandy clay). This was further corroborated by the sedimentary lipid signature which is characteristic of higher order terrestrial plants that could not have grown inside the cave environment and must have washed in from a vegetated landscape outside. The *n*-alkane distribution was characterised by a predominance of long-chain homologues (nC_{29} and nC_{31}) and an OEP derived from terrigenous higher order plants. The weathered condition of the Late Pleistocene long bone shaft fragment (UBA-41820) also indicates it may have originated from outside the cave.

Infilling of Alice Passage was likely gradual, though modelling of the temporal density of the dates suggests three ‘pulses’ of infilling of the cave, *circa* 12,700 cal. BP, 11,300 cal. BP and 10,000 cal. BP (Fig. 4). We conducted a Bayesian analysis (a Direchet process mixture model, see Heaton, 2022) of these data, using the posterior probability of the concentration hyperparameter to estimate the number of distinct ‘clusters’ of activity represented by the thirteen samples dating to this phase of the site’s history (Fig. 4C). The results suggest there were most likely between three and six clusters, lending weight to the idea that the infilling of the cave happened sporadically. There is no indication that human activities took place inside the cave during the terminal Pleistocene or Early Holocene. The majority of the faunal remains, including the humanly butchered bear patella, originated from the limestone plateau overhead.

4.2. Faunal remains: accumulation and dating

The majority of the faunal assemblage recovered in 2019 was of relatively recent date. In Trench 1, a firm mid-pinkish brown sandy clay (0.12 m thick) overlying the natural drainage channel produced a chewed right distal duck tibiotarsus (Anatidae, *Anas* sp.). Comingled deposits that had accumulated above this since 1902 produced a duck (*Anas* sp.) proximal left ulna and a left coracoid. The coracoid was dated to 2124–1942 cal. BP (Table 1), equivalent to the Irish Iron Age. Its size indicated a large duck, potentially domestic (*Anas platyrhynchos*). Pitting suggests it had been chewed and thus may have been introduced by a predator. The comingled strata in Trench 1 also produced bones of cat (*Felis* sp.), Bovidae (sheep or goat), canid (probably modern greyhound skeletons), cattle (*Bos taurus*), passerine birds (most likely blackbird or thrush – Turdidae, genus *Turdus*), larger birds (ducks or geese – Anatidae, one of which is gnawed), frog (*Rana temporania*) and a weathered long bone shaft fragment of an unidentified mammal that returned a Late Pleistocene date of 13,093–12,891 cal. BP. This is the earliest date from Alice and Gwendoline Cave and the only date that (marginally) pre-dates the Younger Dryas (Table 1). From a taphonomic perspective, the 31 mammal, amphibian and bird bones from Trench 1 reflect proximity to the roof opening. The larger taxa (sheep/goat, canids, cattle) derive primarily from ongoing disposal of carcasses from the local farm, while the small vertebrates likely reflect pellet deposition from owls roosting near the opening (e.g. Andrews, 1990) with elements washed in as the pellets degrade. The activities of small carnivores, such as cats, may also contribute. Frogs may have been present in the cave of their own volition. In Trench 2, the basal deposits exposed that had not been investigated in 1902 consisted of a series of sterile interdigitating compact silty clay lenses. A fragment of a brown bear (*Ursus arctos*) centrum from a sacral vertebra was recovered from overlying disturbed strata in this trench.

Table 2

Long chain *n*-alkane concentration (μg/g dry sediment), carbon preference index (CPI), average chain length (ACL), proportion of aquatic plants (P_{aq}), and long alkane ratio (LAR; $C_{29}/C_{29} + C_{31}$). * denotes samples where compound concentrations were below the limit of quantification.

Sample	Depth (cm)	Total alkane	ACL	CPI_{25-33}	P_{aq}	$LAR_{29/29+31}$
AG-19-BM1	0–2	1.08	28.7	6.5	0.19	44.8
AG-19-BM2	2–4	1.15	29.1	5.4	0.14	45.4
AG-19-BM3	4–6	*	*	*	*	*
AG-19-BM4	6–8	0.89	28.7	4.9	0.16	45.3
AG-19-BM5	8–10	0.15	28.5	5.2	0.14	47.3
AG-19-BM6	10–12	0.21	28.8	6.5	0.17	44.5
AG-19-BM7	12–14	0.12	28.3	6.1	0.16	42.6
AG-19-BM8a	14–16	*	*	*	*	*
AG-19-BM8b	16–18	*	*	*	*	*
AG-19-BM9	18–20	0.33	27.1	5.2	0.31	52.2
AG-19-BM10	20–22	*	*	*	*	*
AG-19-BM11	22–24	0.08	28.1	4.9	0.21	47.7
AG-19-BM12	24–26	0.08	27.5	3.1	0.27	51.3
AG-19-BM13	26–28	*	*	*	*	*
AG-19-BM14	28–30	*	*	*	*	*
Avg		0.46	28.3	5.3	0.2	46.8
Max		1.15	29.1	6.5	0.3	52.2
Min		0.08	27.1	3.06	0.1	42.6

4.3. Stable isotopes

Stable carbon and nitrogen isotopes indicate a mixture of dietary sources for the fauna found in the cave (Fig. 4D). Aside from the wrasse, all samples indicated a terrestrial diet, with cervids and bears sharing similarly distributed and largely herbivorous signals with $\delta^{13}C$ around −20‰ and $\delta^{15}N$ 6‰. One Early Holocene bear metatarsal (UBA-20196, 8919 ± 64, 10,227–9886 cal. BP) returned a notably unenriched $\delta^{15}N$ value of 0.63‰. The bird bones from the cave returned variable results, presumably reflecting a wide array of food sources that may have also varied by season. The much later canid had a $\delta^{15}N$ value of 8.7‰, indicating a carnivorous diet.

4.4. Sedimentary biomarkers

Cave settings have been shown to provide chemically stable environments, well-suited to the preservation in sediments of diagnostic molecular compounds, or lipid biomarkers, from higher plants (McAllister-Hayward et al., 2024; Rabett et al., 2017). Long-chain *n*-alkanes are saturated aliphatic hydrocarbons which are synthesised as part of the epicuticular leaf waxes of vascular plants, forming a defense mechanism against UV light, water stress and microbial attack (Eglinton et al., 1962; Eglinton and Hamilton, 1967). These compounds preserve well over geological timescales and are well documented in both Pleistocene and Holocene deposits. Ambient environmental and climatic conditions are important controls on *n*-alkane chain length distributions. Fluctuations in *n*-alkane chain lengths through a sedimentary sequence is therefore being increasingly deployed to provide a record of past environmental conditions (e.g. Carr et al., 2014; Jambrina-Enríquez et al., 2016; Magill et al., 2013).

Building upon established analytical protocols, a novel application of lipid biomarkers was applied to assess the origins of sediments in Alice and Gwendoline Cave. Although cave sediments can contain significant microbial activity, contributing short chain *n*-alkanes with an even/odd predominance (EOP), it is improbable that endogenous cave sediments would yield *n*-alkanes characteristic of higher order plants. Higher plant-derived *n*-alkanes are dominated by long chains and exhibit a strong odd-even predominance (OEP). Exogenous sediments, presumably transported into cave systems via hydrological or colluvial processes, are likely to contain enhanced concentrations of long-chain homologues with a strong odd number predominance, indicative of their terrestrial higher plant origin. To test this hypothesis, the concentration and distribution of sedimentary *n*-alkanes at Alice and Gwendoline Cave were determined. These measurements aim to serve as proxies for distinguishing between endogenous and exogenous sediments within the cave environment. A comparative analysis of lipid concentrations and chain-length distributions was conducted across all collected samples.

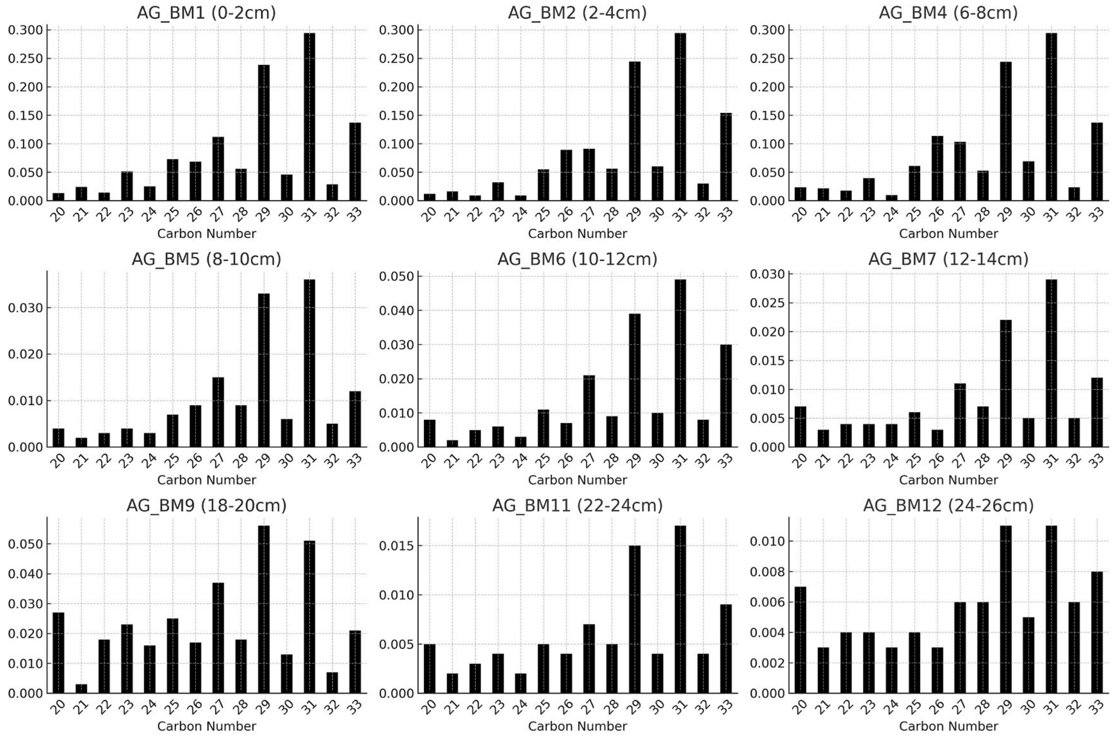

Fig. 5. The distribution of sedimentary leaf wax derived *n*-alkanes at Alice and Gwendoline Cave. Note the shift in dominant alkane from nC_{31} to nC_{29} in samples from 18 to 20 cm and 24–26 cm. IS: 5a-androstane. X-axis: carbon chain length. Y-axis: concentration in μg per g of dry sediment (μg/g), concentration values have been adjusted to better illustrate distribution patterns (Rory Connolly).

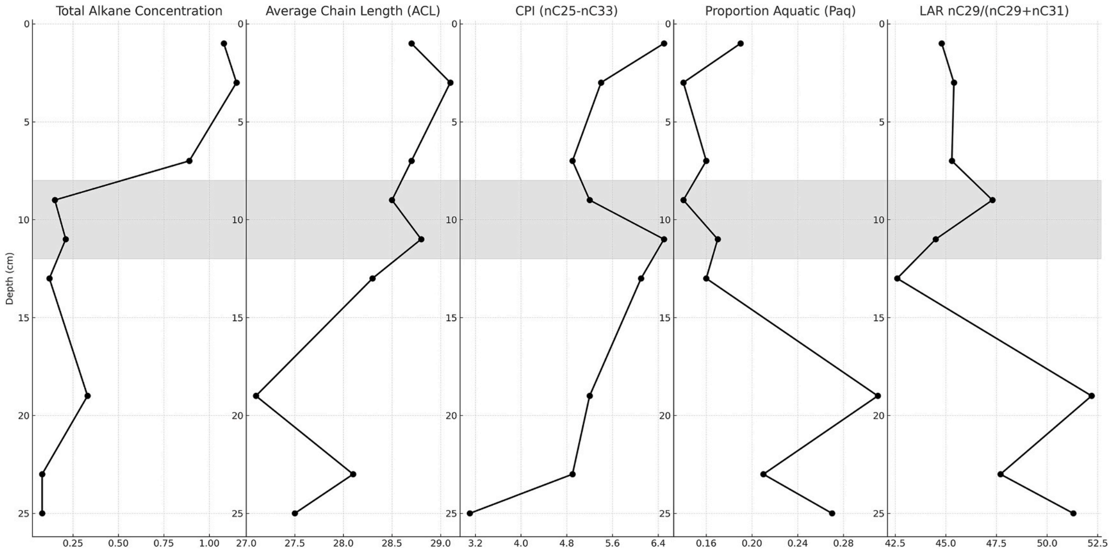

Fig. 6. *N*-alkane molecular ratios through the 30 cm sequence collected from Trench 1 (Grid 6b/7a). Left to right: Total *n*-alkane concentration, Carbon Preference Index (CPI), Long Alkane Ratio (LAR) $nC_{29}/nC_{29}+nC_{31}$. Grey bar indicates a transition zone potentially due to environmental shifts, soil composition alterations, or other ecological factors (Rory Connolly).

This approach leverages the chemical stability and environmental specificity of lipid biomarkers to propose an alternative methodological avenue for understanding sediment provenance.

The distribution of leaf wax derived *n*-alkanes and their associated molecular ratios are outlined below (Table 2; Figs. 5 and 6). All samples display a similar distribution pattern dominated by long chain (C_{29}–C_{31}) compounds and an OEP characteristic of terrigenous higher order plant input. This is corroborated by P_{aq} values consistently <0.4, showing no significant contribution from aquatic plant sources or bryophytes. It is worth noting that some samples, particularly AG-19-BM12, seem to exhibit higher bacterial input as represented by lower carbon numbers and a higher relative contribution of even chain homologues. It was possible to identify *n*-alkanes in their individual chromatograms for all samples but in some (AG-19-BM3, BM8a/b, BM10, BM13, BM14), concentrations remained below the limit of quantification. The 30 cm sequence has an average total *n*-alkane concentration of 0.46 μg/g of dry sediment which ranges from 0.08 to 1.15 μg/g. CPI shows generally good preservation of organic matter (values > 3), with values that range from a minimum of 3.1 to a maximum of 6.5 indicating that lipids have not been significantly altered by microbial degradation. ACL values range from 27.1 to 29.1, while LAR values ($C_{29}/(C_{29} + C_{31})$ range between 42.6 and 52.2 with high values (>50) in BM9 and BM12 reflecting a shift to nC_{29} as the dominant homologue, which contrasts with the rest of the sequence where nC_{31} is the most abundant homologue (Table 2; Figs. 5 and 6).

4.5. *Geophysical surveying underground*

The geophysical surveys highlighted the potential of these techniques for identifying palaeohearths in Irish cave contexts. The strongest volume specific magnetic susceptibility values were encountered over an area of burning in Trench 2. The MS2F probe (<1 cm DoI) determined that the surficial deposit had a very strong magnetic susceptibility consistent with burning, as did the MS2D probe (15 cm DoI), which also identified a wider 3–4 m zone of enhancement surrounding the burnt deposit, suggesting a wider sphere of magnetic influence from deeper deposits rather than surficial ones. Magnetometry mapped a moderate trend of ±8 nT responses over the same area of burning, consistent with Gibson's (1986) experiments on fire pits which revealed weak magnetic anomalies associated with short-term (single use) campfires. The subsequent archaeological excavation revealed two compact areas of burning (0.50 m × 0.50 m x 0.01 m thick and 0.41 m × 0.28 m x 0.03 m thick) in Trench 2. Radiocarbon dating confirmed what was suspected: these were modern areas of localized burning dating to sometime after the 1902 antiquarian excavation.

The geophysical survey also demonstrated that surficial burning can be mapped by strong magnetic susceptibility contrasts with a 1 cm and 15 cm depth of investigation, and that the size of the resulting anomaly is much larger than the excavated burnt deposit. Other burnt deposits in the cave located <15 cm beneath the surface can be expected to create moderate to strong magnetic susceptibility contrasts. Magnetometer anomalies for sustained fires can also be expected at depths of up to 0.5 m beneath the surface. The absence of these responses suggests that there are no palaeohearths within Alice Passage. A discrete increase in the magnetometer data at the end of the passage could be suggestive of burning, however, potentially on the limestone cave floor beneath the exogenous sediment.

4.6. *Re-visiting antiquarian excavations*

The 2019 project confirmed the lack of stratigraphic integrity noted by the 1902 team. The recent excavation involved removing disturbed strata that related to the 1902 investigation, as well as deposits that had accumulated in the intervening century, to expose intact strata that had not been investigated in 1902. These seemingly intact layers had also been disturbed in antiquity, however. For instance, trapped between a slab and the cave wall at the side of Trench 2, two strata were identified in an upstanding column of sediment (0.65 m high x 0.30 m wide) that had escaped the attention of the 1902 team. The deepest stratum, a yellowish-brown silty clay consolidated into a soft breccia with calcite, produced five small bone fragments, including a goose (*Anser* sp.) sternum dated to 11,239–10,887 cal. BP, equivalent to the Early Mesolithic. Much more recent frog and rodent bones were retrieved from this same stratum, which was sealed by a sterile, yellowish-white solidified calcite-rich deposit.

Archaeological excavations revealed the thoroughness of the 1902 antiquarian investigation, the comprehensive removal of deposits, and the paucity of surviving material. Just 47 bone fragments were retrieved in 2019, all of which were fragmentary and less than 50 mm in length. The comprehensive removal of the sedimentary content of Alice and Gwendoline Cave suggests similar results might be expected from other caves excavated under the direction of Richard J. Ussher, such as the adjacent Catacombs Cave, Bats' Cave, Elderbush Cave and Barntick Cave (Scharff et al., 1906), as well as Coffey Cave and Plunkett Cave on Keshcorran Mountain, Co. Sligo (Scharff et al., 1903). The 2022 excavations at Castlepook (Mammoth) Cave, Co. Cork were similarly unrewarding in terms of the sparse Pleistocene fauna recovered (E-article); this cave was first excavated by Richard J. Ussher in 1904 (Scharff et al., 1918). Not all caves that were subject to antiquarian excavations were necessarily so thoroughly emptied, but in cases such as Alice and Gwendoline Cave, the paucity of surviving stratification is unfortunate.

5. Discussion

5.1. *Post-glacial vegetation*

The analysis of lipid biomarkers in the sediment samples from Alice and Gwendoline Cave revealed a consistent distribution pattern dominated by long-chain *n*-alkanes (C_{29}–C_{31}), indicative of a substantial terrestrial plant input. This pattern is corroborated by OEP values characteristic of terrigenous higher plants (Eglinton and Hamilton, 1967). Although microbial contribution of short- and mid-even chain homologues may be reflected in some samples, particularly AG-19-BM12, the degree of alteration is not considered significant. CPI consistently yielded values greater than 3.1, peaking at 6.5, indicating good preservation of the organic matter and minimal alteration by microbial activity (Bray and Evans, 1961; Herrera-Herrera et al., 2020). These plant biomarkers reflect an origin external to the cave environment, likely transported into the cave through natural openings (Dowd et al., 2021). P_{aq} values consistently remained below 0.4 across all samples, suggesting a negligible contribution from aquatic plants or bryophytes and affirming the terrestrial origin of the organic material within the sediments.

Fluctuations in ACL between 27.1 and 29.1 and LAR between 42.6 and 52.2 likely reflect shifts in vegetation dynamics in the area around Alice and Gwendoline Cave. High LAR values (>50) in some samples indicate a change to nC_{29} as the dominant homologue, contrasting with the rest of the sequence where nC_{31} was more abundant. This could point to changes in the predominant vegetation types contributing to the sediment, or alternatively suggest adjustments in plant wax production in response to environmental changes or stresses (Freeman and Pancost, 2013). A possible transition in the sequence is also highlighted by the grey bar (8–12 cm) in Fig. 6, with samples collected above this interval yielding notably higher overall concentration and ACL values. Again, this suggests a change in the depositional environment or local ecological conditions or may relate to other environmental factors that affect the types and quantities of organic matter being deposited. While these shifts might plausibly relate to significant warming or cooling events like Greenland Interstadial 1 or the Younger Dryas, or indeed the transition to the Early Holocene, the coarse resolution of the radiocarbon dating framework for the sequence complicates efforts to correlate these shifts with broader palaeoclimate datasets for the region. Nevertheless, this study represents the first instance of sedimentary lipids being recovered from an archaeological cave context in Ireland. The preservation observed underscores the potential of this approach to provide contextually resolved paleoclimate data in other Irish cave contexts where the chronological framework is more precisely defined. In Ireland, sedimentary lipid biomarkers from non-cave sites have provided insights into past vegetation and climatic conditions. For instance, Jordan et al. (2017) analysed lipid biomarkers from a coastal peat bog in Spiddal, Co. Galway to reconstruct mid-Holocene palaeoclimate conditions. Their results showed significant climatic variations over a *c.* 3400-year period. The *n*-alkane distribution through the sedimentary sequence indicated shifts between cold/wet and warm/dry conditions, correlating with known climatic events such as the 4.2 ka event and the Subboreal-Subatlantic transition. While not chronologically or ecologically analogous, those findings can offer a comparative backdrop for interpreting our data from Alice and Gwendoline Cave, suggesting that similar environmental shifts might have influenced the sedimentary input into the cave.

Variations in the peak concentrations of total *n*-alkanes between 0.08

and 1.15 μg/g through the sequence may suggest episodic deposition or fluctuating intensities of terrestrial input over time. This observation aligns with the dating model that indicates distinct pulses of cave infilling, possibly related to episodic events linked to periods of increased terrestrial runoff or colluvial movements. As such, the sedimentary lipid data provide additional insights for interpretation of the archaeological materials, which in all likelihood were transported into the cave alongside the sediments. This redeposition process is crucial for understanding both the environmental context and human activity within the cave system. A recent study by McAllister-Hayward et al. (2024) at Tam Pà Ling cave in northeast Laos utilised higher plant biomarkers, including *n*-alkanes, to reconstruct past environmental conditions. The authors concluded that the lipid profile reflected the input of exogenous sediments with an *n*-alkane signature reflecting local vegetation from around the cave mouth, transported into the cave through aeolian processes and slopewash events.

This is first time that sedimentary lipids have been recovered in an Irish cave context. The good state of preservation suggests that it could be possible to retrieve contextually resolved palaeoclimate data from similar sites (if the sequence was tightly dated). This is also the first case where sedimentary lipids have been used in an Irish archaeological context to provenance sediments – so the approach is novel. Phytolith analysis was conducted but the samples were sterile. Compound-specific hydrogen isotope data was obtained for a part of the sequence but, without being able to contextualise the samples chronologically, it is difficult to draw meaningful conclusions. The samples also appear almost entirely sterile in the micromorph data (SI).

5.2. *Greenland Interstadial 1 (14,600–12,800 cal. BP) and Younger Dryas (12,800–11,600 cal. BP)*

Though few animal bones were recovered in 2019 due to the comprehensive nature of the 1902 investigation which removed most of the deposits, the radiocarbon date range from both excavations is consistent. Of the new suite of thirteen dates, the unidentified large mammal bone (UBA-41820) related to Greenland Interstadial 1. This sample has a stable nitrogen isotope signature consistent with a mostly terrestrial omnivorous or carnivorous diet (δ^{15}N 8.8‰), although it may also represent a different isotopic baseline given its earlier date in Greenland Interstadial 1. Changing isotope baselines for the period have been modelled for Europe at large scales (Reade et al., 2023), but little is known in detail about the situation in Ireland and the topic warrants further research. Four samples returned dates from the Younger Dryas. A chi-squared test, to assess if these samples derived from the same source of ^{14}C and hence the same individual, suggests the four dates almost certainly represent at least four different animals: two giant deer (*Megaloceros giganteus*), a reindeer (*Rangifer tarandus*) and an unidentified Cervid – probably also reindeer (Table 1; df = 3 T = 16.0, threshold T < 7.8). Differences in stable isotope results between the samples also supports this view; the reindeer has a distinctive stable isotope profile (δ^{13}C −18.4‰, δ^{15}N 5.5‰) which is significantly different to the unidentified Cervid (δ^{13}C −19.6‰, δ^{15}N 6.0‰), likely reflecting different protein sources or metabolic differences between two distinct animals. Similarly, the nitrogen-15 isotope values for the two giant deer differ by more than 2‰ (Table 1). A chi-squared test on the previously obtained two Younger Dryas brown bear dates (UBA-20194 and UBA-6700) similarly indicates that the samples almost certainly derive from different individuals (df = 2, T = 51.0, threshold T < 6.0). Stable isotope results suggest overlapping diets between cervids and bears from the site, both of which are predominantly herbaceous in composition (Fig. 4D). The Cervid samples average −19.65 ± 0.95‰ for δ^{13}C (mean ± standard deviation) and 5.9 ± 0.9‰ for δ^{15}N. The bear samples average −20.5 ± 0.7‰ for δ^{13}C and 4.7 ± 2.7‰ for δ^{15}N.

Giant deer (*Megaloceros giganteus*) bones from nine locations in Ireland have returned reliable dates within Greenland Interstadial 1 (14,600–12,800 cal. BP). The earliest date is 11,839 ± 44 BP (13,758–13,560 cal. BP) on a giant deer femur from Liskelly Stream, Co. Cork; until now, the latest date has been 10,985 ± 45 BP (12,986–12,728 cal. BP) on a giant deer skull from Milewater Dock, Belfast (Lister and Stuart, 2019, S1). Existing data point to the extirpation of giant deer from Ireland shortly after the onset of the Younger Dryas, but the species persisted into the early part of the stadial in Britain and Southern Scandinavia (Hughes et al., 2006, 290; Lister and Stuart, 2019). The new giant deer dates from Alice and Gwendoline Cave (10,571 ± 54 BP, 12,709–12,481 cal. BP; 10,204 ± 91 BP, 12,460–11,403 cal. BP) are the youngest (provenanced) dates for the persistence of this species in Ireland into the Younger Dryas (contra Woodman, 2015, 22, 179; Monaghan, 2017; Warren, 2022, 38).

Woodman et al. (1997, including the work of Stuart and van Wijingaarden-Bakker, 1985) identified four Irish sites with reindeer (*Rangifer tarandus*) bones dating to Greenland Interstadial 1. Recent re-dating with improved radiocarbon dating techniques (ultra-filtration processing) has revealed that in at least one of these cases, Castlepook Cave, Co. Cork, the reindeer antler was more than 7500 years older than the date returned in the 1990s (Carden et al., 2020, 678). Consequently, the radiocarbon dates for the reindeer bones from the Catacombs Cave, Co. Clare and Kilgreany Cave, Co. Waterford (Woodman et al., 1997) must now also be considered unreliable (the Roddan's Port, Co. Down reindeer antler was dated by association only). The Alice and Gwendoline reindeer metapodials (10,394 ± 96 BP, 12,620–11,885 cal. BP and 10,646 ± 72 BP, 12,745–12,487 cal. BP) thus provide the only definitive direct dated post-glacial evidence of this species in Ireland; both dates fall within the Younger Dryas.

There appears to have been a continuous presence of brown bear in Ireland from Greenland Interstadial 1, through the Younger Dryas and into the Holocene (Woodman et al., 1997; Woodman, 2015, 28; Monaghan, 2023). The dates from Alice and Gwendoline Cave reflect the persistence of the species, with samples from both the Younger Dryas and Early Holocene. Our stable isotope results suggest the bears had a herbivorous diet, similar to findings elsewhere in Europe (García-Vázquez et al., 2018). Ancient DNA analysis indicates that the Younger Dryas bear calcaneum (UBA-6700) from the cave is of the 'Clade II' genetic group, a clade that appear to have died out during the Early Holocene (Edwards et al., 2011).

On a European scale, the data from Alice and Gwendoline Cave indicate the persistence of reindeer, bear and giant deer during the early centuries of the Younger Dryas, seemingly until at least 12,500 cal BP, if not beyond. The severe conditions of the Younger Dryas lasted for over a millennium. Mean temperatures may have been as low as −5° to −2 °C, though in summer may have reached 4–5 °C, and occasionally 10 °C (Woodman, 2015, 20; Pettitt and White, 2012, 490). Rich grasslands were replaced by tundra and alpine plants, with extensive permafrost. This project has unequivocally confirmed the presence of giant deer, reindeer and brown bear in Ireland contemporaneous with the butchered bear patella which comprises the first evidence of a human presence in Ireland during the terminal Pleistocene (Dowd and Carden, 2016). Some are hesitant to accept the patella as an indicator of human presence (Warren, 2022). Others reject the evidence entirely, arguing that the island was not ecologically viable for human colonisation due to the harsh climatic conditions (Tune, 2020). However, the presence of cold-adapted species indicates that, during warmer months at least, conditions during the earlier part of the stadial would also have supported a human population. Comparable conditions have not proved an obstacle to the Sámi reindeer hunters of northern Fenno-Scandinavia, for example. Douw et al. (2022, 7) propose that the presence of giant deer during colder periods of the Late Pleistocene may reflect 'enhanced seasonal mobility behaviour' – a model that may also have been relevant to hunter-gatherer groups. In Britain, human settlement during the Younger Dryas is rare and confined to the south and east of the country. It possibly comprised 'infinitely small numbers of humans in the country' for little more than a few months at the Pleistocene-Holocene transition (Pettitt and White, 2012, 497). Ireland may similarly have witnessed small-scale incursions of reindeer hunters (Woodman, 2015, 179).

5.3. Early Holocene (11,600–6000 cal. BP)

Since its discovery and excavation in the 1970s, the hunter gatherer campsite at Mount Sandel, Co. Derry has represented the earliest evidence of the post-glacial human colonisation of Ireland (Woodman, 1985). Initially dating to *c*. 9000 cal. BP, reassessment of the dates has pushed back estimates of its start date to around 9800–9600 cal. BP (Bayliss and Woodman, 2009). A long-standing issue has been the absence of human activity on the island between 11,600–10,000 cal. BP (Woodman, 2015). Two pieces of evidence now indicate human activities slightly earlier than the generally cited start of the Irish Mesolithic: a humanly butchered brown bear vertebra dated to 9414 ± 57 BP (11, 060–10,440 cal. BP) from the Catacombs Cave (Dowd and Carden, 2016; Dowd, 2016) and, potentially, the human clavicle from Alice and Gwendoline Cave (8828 ± 34 BP, 10,146–9700 cal. BP). These are more convincing than the problematic radiocarbon dates on wood and charcoal from several sites across the country that pre-date the 10,000 cal. BP 'start' date for Holocene colonisation of the island (Woodman, 2015, 185–6).

The Early Holocene date on the human clavicle from Alice and Gwendoline Cave represents the earliest direct dated human bone in Ireland. The clavicle was dated in 2007 but the result was not published until recently (Dowd et al., 2021) because of the very early date and the 'unusual' δ^{13}C results. The δ^{13}C had been measured by AMS as not enough collagen survived to measure by IRMS; it has since become apparent that AMS δ^{13}C values are not valid for anything other than the fractionation correction on the radiocarbon age. The clavicle significantly pre-dates the cremated human bones dated to 8350 ± 40 BP (9500–9160 cal. BP) from a burial pit at Hermitage (Castleconnell), Co. Limerick (Collins and Coyne, 2003, 2006; Little et al., 2017), and an unburnt disarticulated human bone from Killuragh Cave, Co. Limerick, dated to 8030 ± 60 BP (8080–8650 cal. BP) (Woodman et al., 2018). At least ten other human bones were discovered in the westernmost passage of Alice and Gwendoline Cave during the 1902 excavations, but all have since been lost (Dowd et al., 2021). The assemblage comprised small skeletal elements, potentially representing Neolithic or Bronze Age excarnation practices within that passage (Dowd, 2008) – almost certainly unrelated to the clavicle, which likely entered the easternmost passage via the roof opening. Though just a single bone, its significance lies in its very early date and the paucity of sites in Ireland that have produced human bone of Mesolithic date; currently less than ten sites are known (Meiklejohn and Woodman, 2012; Woodman, 2015).

Alice and Gwendoline Cave presents the first direct dated goose (*Anser* sp.) bones from the Irish Early Holocene (9836 ± 51 BP, 11,393–11,180 cal. BP and 9728 ± 40 BP, 11,240–10,887 cal. BP). It should be noted that these dates assume no carbon reservoir effects. The carbon-13 isotope values (δ^{13}C −22.6‰ and −21.9‰ respectively) indicate a marine protein source is unlikely, but because goose diet can be very biased towards wetland grazing, it is possible these dates are anomalously old due to a freshwater effect. The samples may derive from the same individual as the calibrated ranges overlap, but the nitrogen isotopes (δ^{15}N 6.9‰ and 4.6‰ respectively) suggest two distinct individuals. The samples had a typically wide range of nitrogen-15 values indicating varied diets (Fig. 4D). Wild fowl were valuable resources for Early Holocene hunter-gatherer communities, not only for meat and eggs, but also for feathers and bones. Avifauna remains from Mesolithic sites are sparse, with no records of goose from any Irish Mesolithic assemblages (Woodman, 2015, 270–1). At the time of the antiquarian investigation, three bones from Alice and Gwendoline Cave were identified by E.T. Newton as possibly white-front goose (Scharff et al., 1906, 57). An ulna of a white-fronted or bean goose was recovered from the Early Mesolithic settlement at Star Carr. The bone had been humanly modified, with both ends snapped or struck off (Knight et al., 2018, 217).

Two brown bear (*Ursus arctos*) bones (a juvenile and an adult) from Alice and Gwendoline Cave also date to the Early Holocene. The cave may have been periodically used by bears; the juvenile zygomatic maybe be indicative of hibernation death. By 9700 cal. BP, however, the cave seems to have become completely choked rendering it largely inaccessible to humans and large mammals.

5.4. Late Holocene

Late Holocene dates, equivalent to the Irish Iron Age, were returned for wrasse (*Labrus* sp.), duck (*Anas platyrhynchos*) and pig/wild boar (*Sus* sp.) (Table 1). While it was not possible to secure permission from the National Museum of Ireland for a direct date, it is worthy of note that the wrasse specimen, dated to 2130–1833 cal. BP, was recovered in the same grid square and excavation unit as a fragment of a pine marten (*Martes*) mandible. Considering the Alice and Gwendoline Cave is located 6 km from the sea, the wrasse likely represents Late Holocene human activities in or near the cave. It is not possible to determine whether the duck and pig/wild boar bones are of anthropogenic or natural origin. An early medieval date was returned for a dog or wolf (*Canis* sp.) calcaneus.

6. Conclusion

In the 25+ years since the publication of the *Irish Quaternary Fauna Project*'s (IQFP) groundbreaking radiocarbon dating of Ireland's Quaternary fauna, new Pleistocene radiocarbon dates have been few. Additional dates have been reported for giant deer bones from Ballyoran Bog, Co. Cork, Liskelly Stream, Co. Cork and Ballynamintra Cave, Co. Waterford (Lister and Stuart, 2019), as well as for brown bear bones from Castlepook Cave, Co. Cork, Shandon Cave, Co. Waterford and Plunkett Cave (Keshcorran), Co. Sligo (Edwards et al., 2011). Recent reassessment of some of the IQFP data has clarified, however, that radiocarbon dates obtained prior to ultrafiltration – essentially all the Pleistocene dates obtained in the 1990s – are now obsolete (Carden et al., 2020). The new suite of dates from Alice and Gwendoline Cave therefore forms a significant contribution to what is a sparse record. The vast collections of Irish Pleistocene fauna from antiquarian investigations (of caves in particular) offer enormous research potential but remain largely uncatalogued, unpublished and often inaccessible.

Alice and Gwendoline Cave is now one of the most rigorously radiocarbon dated Late Pleistocene sites in Ireland. A significant group of radiocarbon dates fall firmly within the Younger Dryas, with a second group clustering at the beginning of the Early Holocene. Only one date, on an unidentified large mammal long bone fragment, may relate to Greenland Interstadial 1. The site has also yielded the earliest proxy evidence for human presence on the island in the terminal Pleistocene, and the earliest directly dated evidence in the Early Holocene. Our study highlights the utility of sedimentary lipid biomarker analysis for assessing sediment provenance in cave environments and reconstructing past environmental conditions. Although the current dating limitations at Alice and Gwendoline Cave prevent direct correlation of lipid data with established climatic phases, the good state of preservation indicated by the CPI values suggests that biogeochemical signatures preserved in archaeological cave sediments in Ireland could be a significant, yet underutilised, source of paleoenvironmental data to complement other proxy records. Overall, this project has demonstrated the utility of on-site investigations combined with taphonomic reconstruction, examination of excavation archives, and novel dating programmes to realise the full potential of archived antiquarian bone assemblages.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by the Royal Irish Academy (RIA) and Atlantic Technological University (ATU). Our thanks to the landowner, George Gallery, for providing every assistance to the project. We are grateful to Sam Moore, Kevin Costello, Leonardo Maciel, Aileen Treacy and Tony Boycott† who worked on the excavation. We acknowledge the support and assistance of the Speleological Union of Ireland (SUI) and the Irish Cave Rescue Organisation (ICRO), with particular thanks to Terry Casserly, Adam de Eyto, Brian Cotter and Stanislaw Drapala. Radiocarbon dating was conducted by the ^{14}Chrono Centre at Queen's University Belfast. The 1902 bones were dated subject to permission from the National Museum of Ireland; the cooperation of Nigel Monaghan (Natural History Division) and Sharon Weadick (Irish Antiquities Division) in that regard is gratefully acknowledged. Nigel Monaghan provided perceptive and useful feedback on this paper. We are grateful to Carolina Mallol and the Archaeological Micromorphology and Biomarker Laboratory (AMBI), Universidad de La Laguna for facilitating the sedimentary analyses.

The archaeological excavation was carried out under NMS Licence 19E381, held by M. Dowd; the 2019 bones were dated under NMI Licences 6856 and 6878; the 1902 bones were dated under NMI Licence 6936; samples were exported for analyses under NMI Licences 6832, 6833 and 6834. Geophysical survey of the site was carried out by J. Bonsall under NMS Consent no. 19R0089.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2024.108827.

References

Adams, A.L., Kinahan, G.H., Ussher, R.J., 1881. Explorations in the bone cave of Ballynamintra, near Cappagh, County Waterford. Sci. Trans. R. Dublin Soc. 1, 177–226.

Anastassiades, M., Lehotay, S.J., Tajnbaher, D., Schenck, F.J., 2003. Fast and easy multiresidue method employing acetonitrile extraction/partitioning and dispersive solid-phase extraction for the determination of pesticide residues in produce. J. AOAC Int. 86, 412–431.

Andrews, P., 1990. Owls, Caves and Fossils. University of Chicago Press, Chicago.

Bayliss, A., Woodman, P., 2009. A new Bayesian chronology for Mesolithic occupation at Mount Sandel, Northern Ireland. Proc. Prehist. Soc. 75, 101–123.

Bray, E.E., Evans, E.D., 1961. Distribution of n-paraffins as a clue to recognition of source beds. Geochem. Cosmochim. Acta 22, 2–15.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51, 337–360.

Cage, A.G., Heinemeier, J., Austin, W.E.N., 2006. Marine radiocarbon reservoir ages in Scottish coastal and fjordic waters. Radiocarbon 48, 31–43.

Carden, R.F., Higham, T.F.G., Woodman, P.C., 2020. A reconsideration of the radiocarbon dating of the Marine Isotope Stage 3 fauna from southern Ireland. Boreas 49, 674–684.

Carden, R.F., McDevitt, A.D., Zachos, F.E., Woodman, P.C., O'Toole, P., Rose, H., Monaghan, N.T., Campana, M.G., Bradley, D.G., Edwards, C.J., 2012. Phylogeographic, ancient DNA, fossil and morphometric analyses reveal ancient and modern introductions of a large mammal: the complex case of red deer (*Cervus elaphus*) in Ireland. Quat. Sci. Rev. 42, 74–84.

Carr, A.S., Boom, A., Grimes, H.L., Chase, B.M., Meadows, M.E., Harris, A., 2014. Leaf wax n-alkane distributions in arid zone South African flora: environmental controls, chemotaxonomy and palaeoecological implications. Org. Geochem. 67, 72–84.

Clark, J., McCabe, A.M., Bowen, D.Q., Clark, P.U., 2012. Response of the Irish ice sheet to abrupt climate change during the last deglaciation. Quat. Sci. Rev. 35, 100–115. https://doi.org/10.1016/j.quascirev.2012.01.001.

Collins, T., Coyne, F., 2003. Fire and water… Early Mesolithic cremations at Castleconnell, Co. Limerick. Archaeol. Ireland 17 (2), 24–27.

Collins, T., Coyne, F., 2006. As old as we felt. Archaeol. Ireland 20 (4), 21.

Douw, D.S., Giltaij, T.J., Kootker, L.M., Reumer, J.W.F., Monaghan, N.T., Schulp, A.S., 2022. Investigating seasonal mobility in Irish giant deer *Megaloceros giganteus* (Blumenbach, 1799) through strontium isotope (^{87}Sr/^{86}Sr) analysis. J. Quat. Sci. 37 (8), 1–11.

Dowd, M.A., 2008. The use of caves for funerary and ritual practises in Neolithic Ireland. Antiquity 82, 305–317.

Dowd, M., 2016. A remarkable cave discovery: first evidence for a late Upper Palaeolithic human presence in Ireland. Archaeol. Ireland 30 (2), 21–25.

Dowd, M., Bonsall, J., Kahlert, T., Connolly, R., Stimpson, C., 2021. In: Revisiting Alice and Gwendoline Cave, Co. Clare: new insights on the 1902 excavations. Proc. Roy. Irish Acad. 121C, pp. 1–53.

Dowd, M., Carden, R.F., 2016. First evidence of a late Upper Palaeolithic human presence in Ireland. Quat. Sci. Rev. 139, 158–163.

Edwards, C.J., Suchard, M.A., Lemey, P., Welch, J.J., Barnes, I., Fulton, T.L., Barnett, R., O'Connell, T.C., Coxon, P., Monaghan, N., Valdiosera, C.E., 2011. Ancient hybridization and an Irish origin for the modern polar bear matriline. Curr. Biol. 21, 1251–1258.

Edwards, R., Craven, K., 2017. Relative sea-level change around the Irish coast. In: Coxon, P., McCarron, S., Mitchell, F. (Eds.), Advances in Irish Quaternary Studies. Atlantis Press, Paris, pp. 181–215.

Eglinton, G., Hamilton, R.J., Raphael, R.A., Gonzalez, A.G., 1962. Hydrocarbon constituents of the wax coatings of plant leaves: a taxonomic survey. Nature 193, 739–742.

Eglinton, G., Hamilton, R.J., 1967. Leaf epicuticular waxes. Science 156, 1322–1335.

Fibiger, L., 2016. Osteoarchaeological analysis of human skeletal remains from 23 Irish caves. In: Dowd, M. (Ed.), Underground Archaeology: Studies on Human Bones and Artefacts from Ireland's Caves. Oxbow Books, Oxford, pp. 3–37.

Ficken, K.J., Li, B., Swain, D.L., Eglinton, G., 2000. An n-alkane proxy for the sedimentary input of submerged/floating freshwater aquatic macrophytes. Org. Geochem. 31, 745–749.

Freeman, K.H., Pancost, R.D., 2013. Biomarkers for terrestrial plants and climate. In: Holland, H.D., Turekian, K.K. (Eds.), Treatise on Geochemistry, second ed. Elsevier Inc., pp. 395–416

García-Vázquez, A., Pinto-Llona, A.C., Grandal-d'Anglade, A., 2018. Brown bear (*Ursus arctos* L.) palaeoecology and diet in the Late Pleistocene and Holocene of the NW of the Iberian Peninsula: a study on stable isotopes. Quat. Int. 481, 42–51.

Gibson, T.H., 1986. Magnetic prospection on prehistoric sites in Western Canada. Geophysics 51, 553–560.

Heaton, T.J., Köhler, P., Butzin, M., Bard, E., Reimer, R.W., Austin, W.E.N., Ramsey, C.B., Grootes, P.M., Hughen, K.A., Kromer, B., Reimer, P.J., Adkins, J.F., Burke, A., Cook, M.S., Olsen, J., Skinner, L.C., 2020. Marine20 – the marine radiocarbon age calibration curve (0-55,000 cal BP). Radiocarbon 62 (4), 779–820.

Heaton, T.J., 2022. Non-parametric calibration of multiple related radiocarbon determinations and their calendar age summarisation. J. Roy. Stat. Soc. C Appl. Stat. 71, 1918–1956.

Herrera-Herrera, A.V., Mohamed-Rodríguez, N., Socas-Rodríguez, B., Mallol, C., 2020. Development of a QuEChERS-based method combined with gas chromatography-mass spectrometry for the analysis of alkanes in sediments. Microchem. J., 104774

Higham, T., 2011. European Middle and Upper Palaeolithic radiocarbon dates are often older than they look: problems with previous dates and some remedies. Antiquity 85, 235–249.

Hughes, S., Hayden, T.J., Douady, C.J., Tougard, C., Germonpré, M., Stuart, A.J., Lbova, L., Carden, R.F., Hänni, C., Say, L., 2006. Molecular phylogeny of the extinct giant deer, *Megaloceros giganteus*. Mol. Phylogenet. Evol. 40 (1), 285–291.

Jacobi, R.M., Higham, T.F., 2008. The "Red Lady" ages gracefully: new ultrafiltration AMS determinations from Paviland. J. Hum. Evol. 55, 898–907.

Jambrina-Enríquez, M., Sachse, D., Valero-Garcés, B.L., 2016. A deglaciation and Holocene biomarker-based reconstruction of climate and environmental variability in NW Iberian Peninsula: the Sanabria Lake sequence. J. Paleolimnol. 56, 49–66.

Jennings, R., 2022. 2022:564 - Castlepook cave, Castlepook South, Cork. https://excavations.ie.

Jordan, S.F., Murphy, B.T., O'Reilly, S.S., Doyle, K.P., Williams, Grey, A., Lee, S., McCaul, M.V., Kelleher, B.P., 2017. Mid-Holocene climate change and landscape formation in Ireland: evidence from a geochemical investigation of a coastal peat bog. Org. Geochem. 109, 67–76.

Knight, B., Milner, N., O'Connor, T., Elliott, B., Robson, H.K., Buckley, M., Witkowski, P., Charlton, S., Craig, O., Collins, M., 2018. Faunal remains: results by species. In: Milner, N., Conneller, C., Taylor, B. (Eds.), Star Carr. Volume 2: Studies in Technology, Subsistence and Environment. White Rose University Press, York, pp. 195–254.

Lister, A.M., Stuart, A.J., 2019. The extinction of the giant deer *Megaloceros giganteus* (Blumenbach): new radiocarbon evidence. Quat. Int. 500, 185–203.

Little, A., van Gijn, A., Collins, T., Cooney, G., Elliott, B., Gilhooly, B., Charlton, S., Warren, G., 2017. Stone dead: uncovering Early Mesolithic mortuary rites, Hermitage, Ireland. Camb. Archaeol. J. 27, 223–243.

Magill, C.R., Ashley, G.M., Freeman, K.H., 2013. Ecosystem variability and early human habitats in eastern Africa. Proc. Natl. Acad. Sci. U.S.A. 110, 1167–1174.

McAllister-Hayward, M.S., Blyth, A.J., McInerney, F.A., Holman, A.I., Grice, K., Tyler, J. J., Westaway, K.W., Joannes-Boyau, R., Boualaphane, S., Bourgon, N., Dunn, T.E., Frangeul, S., Luangkhoth, T., Ponche, J.-L., Sichanthongtip, P., Souksavatdy, V., Suzzoni, E., Zachwieja, A., Zanolli, C., Bacon, A.-M., Duringer, P., Hublin, J.-J., Shackelford, L., Demeter, F., Morley, M.W., 2024. Reconstructing the environmental conditions experienced by early modern humans at Tam Pà Ling (northeast Laos) using higher plant wax biomarkers. Quat. Sci. Rev. 325, 108471.

McLaughlin, T.R., 2019. On applications of space–time modelling with open-source ^{14}C age calibration. J. Archaeol. Method Theor 26, 479–501.

Meiklejohn, C., Woodman, P.C., 2012. Radiocarbon dating of Mesolithic human remains in Ireland. Mesolithic Miscellany 22 (1), 22–41.

Monaghan, N., 2016. Bronze Age Great spotted woodpecker (*Dendrocopos major*) from Co. Clare caves. Ir. Nat. J. 35, 72.

Monaghan, N.T., 2017. Irish Quaternary vertebrates. In: Coxon, P., McCarron, S., Mitchell, F. (Eds.), Advances in Irish Quaternary Studies. Atlantis Press, Paris, pp. 255–292.

Monaghan, N.T., 2023. The Brown bear (*Ursus arctos* L.) in Ireland. Ir. Nat. J. 40, 1–19.

Montgomery, W.I., Provan, J., McCabe, A.M., Yalden, D.W., 2014. Origin of British and Irish mammals: disparate post-glacial colonisation and species introductions. Quat. Sci. Rev. 98, 144–165.

Pettitt, P., White, M., 2012. The British Palaeolithic: Human Societies at the Edge of the Pleistocene World. Routledge, Oxford.

Power, R.C., Stuijts, I., McCormick, F., Talamo, S., 2023. Direct dating confirms the presence of otter and badger in early Holocene Ireland, STAR. Sci. Technol. Archaeol. Res. 9 (1), 2253082 https://doi.org/10.1080/20548923.2023.2253082.

Poynter, J.G., Farrimond, P., Brassell, S.C., Eglington, G., 1989. Molecular stratigraphic study of sediments from holes 658A and 660A, leg 108. In: Proceedings of the Ocean Drilling Program, 108. Scientific Results.

Rabett, R., Ludgate, N., Stimpson, C., Hill, E., Hunt, C., Ceron, J., Farr, L., Morley, M., Reynolds, T., Zukswert, H., Simpson, D., Nyiri, B., Verhoeven, M., Appleby, J., Meneely, J., Phan, L., Dong, N.-N., Lloyd-Smith, L., Hawkes, J., Blyth, A., Tân, N.C., 2017. Tropical limestone forest resilience and late Pleistocene foraging during MIS-2 in the Tràng an massif, Vietnam. Quat. Int. 448, 62–81.

Reade, H., Tripp, J.A., Frémondeau, D., Sayle, K.L., Higham, T.F.G., Street, M., Stevens, R.E., 2023. Nitrogen palaeo-isoscapes: changing spatial gradients of faunal δ15N in late Pleistocene and early Holocene Europe. PLoS One 18 (2), e0268607. https://doi.org/10.1371/journal.pone.0268607.

Reimer, P., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P.G., Bronk Ramsey, C., Butzin, M., Cheng, H., Lawrence Edwards, R., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kromer, B., Manning, S.W., Muscheler, R., Palmer, J.G., Pearson, C., van der Plicht, J., Reimer, R., Richards, D.A., Scott, E.M., Southon, J.R., Turney, C.S.M., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S., Fogtmann-Schulz, A., Friedrich, R., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., Talamo, S., 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0-55 kcal BP). Radiocarbon 62, 725–757.

Scharff, R.F., Coffey, G., Cole, G.A.J., Ussher, R.J., Lloyd Praeger, R., 1903. The exploration of the Caves of Kesh, County Sligo. Trans. Royal Irish Acad. 32, 171–214.

Scharff, R.F., Seymour, H.J., Newton, E.T., 1918. The exploration of Castlepook Cave, County Cork. Proc. Roy. Irish Acad. 34, 33–72.

Scharff, R.F., Ussher, R.J., Cole, G.A.J., Newton, E.T., Dixon, A.F., Westropp, T.J., 1906. The exploration of the caves of County Clare. Trans. Royal Irish Acad. 33, 1–76.

Searle, J.B., 2008. The colonisation of Ireland by mammals. In: Davenport, J.L., Sleeman, D.P., Woodman, P.C. (Eds.), Mind the Gap: Postglacial Colonization of Ireland. Irish Naturalists' Journal, Belfast, pp. 109–115.

Sleeman, D.P., 2014. Ireland, an unexpected focus for genetic biodiversity and the ecological implications. In: Sleeman, D.P., Carlsson, J., Carlsson, J.E.L. (Eds.), Mind the Gap II: New Insights into the Irish Postglacial. Irish Naturalists' Journal, Belfast, pp. 3–7.

Stimpson, C.M., 2024. The long view: ancient bones and biological conservation. In: Coughlan, N., Sleeman, D.P., Monaghan, N.T. (Eds.), Origins of Ireland's Biodiversity. Irish Naturalists' Journal, Belfast.

Stuart, A.J., van Wijngaarden-Bakker, L.H., 1985. Quaternary vertebrates. In: Edwards, K.J., Warren, W. (Eds.), The Quaternary History of Ireland. Academic Press, London, pp. 221–249.

Tune, J.W., 2020. The colonization of Ireland: a human ecology perspective. Quat. Sci. Rev. 249, 1–13.

Warren, G., 2022. Hunter-Gatherer Ireland. Oxbow, Oxford.

Woodman, P.C., 1985. Excavations at Mount Sandel 1973-77. Her Majesty's Stationery Office, Belfast.

Woodman, P.C., 2014. Ireland's native mammals: a survey of the archaeological record. In: Sleeman, D.P., Carlsson, J., Carlsson, J.E.L. (Eds.), Mind the Gap II: New Insights into the Irish Postglacial. Irish Naturalists' Journal, Belfast, pp. 28–43.

Woodman, P., 2015. Ireland's First Settlers; Time and the Mesolithic. Oxbow, Oxford.

Woodman, P., Dowd, M., Fibiger, L., Carden, R.F., O'Shaughnessy, J., 2018. Archaeological excavations at Killuragh Cave, Co. Limerick: a persistent place in the landscape from the Early Mesolithic to the Late Bronze Age. J. Irish Archaeol. 26 (2017), 1–32.

Woodman, P., McCarthy, M., Monaghan, N., 1997. The Irish Quaternary Fauna Project. Quat. Sci. Rev. 16, 129–159.