Historic England

Scientific Dating of Pleistocene Sites

Guidelines for Best Practice

Foreword

Alex Bayliss

These guidelines provide advice on best practice for the use of scientific dating on Pleistocene sites. They are applicable to all archaeological projects but are aimed primarily at those undertaken as part of the planning process. Pleistocene sites typically produce limited material that is suitable for dating. Some of the methods that can be employed are familiar to those working in later periods (e.g. Radiocarbon Dating), although special considerations for their effective use may apply. Other methods (e.g. The 'Vole Clock') are only used in the Pleistocene.

Historic England's *Curating the Palaeolithic* guidance (Historic England 2023, section 7) outlines the key Pleistocene deposits within which Palaeolithic remains may be found. Many of these deposits are suitable for scientific dating. The selection of appropriate techniques is key, given the available types of datable material: its taphonomic relationship to the archaeological objectives of the project and the expected time-range of the site. Different strands of evidence can be explicitly combined using Bayesian chronological modelling, and the resultant chronologies can be validated, not only by comparison to relative dating from stratigraphy, but also by employing multiple scientific dating techniques.

Above all, it is important to seek expert advice at an early stage in the project, as some of the techniques applicable in this timeframe require on-site sampling by dating specialists. All laboratories will be happy to advise on applying their technique to Pleistocene deposits and will welcome the opportunity to discuss sample selection and potential methods of cross-checking their results.

It is by working together with a range of specialists that you will provide the best chronology possible for your site.

Contributors

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Front cover: Excavations at Happisburgh Site 3 viewed from the cliff top.
[P Crabb © Trustees of the Natural History Museum]

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1. Introduction

David R Bridgland

1.1 The Pleistocene

The Pleistocene is the geological period during which multiple ice ages, or glacials, occurred. The last glacial ended *c.* 11,700 years ago, at the beginning of the Holocene. The Pleistocene and Holocene Epochs together are termed the Quaternary Period. The Pleistocene began 2.58 million years ago (2.58 Ma), and we now know that there were numerous ice ages during this epoch. Those of the Middle and Late Pleistocene (together accounting for the last *c.* 0.8 million years) were more severe than those occurring earlier.

The Pleistocene was not continuously cold; instead, there were periodic warmer episodes, termed interglacials, during which conditions were similar to those of the Holocene, which is generally regarded as merely the latest of numerous interglacials. This glacial–interglacial oscillation is a principal characteristic of the Pleistocene and has been used as a framework for dividing the Quaternary into different climatic phases (Shotton 1973; Imbrie and Imbrie 1979; Bowen 1999).

The sequence of alternating warm and cold Pleistocene climatic episodes is best understood from long sedimentary sequences in the deep oceans and from the deepest ice cores from Antarctica. Both of these data sources yield their climatic signal as fluctuations in the proportion of the oxygen isotopes ^{18}O and ^{16}O (Shackleton and Opdyke 1973; Lisiecki and Raymo 2005; Text Box 1). The greater resolution now available, especially from ice cores, has revealed shorter-timescale climatic fluctuation overprinting the glacial–interglacial cycles.

High-resolution records of late Pleistocene climate — gleaned from palaeoenvironmental studies from the last glacial — suggest that this cold stage was punctuated by several oscillations of warmer climate, although these were not as warm as full interglacials. Such fluctuations are called interstadials, and the term stadial is used for the particularly cold parts of glacial stages during which ice sheets extended beyond the present Arctic and Antarctic regions.

The distinction between interglacials and interstadials is essentially one of length and intensity. The formal definition of an interglacial in north-west Europe requires the presence of deciduous woodland (Turner and West 1969).

The glacials and interglacials recognised in Marine Oxygen Isotope curves are classified as numbered stages. These are counted downwards through the oceanic sedimentary sequence: the Holocene is Marine Oxygen Isotope stage 1 (MIS 1); the last glacial maximum is MIS 2 (Fig. 1). The MIS curve is not a simple fluctuation between interglacial and glacial maxima and minima. It shows considerable complexity, with substages recognised during the various interglacial stages. Thus MIS 5 is subdivided into MIS 5e to 5a: 5e is the Ipswichian interglacial; 5d a cold stadial; 5c a warm interstadial; 5b another stadial; and 5a another interstadial.

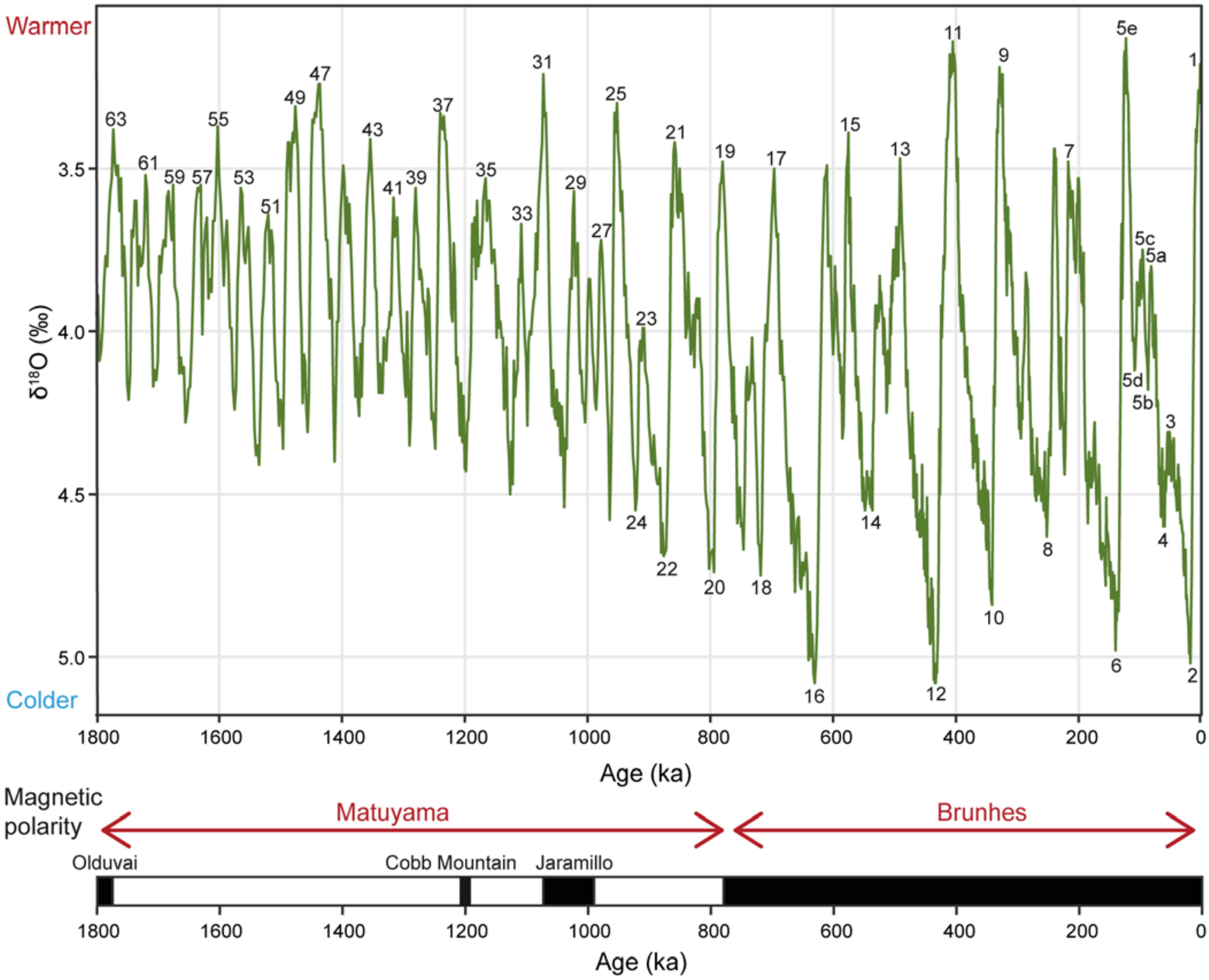


Figure 1: The Marine Oxygen Isotope record from deep marine sediments for the last 1.8 Ma, based on the LR04 benthic $\delta^{18}O$ stack constructed by Lisiecki and Raymo (2005) through the graphic correlation of 57 globally distributed benthic records. MIS stages are labelled. The record of palaeomagnetic polarity is shown below with main intervals named.

Text Box 1: Oxygen isotopes in ocean sediments

The modern-day record for Quaternary glacial–interglacial climatic fluctuation is derived from oceanic sediments, which arguably provide a continuous sequence. Climatic fluctuation during the deposition of these sediments has been reconstructed from the study of the oxygen isotope content of the calcium carbonate tests of foraminifera, specifically the ratio of the isotope ^{18}O to ^{16}O (for example Shackleton and Opdyke 1973).

Changes in the relative abundance of these isotopes in foraminifera reflect the isotopic composition of the seawater in which they live, which varies according to the amount of global ice. The lighter isotope ^{16}O represents a slightly greater proportion of the oxygen in water evaporated from the oceans (and thus entering the global hydrological cycle) compared with the sea water from which it originates. So when larger volumes of water are locked up in enlarged ice sheets, as occurs during glacials, the world's oceans become relatively enriched in the heavy isotope ^{18}O.

Thus, the oxygen isotopic signature of oceanic sediments records global ice volume. It can be expressed as $\delta^{18}O$, or the ratio of ^{18}O to ^{16}O, and is generally presented as a curve plotted against time (Fig. 1). The extremes (peaks and troughs) in this curve represent the warmest (interglacial) and the coldest (glacial) episodes. Some 60–70% of the Pleistocene is seen to fall between the two, although such intervals were significantly colder than the Holocene.

The changes in climate through the Quaternary have been driven by the effects of variations in the eccentricity, axial tilt and wobble of the spinning Earth and its orbit around the Sun, known as Croll–Milankovitch cycles. In the last million years or so the dominant influence has been the shape (eccentricity) of the Earth's orbit around the Sun, which gives rise to the 100,000 years (100 ka) climate cycles that have dominated during this period (for example Imbrie et al. 1993; Fig. 2).

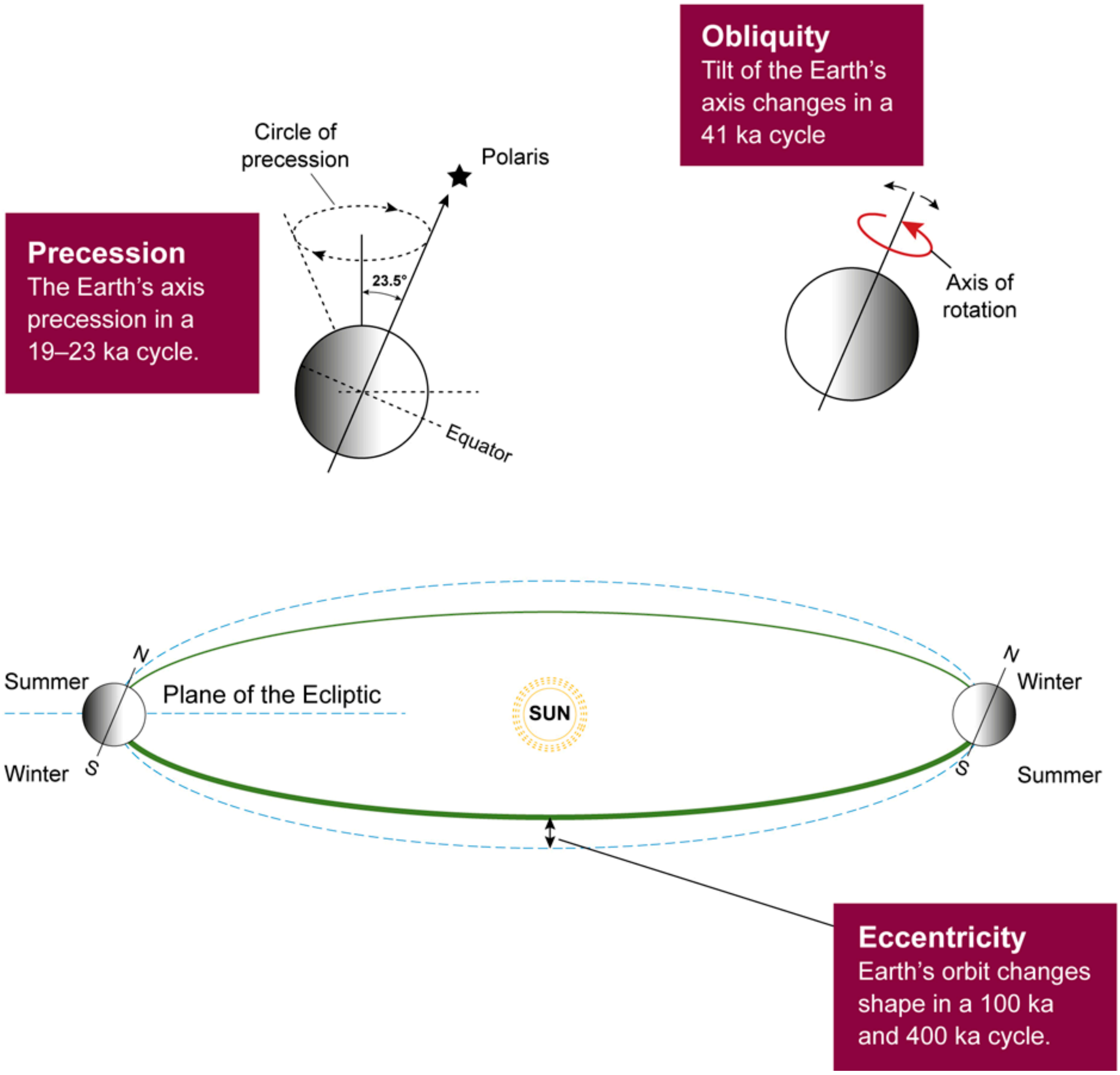
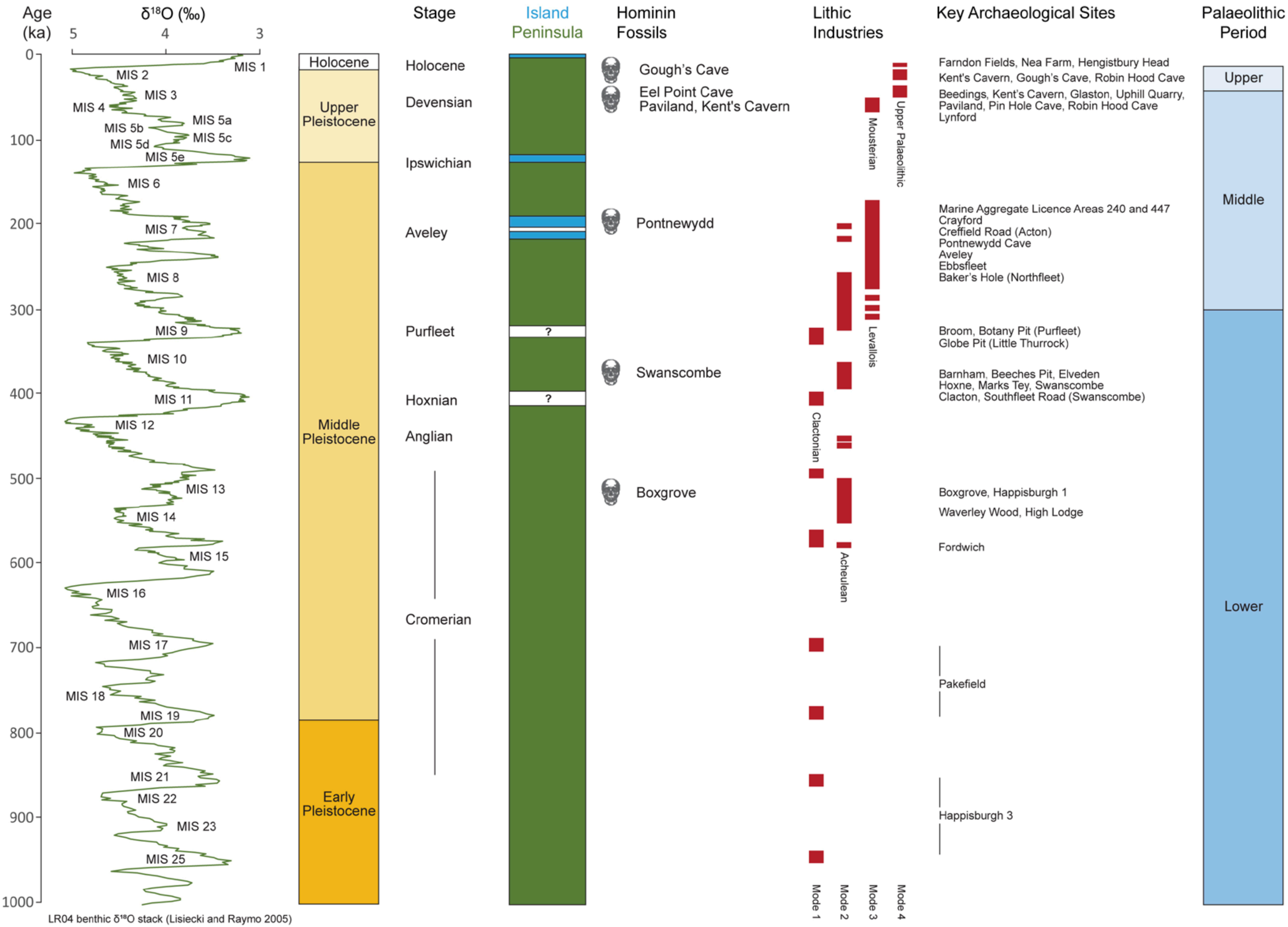


Figure 2: Summary of astronomical cycles (orbital eccentricity, obliquity and precession) involved in solar input that drives long-term climate variation.

1.2 The Quaternary stratigraphic framework

Figure 3 summarises our current understanding of the chronology of the British Palaeolithic record, compared to the MIS record and the timing of the connection of Britain to mainland Europe.

Figure 3 (page 5): Correlation of British Palaeolithic archaeology with the Marine Oxygen Isotope record, British Quaternary stages and palaeogeography.



Age (ka)
δ18O (‰)
MIS 1
MIS 2
MIS 3
MIS 4
MIS 5a
MIS 5b
MIS 5c
MIS 5d
MIS 5e
MIS 6
MIS 7
MIS 8
MIS 9
MIS 10
MIS 11
MIS 12
MIS 13
MIS 14
MIS 15
MIS 16
MIS 17
MIS 18
MIS 19
MIS 20
MIS 21
MIS 22
MIS 23
MIS 25
LR04 benthic δ18O stack (Lisiecki and Raymo 2005)
Holocene
Upper Pleistocene
Middle Pleistocene
Early Pleistocene
Stage
Holocene
Devensian
Ipswichian
Aveley
Purfleet
Hoxnian
Anglian
Cromerian
Island
Peninsula
Hominin Fossils
Gough's Cave
Eel Point Cave
Paviland, Kent's Cavern
Pontnewydd
Swanscombe
Boxgrove
Lithic Industries
Upper Palaeolithic
Mousterian
Levallois
Acheulean
Clactonian
Mode 1
Mode 2
Mode 3
Mode 4
Key Archaeological Sites
Farndon Fields, Nea Farm, Hengistbury Head
Kent's Cavern, Gough's Cave, Robin Hood Cave
Beedings, Kent's Cavern, Glaston, Uphill Quarry, Paviland, Pin Hole Cave, Robin Hood Cave
Lynford
Marine Aggregate Licence Areas 240 and 447
Crayford
Creffield Road (Acton)
Pontnewydd Cave
Aveley
Ebbsfleet
Baker's Hole (Northfleet)
Broom, Botany Pit (Purfleet)
Globe Pit (Little Thurrock)
Barnham, Beeches Pit, Elveden
Hoxne, Marks Tey, Swanscombe
Clacton, Southfleet Road (Swanscombe)
Boxgrove, Happisburgh 1
Waverley Wood, High Lodge
Fordwich
Pakefield
Happisburgh 3
Palaeolithic Period
Upper
Middle
Lower

This classification of Pleistocene strata is based on the recognition of temperate and (less commonly) cold-climate proxies in certain deposits, together with evidence for the deposition of some sediments under warm (temperate) conditions and others under intensely cold or even glacial conditions. For many years in Britain, this division was based on palynological distinctions between interglacials (summarised by Mitchell et al. 1973).

The glacial episodes were characterised by major continental ice sheets. During two of these, land-based ice extended across large parts of Britain (Bowen et al. 1986; Clark et al. 2012). These were the Anglian (*c.* 450,000 years ago; equivalent to MIS 12) and the Devensian (*c.* 110,000–11,700 years ago; equivalent to MIS 5d–MIS 2). The Anglian was Britain's most extensive ice covering (Fig. 4).

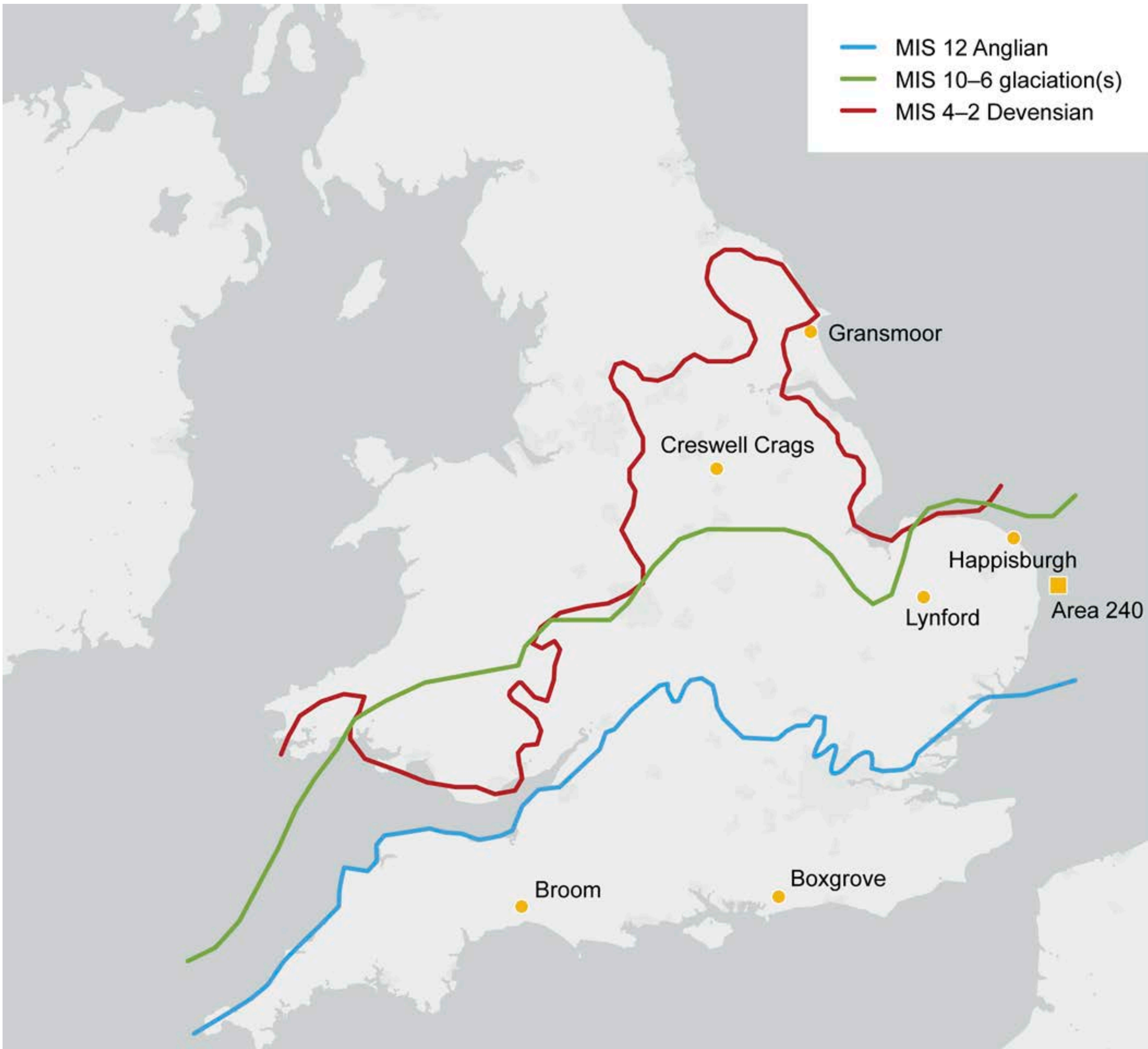


Figure 4: Map showing the limit of Pleistocene glaciations and the location of sites included in the case studies.

Together these two glaciations were responsible for almost all glaciogenic diamicton (formerly called 'boulder clay') surface deposits in Britain. Between the Anglian and Devensian there may have been more than one glacial ice advance southward across England, although the evidence only remains where it was not destroyed by the later Devensian ice advances (Lee et al. 2011). It is thought that people did not live in Britain during glaciations.

Mitchell et al. (1973) recognised just two interglacials between the Anglian Stage and the Holocene. These are the Hoxnian Stage (equivalent to MIS 11) and the Ipswichian Stage (equivalent to MIS 5e). The Ipswichian and the Holocene are separated by a final glaciation in the latter part of the Devensian. The time interval between the Hoxnian and Ipswichian interglacials, however, appears to represent more than a single interglacial–glacial cycle (Bowen et al. 1986; Bridgland 1994; 2006).

Mitchell et al. (1973) also identified by palynology an interglacial immediately before the Anglian glaciation, the Cromerian. This is also recognised to be an oversimplification, and the Cromerian is now divided into at least four interstadials. Data from vertebrates and non-marine Mollusca, however, suggest at least five distinct warm episodes within what would once have been called 'Cromerian'. These probably represent isotopic substages within MIS 21–13.

The term 'Cromerian Complex' is now generally used for this sequence of interglacials and the cold periods that bridge the late Early Pleistocene and the early Middle Pleistocene. The oldest of these interglacials has a reversed magnetic polarity, indicating that it pre-dates the Matuyama–Brunhes palaeomagnetic reversal (*c.* 780 ka) when the Earth's magnetic north and south poles changed to their present polarity (*see* Fig. 1).

Artefacts have been recovered from Cromerian Complex interglacial deposits. Of particular importance in distinguishing between these interglacials is the change, during MIS 15, in water-vole molar tooth morphology (*see* The 'Vole Clock').

MIS 22, immediately before the Cromerian Complex, coincides with the first of the intensely cold glacials that have occurred only since the 100 ka climate cycles began (see above). One British archaeological site could be older than this — Happisburgh 3 — where artefacts occur in reverse-magnetised sediments. These have been attributed to MIS 25 or 21, late in the (reversed polarity) Matuyama chron (Parfitt et al. 2010). This dating would make Happisburgh 3 the earliest known occupation of Britain during the Lower Palaeolithic (but see Happisburgh 3 for discussion of the complexity of dating this site).

The MIS 11 Hoxnian interglacial is well represented in lacustrine basins formed during the preceding MIS 12 Anglian glaciation. The Hoxnian type locality is a kettle-hole lake overlain by fluvial deposits in Suffolk (Ashton et al. 2008); and the para-stratotype is a complete lake sequence at Marks Tey in Essex.

In the Lower Thames, the Hoxnian interglacial is well represented in the north Kent sites of Dartford Heath and Swanscombe (Fig. 5). At Swanscombe a hominin skull fossil was found, along with many flint artefacts, animal vertebrae and molluscan fossils. There are three superimposed Lower Palaeolithic industries at this site: a basal Clactonian, an assemblage with pointed handaxes, and an upper handaxe assemblage with distinctive twisted edges, the latter thought to represent MIS 11a (Bridgland and White 2015).

The MIS 9 'Purfleet' interglacial is securely established in the British terrestrial record in the Corbets Tey Terrace, east of London.

The Lower Thames sequence is of considerable importance because it forms a staircase of four terraces, within which all four of the post-Anglian interglacials are represented (Fig. 5). Investigations at Purfleet, Essex confirm the correlation of the sediments there with the relatively short but strikingly warm MIS 9e interglacial optimum (Bridgland et al. 2013). This site contains three major Palaeolithic tool industries in superposition: Clactonian, overlain by Acheulian, overlain by Levallois. The Acheulian represents the Lower to Middle Palaeolithic transition (Wymer 1999; White and Ashton 2003; White et al. 2011; but *see* White et al. 2024).

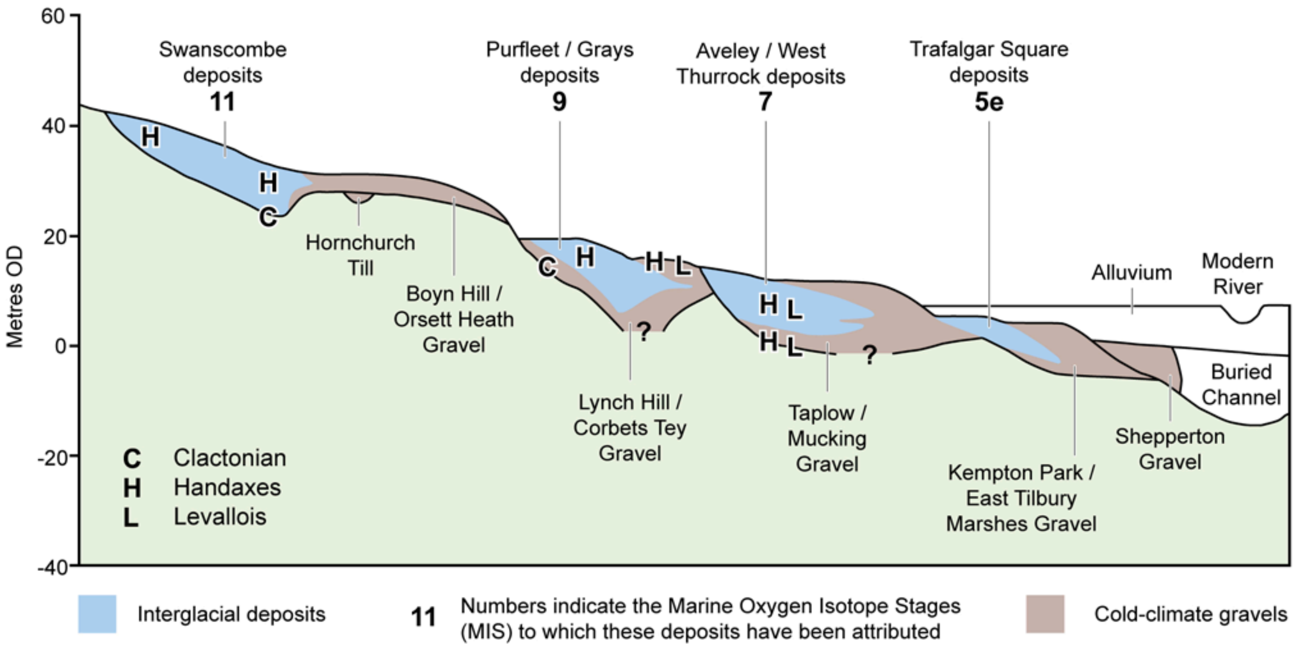


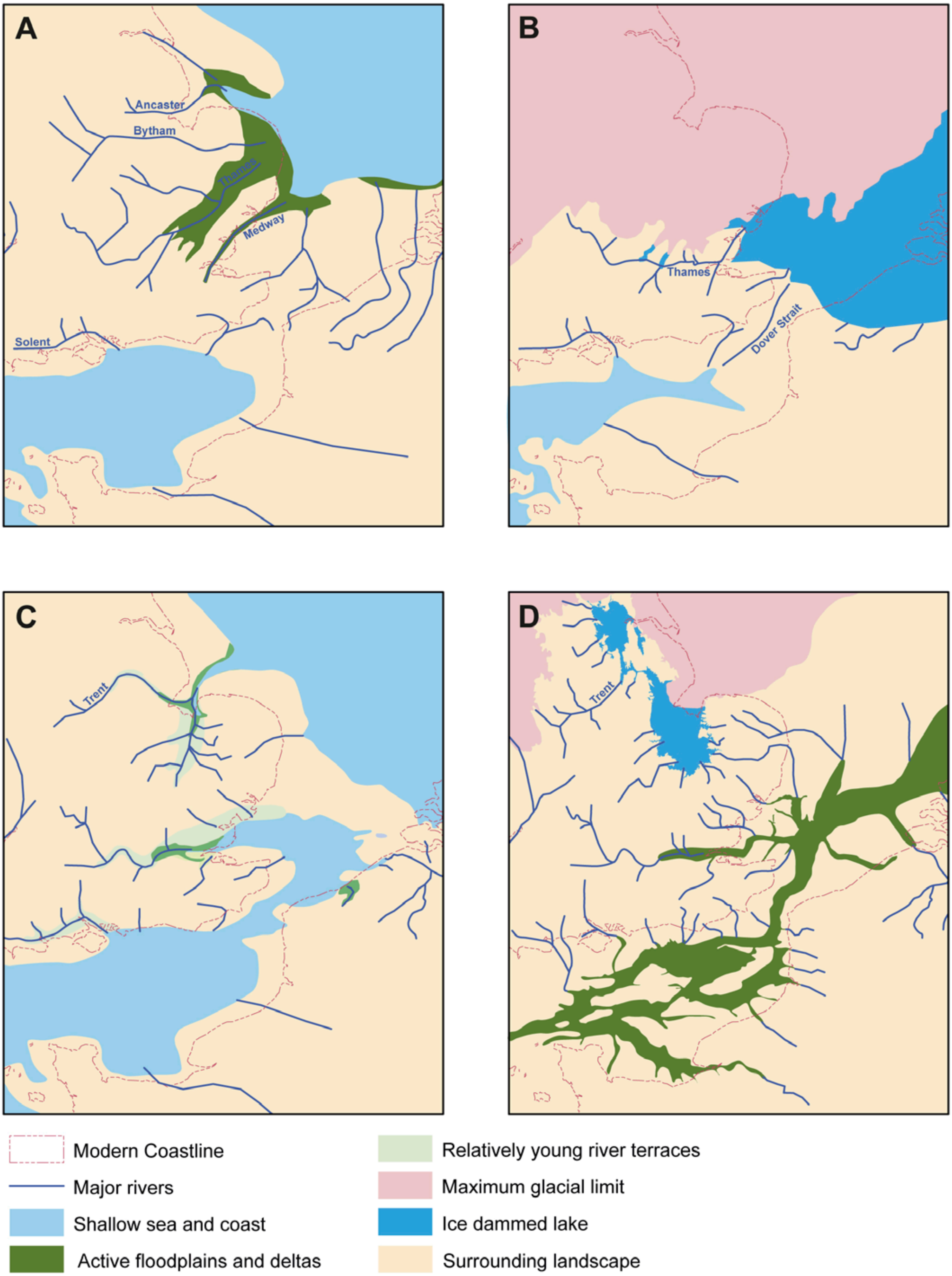
Figure 5: Summary of the Lower Thames terrace staircase, showing the distribution of main Palaeolithic artefact types and Marine Oxygen Isotope stages of the interglacial deposits. [Modified from Bridgland 2006]

The next-youngest interglacial, equivalent to MIS 7, is known as the Aveley interglacial. It is complex, with perhaps three temperate peaks, although none was as warm as the Ipswichian or earlier Purfleet interglacials. Human occupation of Britain during MIS 7, within the early Middle Palaeolithic, shows consolidation of Levallois knapping and a decline in handaxe use. An exception is Pontnewydd Cave, Clwyd, a rare North Wales interglacial context where numerous handaxes of MIS 7 age were found (Green 1984).

There is no conclusive evidence for hominin presence between MIS 6 and 4, which includes the Ipswichian MIS 5e interglacial. No archaeological material or butchery damage to any of the large vertebrate bone collections from that stage has been found. This is probably because Britain was an island at this time. The return of hominins to Britain in the later Middle Palaeolithic, during MIS 4/MIS 3, has been observed at a few open-air (e.g. Lynford Quarry) and cave sites (e.g. Pin Hole, Creswell Crags). Humans do not appear to have been present in Britain during the Last Glacial Maximum (MIS 2).

Terrestrial records are typically discontinuous, patchy and confined to single glacial–interglacial periods. Therefore a robust chronological framework is required to enable correlation with the universally applicable and continuous framework provided by the oceanic oxygen isotope signal and with the ice core records. River terrace and raised beach sequences, however, can provide terrestrial frameworks in uplifting areas (e.g. Bridgland 2000; 2006; Bridgland et al. 2004), as these contain a sequence of distinct interglacial deposits in many parts of Britain (e.g. Bridgland 2010; Bridgland and Allen 2014).

Figure 6 (page 10): Key elements of Pleistocene palaeogeography: (A) drainage systems during the Early to Middle Pleistocene (1 Ma to 0.5 Ma, *c*. MIS 25–13) before the Anglian (MIS 12) glaciation; (B) Maximum extent of Anglian (MIS 12) glaciation, showing the southern migration of the palaeo-Thames, formation of the extensive pro-glacial lake within the southern North Sea and initial drainage through the Dover Straits; (C) Middle Pleistocene configuration for highstands between 420–170 ka (MIS 11, MIS 9 and MIS 7), showing a partially eroded connection between East Anglia and the Netherlands; (D) drainage pattern during the Devensian glacial lowstand (80–20 ka; MIS 4–2), showing the maximum extent of the Devensian glaciation, formation of ice-dammed lakes and drainage network within southern North Sea and English Channel (based upon data from Antoine et al. (2003), Bridgland and Allen (2014), Clark et al. (2017), Cohen et al. (2012; 2014; 2017), Hijma et al. (2012), Murton and Murton (2012) and Odé et al. (2022)).


A
Ancaster
Bytham
Thames
Medway
Solent
B
Thames
Dover Strait
C
Trent
D
Trent
Modern Coastline
Major rivers
Shallow sea and coast
Active floodplains and deltas
Relatively young river terraces
Maximum glacial limit
Ice dammed lake
Surrounding landscape

1.3 Palaeogeography

The landscape and environment that the early occupants of Britain inhabited was, for much of the time, very different to today's. During the predominantly colder Pleistocene, sea level was generally much lower because global water was locked up in larger polar ice caps. Before MIS 12 there was a 'British Peninsula' at the north-west extremity of the European continent, rather than an island Britain (Preece 1995; Fig. 6a). The timing of and mechanism for the formation of the Strait of Dover is controversial, but it seems likely that this took place during the Anglian (MIS 12) as a result of the overflow of a glacially dammed lake in the southern North Sea basin (Fig. 6b). This drained into the English Channel and cut the earliest Dover Strait.

At the same time, the route of the Thames moved farther south into its modern valley through London (Bridgland 1994) and the Bytham river was obliterated by the Anglian ice sheet, which engulfed its valley. Parts of the former valley provided post-Anglian drainage routes (Fig. 6c), but the huge river system was not restored. It was replaced by a proto-Trent system that required two further climate cycles and another glaciation before it reached anything like its modern configuration. Its drainage into the Humber did not occur until deglaciation at the end of the Devensian (Bridgland et al. 2014; 2015; Fig. 6d). The Solent river was unaffected by glaciation; its eventual demise was caused by the widening of the English Channel, probably during MIS 6, which drowned its lower reaches and separated the Isle of Wight from the English mainland (Westaway et al. 2006).

1.4 Fitting the archaeological record into this dynamic landscape

The Ancient Human Occupation of Britain (AHOB) project has revealed human occupation in the Early Pleistocene (http://www.ahobproject.org). Sites are known at Happisburgh 3, Norfolk, and at Pakefield, Suffolk, which produced Lower Palaeolithic artefacts dated to MIS 25/MIS 21 and to MIS 17, respectively. The British archaeological record also covers much of the Middle Pleistocene. Lower Palaeolithic human occupation is known from sites such as MIS 13 Happisburgh 1 and the Boxgrove raised beach, West Sussex.

During the MIS 6 glacial, the final stage of the Middle Pleistocene, hominins disappeared from Britain and were absent during the last (Ipswichian) interglacial. Hominins probably did not return until MIS 4/MIS 3, when Late Pleistocene Neanderthals, using Middle Palaeolithic Mousterian stone tools, have been found at a number of sites (e.g. Lynford Quarry). Modern humans appeared slightly later, using a more sophisticated Upper Palaeolithic technology.

Two separate lithic technologies coexisted in Britain during the latter part of the early Middle and most of the late Middle Pleistocene. These are Clactonian assemblages (Mode 1, characterised by flakes) and Acheulian assemblages (Mode 2, characterised by handaxes). The distinction between these two knapping technologies is far from straightforward, however, as both industries produced identical flakes and cores. Clactonian assemblages cannot be recognised definitively unless handaxe making is not represented at all (McNabb 2007).

A further potential advance is the matching of handaxe typology to particular Pleistocene stages (Bridgland and White 2015), which has developed out of a more reliable understanding of the climatostratigraphy and dating of Quaternary deposits across Britain. Handaxe making dwindled in importance once the Levallois technique using prepared cores (Mode 3) appeared. The Levallois industry heralded the transition into the Middle Palaeolithic, and occurred over a wide area around the MIS 9–8 transition.

The Upper Palaeolithic probably first appeared during MIS 3 (by *c.* 43 ka) with the arrival of *Homo sapiens* (e.g. Kent's Caverns; Proctor et al. 2017). Upper Palaeolithic technologies are characterised by blades from prepared cores (Mode 4).

During MIS 2, however, there was probably another complete depopulation of Britain. People returned only as the climate ameliorated at the beginning of the Lateglacial and into the Holocene.

1.5 Shorter-timescale divisions of the Late Pleistocene

The Late Pleistocene began with the warming transition that led to the MIS 5e Ipswichian interglacial (*see* Fig. 3). The preceding glacial produced the most extensive glaciation of the neighbouring part of the European mainland, although the equivalent British ice sheet was smaller than at least two earlier ones (White et al. 2016). This episode was clearly one of severe cold, which probably explains the lack of compelling evidence for human occupation of Britain during MIS 6 and MIS 5e. There is no good evidence that humans returned before MIS 3.

The level of resolution available for the various palaeoclimatic records of the Late Pleistocene is significantly greater than that for the Early and Middle Pleistocene thanks to evidence from ice cores, especially for fluctuations during the last climate cycle (Text Box 2; Fig. 7). The MIS 3 interstadial was relatively cold and unstable compared to the previous warm stages of the last million years.

The ice-core record shows that much of the last climate cycle (since MIS 5e) has been characterised by high-frequency, high-amplitude climate oscillations of *c.* 500 to 2000 years duration (Fig. 7), known as 'Dansgaard–Oeschger' cycles. These cycles show abrupt warming by 5–8°C within 50 years, perhaps within as little as a decade, followed by more protracted cooling.

The high-resolution temperature record derived from the ice cores can be used to define Late Devensian chronostratigraphy. The record is divided into a series of alternating Greenland Stadial (GS) and Greenland Interstadial (GI) stages. GS-1 represents the pre-Holocene Younger Dryas (in Britain called the Loch Lomond) Stadial and GI-1 represents the Bølling–Allerød (in Britain called the Windermere) Interstadial (Fig. 8).

Text Box 2: Oxygen isotopes in ice cores

Ice cores drilled through the Arctic and Antarctic ice sheets provide a high-resolution record of $\delta^{18}O$, which varies according to the temperature at the time of snowfall (Wolff 2005). Ice is deposited in these archives as a series of annual layers, which can be counted backwards from the present. This is not a straightforward process and missing and false layers lead to a cumulative counting error, but this is in the order of a few hundred years at MIS 2 and of a few thousand years at MIS 5e.

The $\delta^{18}O$ ratios from the Greenland ice cores show that much of the last climate cycle (since MIS 5e) has been characterised by high-frequency, high-amplitude climate oscillations (Bond et al. 1993; Dansgaard et al. 1993; Alley 2000; Rasmussen et al. 2014; Seierstad et al. 2014; Fig. 7). These 'Dansgaard–Oeschger' cycles show abrupt warming by 5–8°C within 50 years, perhaps within as little as a decade, followed by more protracted cooling. Each cycle lasted on the order of 500–2000 years.

There are 25 such cycles evident in the ice-core record between *c*. 122 and 25 ka, the latter coinciding with the Last Glacial Maximum (MIS 2). Although it required the exceptional resolution of the ice cores to reveal this cyclicity, which could probably never have been determined from fragmentary terrestrial records, recent studies of vegetation change across Europe have revealed a degree of synchrony between palaeoclimate reconstructions from terrestrial proxies and from ice-cores (Fletcher et al. 2010).

The high-resolution temperature record derived from the ice cores can be used, in a similar manner to the Marine Oxygen Isotope Stages, to define Late Devensian chronostratigraphy. This record is divided into a series of alternating Greenland Stadial (GS) and Greenland Interstadial (GI) stages (Figs 7 and 8).

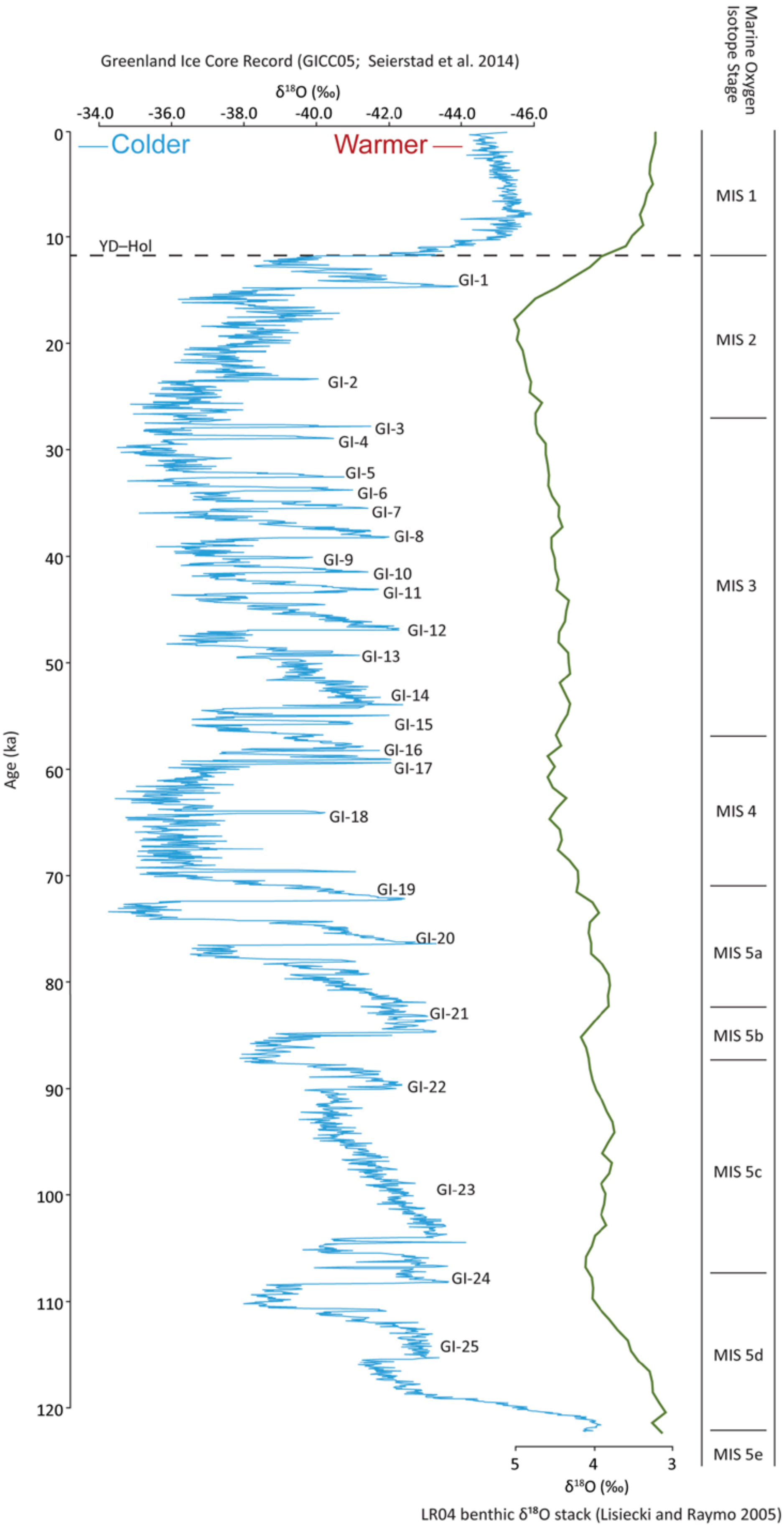


Figure 7: Greenland Ice Core $\delta^{18}O$ record for the Late Pleistocene–Holocene, with Greenland Interstadials ((GI); Rasmussen et al. 2014); 'YD–Hol' marks the Younger Dryas–Holocene transition (*see* Walker et al. 2009); the Marine Oxygen Isotope record and stages are to the right.

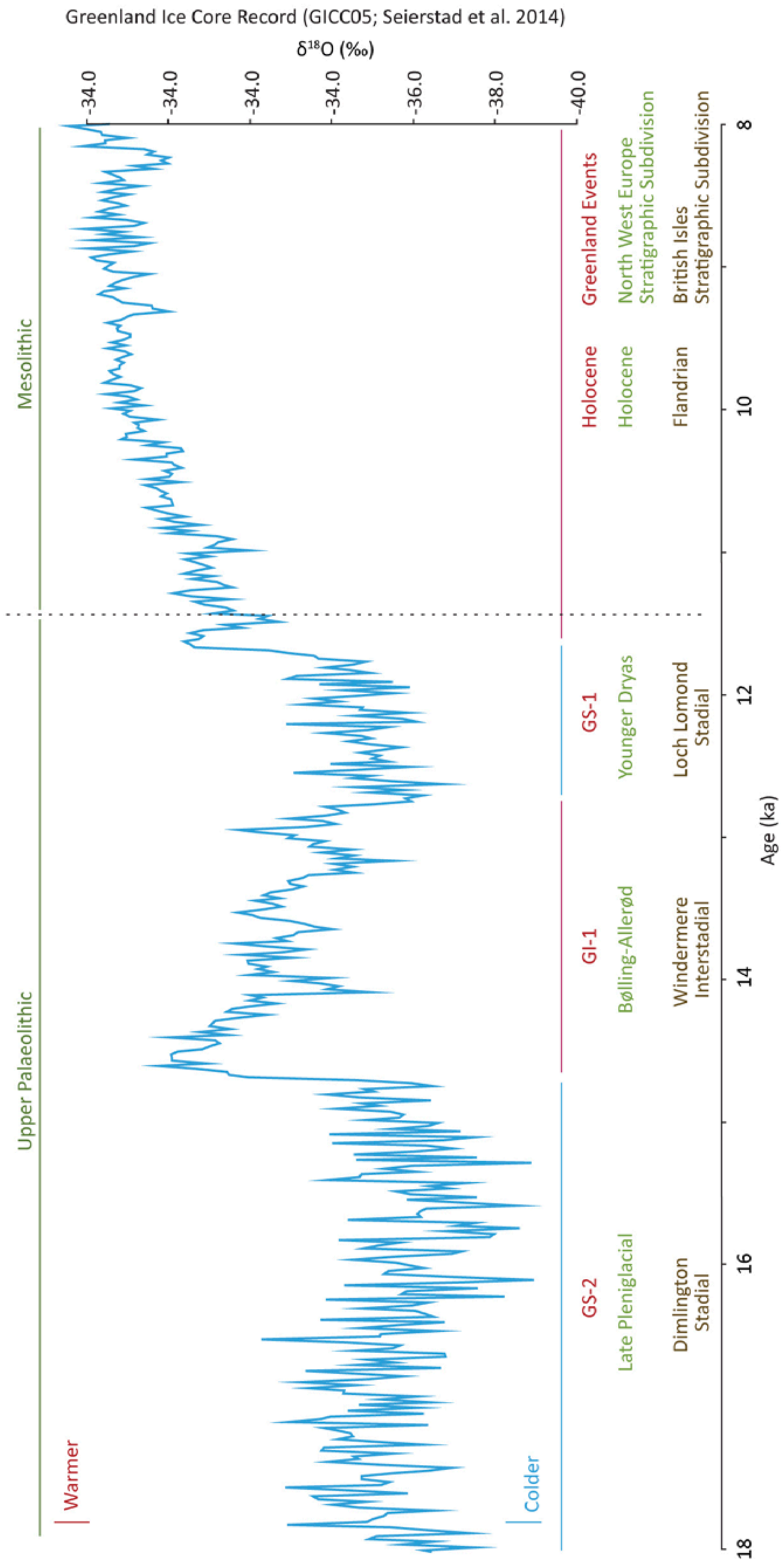


Figure 8: Greenland Ice Core record for the Lateglacial; related to British and European Lateglacial stages and British archaeological periods.

2. Scientific dating methods for the Pleistocene

David R Bridgland

The relative sequence provided by stratigraphy can be placed on a calendar timescale using various methods of scientific dating. Many of the most important advances come from understanding radioactivity. Detailed explanations of the major techniques follow, including a series of case studies. Further information is provided by Walker (2005), Lowe and Walker (2015) and Rixhon et al. (2017).

The application of scientific dating methods in the Pleistocene is generally limited by the availability of suitable material for dating. Replicate measurements should be obtained and, wherever possible, ages should be obtained from more than one technique. This enables comparison of the results produced by different dating techniques to be assessed and a chronology to be constructed.

Stratigraphy also provides a key method for assessing the reliability of scientific dating. Results should be consistent with the relative dating provided by the stratigraphy. Bayesian chronological modelling can be employed as an explicit methodology for combining these disparate strands of evidence.

Certain questions must be considered before embarking on any dating programme:

- Applicability: is there something datable within the deposit?
- Taphonomy: how did the material being dated become incorporated into the deposit?
- Time range: is there a technique suitable for the expected time-range of the deposit? (*see* Fig. 9)
- Precision/Accuracy: are the available techniques capable of providing sufficient precision/accuracy to resolve the archaeological problem of interest?
- Cost/facilities: is there sufficient funding and can the necessary measurements be obtained within the required timescale?

Some general rules should be adopted for scientific dating programmes in the Pleistocene:

- The application of scientific dating techniques should, wherever possible, be underpinned by a thorough understanding of the site sediments and their stratigraphy.
- Some types of material or deposit may provide a means of relative dating (e.g. biostratigraphy, pedostratigraphy, morphostratigraphy).
- Multiple age determinations from a single stratigraphical unit should be compatible.
- Independent dating techniques from the same stratigraphical unit should give consistent ages.
- Scientific dates should conform with the stratigraphy (i.e. the oldest dates at the bottom and youngest at the top).
- Where deposits can be tied into the Marine Oxygen Isotope stages or the Greenland Ice Core record, results should be comparable to these timescales.

2.1 Radiometric methods

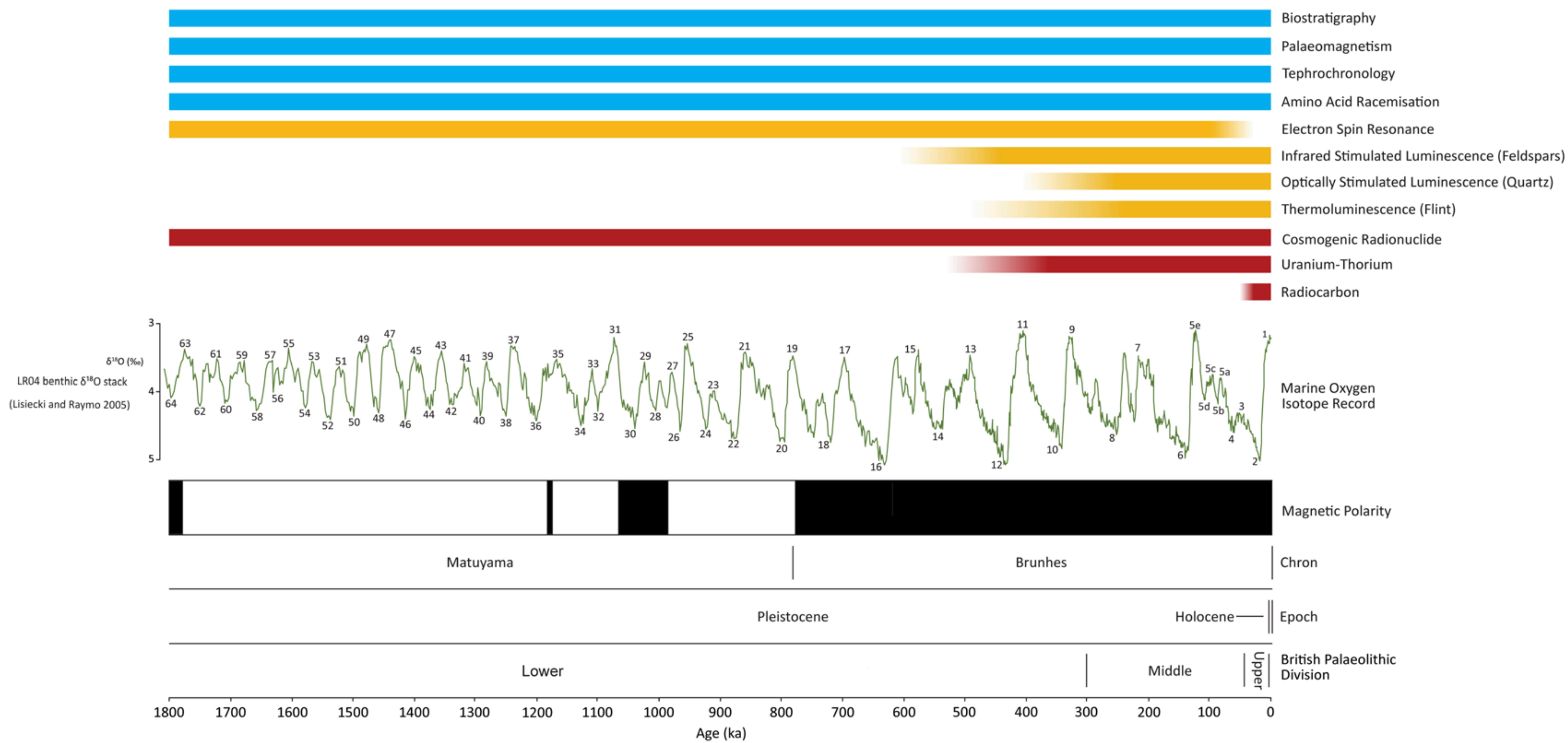
These methods make use of radioactive isotopes, which decay at rates predicted by their half-lives. Different isotopes are used for dating different time ranges (Fig. 9).

Radiocarbon dating is used in the very Late Pleistocene and through the Holocene because its half-life is 5730 years.

Isotopes with half-lives suited to dating earlier parts of the Pleistocene are more restricted. Argon-Argon (^{40}Ar-^{39}Ar) and Potassium-Argon (^{40}K-^{40}Ar) dating is of considerable precision, but lavas and tephra suitable for these methods are not commonly found in the English Quaternary record.

Uranium-series (including Uranium-Thorium dating) requires that these elements are present and for there to be a closed system. It has mainly been applied to calcareous deposits in caves.

Figure 9 (page 18): Applicable timespans for scientific dating methods covered in this guidance. For some methods, local conditions may affect the maximum age limit.


Biostratigraphy
Palaeomagnetism
Tephrochronology
Amino Acid Racemisation
Electron Spin Resonance
Infrared Stimulated Luminescence (Feldspars)
Optically Stimulated Luminescence (Quartz)
Thermoluminescence (Flint)
Cosmogenic Radionuclide
Uranium-Thorium
Radiocarbon
Marine Oxygen Isotope Record
δ18O (‰)
LR04 benthic δ18O stack
(Lisiecki and Raymo 2005)
Magnetic Polarity
Matuyama
Brunhes
Chron
Pleistocene
Holocene
Epoch
Lower
Middle
Upper
British Palaeolithic Division
Age (ka)

Cosmogenic nuclide dating is based on the reaction between cosmic rays and certain elements in minerals within rocks. The continuous bombardment by cosmic rays is predictable, with certain provisos. It leads to the formation and accumulation of ‘cosmogenic isotopes’ in rock surfaces (Text Box 3). This technique is potentially a powerful tool but requires a good understanding of erosion history and adequate sampling strategies. At present, its use for archaeological applications has been limited. It is expensive and should only be used in collaboration with expert practitioners.

Text Box 3: Cosmogenic Nuclide dating

There are two contrasting approaches to using cosmogenic nuclides for age estimation: exposure dating and burial dating.

Exposure dating measures the time that has elapsed since rock surfaces became exposed to cosmic radiation. It has been used to date past glaciation, for example by dating ice-moulded bedrock and erratic boulders (e.g. Ballantyne 2010). ^{36}Cl, ^{10}Be and ^{26}Al isotopes collectively cover timescales from a few ka to 4 Ma. The amount of an isotope accumulated in the uppermost few cm of exposed rock is proportional to the length of time elapsed since the initial exposure of the rock surface.

Burial dating is based on the differential decay of at least two nuclides, where at least one of them is a radionuclide. These can indicate the time elapsed since they were sealed from cosmic-ray bombardment (Dunai 2010).

The nuclide pair $^{26}Al/^{10}Be$ is frequently employed for this method, as both isotopes are readily produced in quartz by the action of cosmic rays at a ratio that is essentially independent of latitude and altitude.

Burial dating using these isotopes depends on the quartz having been exposed to cosmic rays for a period during which they accumulate in the sediment. Burial must then be rapid and at sufficient depth to prevent further cosmogenic nuclide production. As the isotopes decay at differing rates, and the surface concentration ratio is well understood, the ratio of the buried sample can be measured and dated.

2.2 Trapped charge methods

These techniques use signals from charge trapped in the structure of crystalline minerals to calculate the time since the ‘traps’ were emptied by a ‘zeroing’ event, for example exposure to sunlight or heating. Radioactive decay within the environment supplies a stream of charge that will progressively fill these traps at a predictable rate after the ‘zeroing’ event. Once the majority of traps are occupied, the mineral is saturated, which constitutes a limitation to the dating timescale.

- For luminescence techniques, the trapped charge is measured by the amount of light emitted by charge released from traps.

- Electron Spin Resonance (ESR) does not evict the charge. Instead, the strength of the signal emitted by the trapped charge is measured.

In both techniques, measurements are made on each sample following laboratory irradiation with calibrated radiation sources. These enable calculation of how much radiation dose the samples were exposed to during burial. This burial dose must be divided by the dose rate (how much dose per thousand years). The dose rate is generated by the level of radioactivity in the sediment from which the dating sample was collected.

Different techniques have different applications and timespans. The timespan is always dependent on the natural level of radioactivity on the site. Low levels of natural radioactivity can allow dating over a longer-timescale (*see* Luminescence dating):

- **Thermoluminescence (TL).** This was the first luminescence dating technique to be used widely. Heat is used to release the trapped charge. It is applicable as a measure of the time that has passed since the heating of burnt flint recovered from hearths.

- **Optically Stimulated Luminescence (OSL)** is applied to sediments. Blue or green light is used to release the trapped charge from grains of quartz. When used, it is important to consider whether the grains were fully zeroed by light exposure when deposited, which is why the method works best for dating wind-blown sediments.

- **Infrared-Stimulated Luminescence (IRSL)** is also applied to sediments. Infra-red light is used to release the trapped charge in feldspars, not quartz. This technique has the advantage that feldspars normally saturate at higher doses than quartz and thus can date older sediments.

- **Electron Spin Resonance (ESR)** measures the trapped charge by looking at the absorption of microwave energy by a mineral as the strength of an applied magnetic field is varied. The dating range is dependent on the type of sample (i.e. tooth enamel or sedimentary quartz grains) and on the concentration of radionuclides in the surrounding environment. Its range is between a few thousand and more than a million years (*see* Text Box 4).

Text Box 4: Electron Spin Resonance (ESR)

Electron Spin Resonance (ESR) is a trapped-charge dating technique in the same group as luminescence (Duval 2016; Rixhon et al. 2017). The materials that can be dated include phosphates, carbonates and silicates. Fossils (especially teeth) and optically bleached quartz grains are the most common applications to Pleistocene deposits in Britain. The main difference from luminescence dating (*see* Luminescence dating) is that the equivalent dose is obtained using ESR spectroscopy — i.e. the measure of energy stored in traps in the crystal lattice.

For teeth, uptake of Uranium is common, and this makes the dose rate change through time, so it is normally necessary to undertake Uranium-series analyses in parallel with ESR to quantify this effect. For sedimentary quartz a number of different ESR signals can be used, some of which are reset by light faster than others, and some of which are more stable than others. Quoted errors are typically 15% of the estimated age.

OSL has been applied successfully to sediments in many areas of Britain, especially in the past two decades (*see* The Axe Valley at Broom; Marine Aggregate Licence Area 240; Lynford Quarry). Incomplete bleaching of sediments and the unsuitability of the available quartz sand grains, however, may prevent successful dating (for example Pennine quartz in northern England). The IRSL signal from feldspars is less variable from region to region and, although the method is more complex, it may be more suitable in some areas.

ESR has been widely used in France but applications in Britain have been infrequent and yielded inconsistent outcomes (Grün and Schwarcz 2000; Voinchet et al. 2015). This technique should only be employed in collaboration with expert practitioners.

2.3 Other scientific dating methods

There are also non-radiometric methods that have proved to be valuable for dating Pleistocene contexts:

- **Amino-Acid Racemisation** dating (AAR) is based on the predictable diagenesis of proteins within biological materials after organisms die, particularly the shells of molluscs. The method has been applied to British Lower to Middle Palaeolithic materials, with emphasis on fluvial localities containing both artefacts and molluscan fauna.

- **Palaeomagnetism** is valuable in providing isochrons (age-equivalent stratigraphical horizons). One of the most important is the Matuyama–Brunhes magnetic reversal (when the north and south poles reversed) marking the start of the Middle Pleistocene (780 ka; *see* Fig. 1). This marker can be an important element in dating river terrace sequences, although the reversal itself has yet to be located in Britain.

- **Tephrochronology** is a useful means for identifying isochrons across widespread areas, making use of volcanic ash layers (tephras) distributed by wind. It is used when such layers can be correlated with particular eruptions using geochemical analyses. In Britain work has mainly focused on Late Pleistocene isochrons.

2.4 Relative dating methods

There are several approaches which provide relative, rather than calendar, dating. These underpin the understanding of landscape development and stratigraphy, providing a framework into which other dating evidence can be incorporated.

Biostratigraphy is a key relative dating method. This may consist of identifying remains that are only known to have lived at a certain time, or taxa with particular niche requirements, such as temperature, that only occur at specific times in a glacial–interglacial cycle. An important part of the approach is the correlation of sediments in different geographical locations using biostratigraphic characteristics.

Biostratigraphy may be based on a single taxon, on assemblages of taxa, on relative abundances, and on specified morphological features, including evolutionary changes. The last can be the most powerful biostratigraphical technique (*see* The 'Vole Clock'). Mammalian faunas have proved to be the most effective for dating, as they show greater change during the Quaternary than other biological remains.

This principle is also the basis for 'archaeostratigraphy', in which diagnostic archaeological artefacts (for example, types of worked flint) are used to infer the age of the deposits.

3. Bayesian chronological modelling

Alex Bayliss and Peter Marshall

Bayesian statistics provide an explicit, probabilistic method for combining different sorts of evidence to estimate formally the dates of events that happened in the past. The basic idea is encapsulated in Bayes' theorem, which simply states that we analyse the new data we have collected about a problem ("the standardised likelihoods") in the context of our existing experience and knowledge about that problem (our "prior beliefs"). This enables us to arrive at a new understanding that incorporates both our existing knowledge and our new data (our "posterior beliefs"). This is not the end of the matter, however, since models will be updated as new information becomes available.

At its most basic, this approach simply takes account of the fact that a group of dates are related in some way, for example by being from the same site or associated with the same type of artefact. It is essential to account for this in the analysis of any scientific dates, or there is a significant risk that past activity will be interpreted as starting earlier, ending later, and enduring for longer than was actually the case (Bayliss et al. 2007). This is because the probabilistic date estimates provided by a range of scientific techniques 'scatter' around the actual age of the sample; and this scatter matters (Bayliss and Marshall 2022, section 2.1).

Figure 10 illustrates this using the assemblage of radiocarbon dates on ultra-filtered gelatin extracted from human and cut-marked animal bones found in Gough's Cave, Somerset (Table 1; Jacobi and Higham 2009; note that following their interpretation, OxA-18067 has been excluded as this related to later activity).

In this graph the 'raw' scientific dates are shown in outline, and the posterior beliefs from the Bayesian model are shown in black. Some posterior distributions relate to particular objects. For example, cut-marked bone GC 1990 184 dates to *15,010–14,820 cal BP* (*93% probability*; *OxA-18035*; Fig. 10) or *14,680–14,630 cal BP* (*2% probability*), probably to *14,950–14,860 cal BP* (*68% probability*). Other posterior distributions estimate the time of events in the past that do not relate to a particular sample. For example, this model estimates that human occupation in the cave began in *15,060–14,850 cal BP* (*93% probability*; *StartGough'sCave*; Fig. 10) or *14,680–14,650 cal BP* (*2% probability*), probably in *14,980–14,890 cal BP* (*68% probability*).

Date ranges deriving from Bayesian modelling are conventionally given in italics to distinguish them from unmodelled scientific dates. They should be cited with the relevant parameter name and a reference to the model from which they derive.

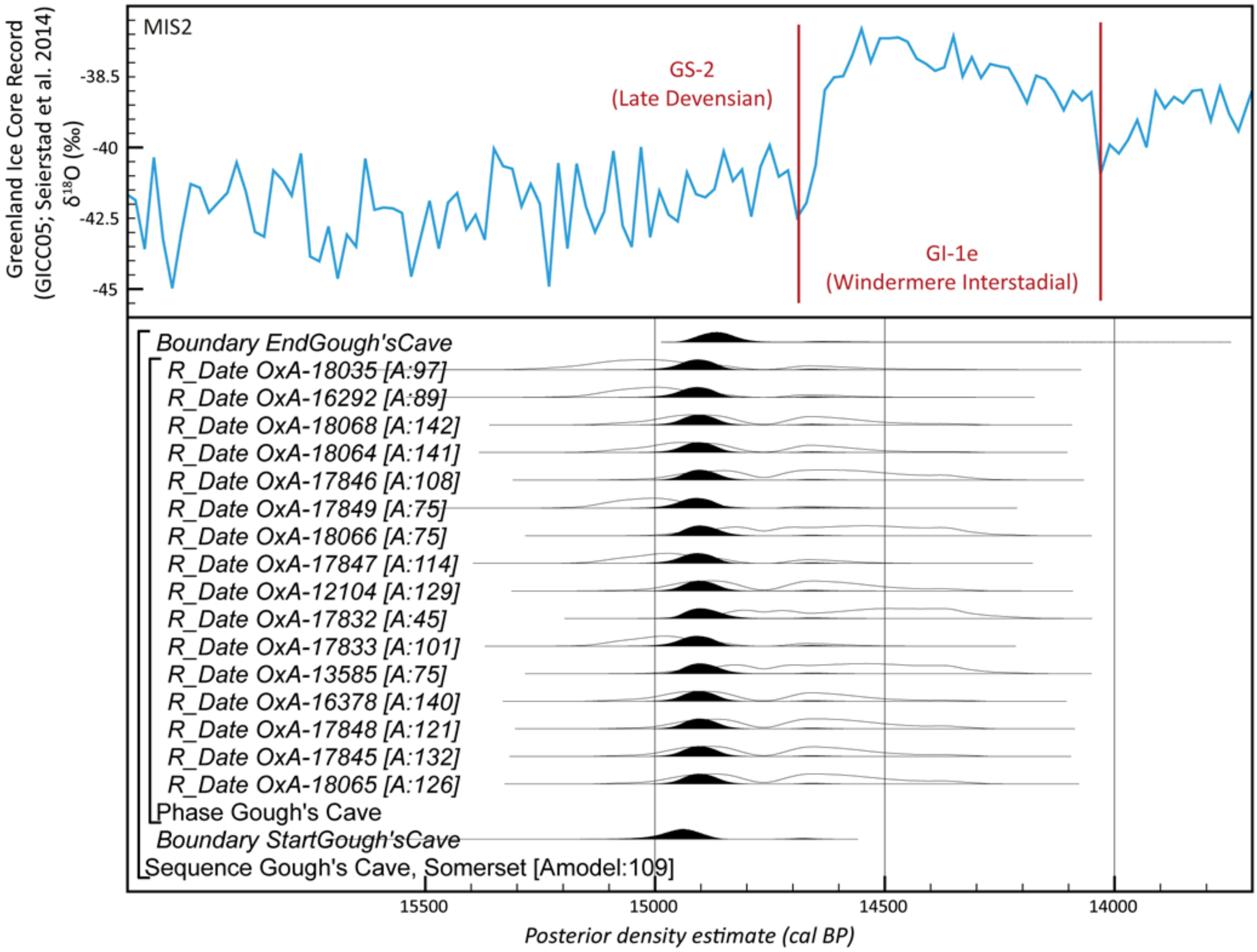


Figure 10: Probability distributions of dates from Gough's Cave, Somerset.
Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the result of simple radiocarbon calibration, and a solid one, based on the chronological model used. Other distributions correspond to aspects of the model. For example, the distribution '*StartGough'sCave*' is the estimated date when people began to occupy the site. The large square brackets down the left-hand side of the diagram, along with the OxCal keywords, define the overall model exactly. The upper panel shows the Greenland Ice Core record.

Table 1: Radiocarbon ages and associated measurements on ultra-filtered gelatin from Gough's Cave, Somerset (*see* Jacobi and Higham 2009, table 1 for further measurements from this site).

Laboratory Code	Material and context	Radiocarbon Age (BP)	$\delta^{13}C_{IRMS}$ (‰)	$\delta^{15}N_{IRMS}$ (‰)	%C	C/N_{atomic} ratio	Gelatin yield (mg)
OxA-18065	M.49797, *Equus ferus*, cut left 1 phalange from Layer 8 of R F Parry's excavation (1927–31)	12,490±55	−20.5±0.2	1.6±0.3	43.2	3.2	26.2
OxA-17845	M.49758, *Cervus elaphus*, cut 2nd phalange from Layer 11 of R F Parry's excavation (1927–31)	12,500±50	−19.6±0.2	2.8±0.3	47.4	3.2	37.3
OxA-17848	1.1/4, adult human calotte conjoined to frontal (GC 1987 169) from Layer 12/13 of R F Parry's excavation (1927–31)	12,485±50	−19.3±0.2	8.5±0.3	49.7	3.2	11.8
OxA-16378	M.49847, *Cervus elaphus*, cut distal right metatarsal from Layer 13 of R F Parry's excavation (1927–31)	12,515±50	−19.8±0.2	3.2±0.3	43.7	3.2	28.8
OxA-13585	M.49877, *Canis* cf *familiaris*, right dentary from Layer 14 of R F Parry's excavation (1927–31)	12,440±55	−18.5±0.2	5.8±0.3	54.0	3.5	26.3
OxA-17833	M.49955, *Equus ferus*, cut right 2nd phalange from Layer 14 of R F Parry's excavation (1927–31)	12,570±45	−20.7±0.2	1.1±0.3	43.7	3.2	53.5
OxA-17832	M.50024, *Equus ferus*, cut distal right metacarpal from Layer 18 of R F Parry's excavation (1927–31)	12,415±50	−20.9±0.2	1.5±0.3	43.8	3.2	42.4
OxA-12104	M.50048, *Equus ferus*, right M^1/M^2 from Layer 24 of R F Parry's excavation (1927–31)	12,495±50	−20.6±0.2	1.0±0.3	42.5	3.1	30.6
OxA-17847	M23.1/2, human, cut right scapula from lip of 'Cheddar Man Fissure' (1959)	12,565±50	−19.0±0.2	7.9±0.3	45.2	3.2	42.1
OxA-18067	GC 1986 1, *Cervus elaphus*, cut distal right tibia from top of temporary section on western edge of 'Cheddar Man Fissure' (1986)	12,245±55	−20.2±0.2	2.6±0.3	42.8	3.2	51.0

Laboratory Code	Material and context	Radiocarbon Age (BP)	$\delta^{13}C_{IRMS}$ (‰)	$\delta^{15}N_{IRMS}$ (‰)	%C	C/N_{atomic} ratio	Gelatin yield (mg)
OxA-18066	GC 1986, 27A, *Lynx lynx*, cut shaft of left femur from base of temporary section on western edge of 'Cheddar Man Fissure' (1986).	12,440±55	−19.3±0.2	4.8±0.3	43.2	3.2	15.8
OxA-17849	GC 1987 190, adult human cut calotte from Area I of the Natural History Museum excavation (1987–9)	12,590±50	−19.3±0.2	7.7±0.3	50.4	3.1	51.4
OxA-17846	GC 1987 25, bevel-based rod of *Mammuthus primigenius* ivory from Area I of the Natural History Museum excavation (1987–9)	12,470±55	−21.2±0.2	6.8±0.3	48.4	3.2	9.4
OxA-18064	GC 1989 99, *bâton percé* of *Rangifer tarandus* antler from Area I of the Natural History Museum excavation (1987–9)	12,535±55	−19.2±0.2	1.8±0.3	42.5	3.2	56.2
OxA-18068	GC 1987 191, *Equus ferus* cut cervical vertebra from Area I of the Natural History Museum excavation (1987–9)	12,520±55	−20.1±0.2	3.1±0.3	42.8	3.2	52.8
OxA-16292	GC 1987 187, *Equus ferus* cut cervical vertebra from Area I of the Natural History Museum excavation (1987–9)	12,585±55	−19.8±0.2	0.4±0.3	41.9	3.2	19.8

Archaeologists have a whole range of other information that can be included as prior information in Bayesian models. Relative dating can be provided by typological analysis of artefacts or, most commonly, by stratigraphy. This stratigraphy can be within a single site (*see* Gransmoor) or within the geomorphology of sets of related features, such as river terraces (*see* The Axe Valley at Broom). Often an archaeological site, considered in isolation, will provide limited new evidence on a particular issue. However, this evidence can contribute to larger questions in an updated chronological model of the problem at hand (*see* Marine Aggregate Licence Area 240).

The need for constant revision and rebuilding of Bayesian chronological models means that a report on chronological modelling must not only explain and justify the models presented, but also provide sufficient information to allow them to be criticised and reconstructed in the future. Reports should include:

- **Objectives of the study:** including the dating precision needed to achieve the objectives and how the objectives may have been (re)cast in the light of the available material, prior information, funding, etc.

- **Methodology:** including a statement of the approach adopted and the statistical methods and software used.

- **Sampling strategy:** including a discussion of the selection of the scientific dating techniques employed; the available prior information; the available pool of potential samples; the results of any simulation models; and the rationale by which these elements have been combined into a strategy.

- **Details of scientific dates:** see the appropriate sections of these guidelines for the information required for different techniques.

- **Model definition and description:** each model must be explicitly defined so that it can be reproduced. Most models can be defined using procedures provided by publicly-available software packages, although models that use new statistical procedures will need mathematical appendices. Prior information should be described, and its strengths and weaknesses assessed; the robustness of the associations between the scientific dates and the prior information should be considered; the compatibility of the scientific dates with each other and with the prior information should be assessed; outliers or misfits should be identified and described.

- **Sensitivity analyses:** alternative models, which vary components of a model to determine how sensitive the modelled chronology is to changes in the interpretations on which it is based.

Further information on Bayesian chronological modelling can be found in Bayliss and Marshall (2022).

4. Scientific dating methods

4.1 Radiocarbon dating

Alex Bayliss and Peter Marshall

Radiocarbon (^{14}C) is a naturally occurring radioactive isotope of carbon that is formed in the upper atmosphere when cosmic radiation interacts with nitrogen atoms. It is unstable, with a half-life of 5730±40 years. It is taken up by living organisms, but decays after death so that the proportion of ^{14}C in the dead organism decreases over time. By measuring the proportion that remains, the elapsed time since death can be estimated.

In principle any organic material that was once alive can be dated, including bone, carbonised or waterlogged plant materials, and marine shell. Radiocarbon is, however, very difficult to measure, in large part because the ^{14}C concentration in living material is extremely low (about 1 in every 1 million carbon atoms). This makes detecting a radiocarbon atom in a sample at the limit of detection (about 55 ka) equivalent to identifying a single specific human hair that might occur on the head of any of the human beings alive on earth today!

This means that it is much more difficult to date Pleistocene samples accurately than to date more recent samples (which contain more radiocarbon). This is illustrated in Table 2, which shows the impact on the reported radiocarbon age of modern contaminants on samples of different actual ages. Since the introduction of Accelerator Mass Spectrometry (AMS), which dates samples less than 1g in weight, the absolute amount of contaminant needed to cause such offsets is tiny. Such contamination can cause samples that are much earlier than the limit of radiocarbon dating to produce finite ages (Busschers et al. 2014). The pressing need to avoid or remove contamination in older samples has practical implications for how Pleistocene samples are collected in the field and processed in the laboratory.

In the field extreme care should be taken to ensure that modern contaminants such as hair or hand-cream do not come into contact with samples. Bone, antler, ivory, charcoal and shell samples should be wrapped in tin foil and placed in clearly labelled plastic bags. Irreplaceable artefacts are often sampled by specialists from the dating laboratory to minimise intervention. Sediment samples must be securely wrapped in black plastic and refrigerated as soon as possible after retrieval. Sub-sampling for radiocarbon dating, either by hand-picking macrofossils using tweezers or sieving in water, should be undertaken swiftly in a clean environment. Be particularly wary of fibres from paper towelling.

Table 2: Measured ^{14}C ages of samples of varying actual ages contaminated by varying amounts of modern carbon.

Actual ^{14}C Age (BP)	1% contamination	5% contamination	10% contamination
5,000	4,950	4,650	4,350
10,000	9,800	9,050	8,250
15,000	14,550	13,050	11,500
20,000	19,150	16,450	14,000
25,000	23,450	19,150	15,800
30,000	27,250	21,050	16,950
35,000	30,400	22,300	17,600
40,000	32,800	23,100	18,000
45,000	34,500	23,500	18,250
50,000	35,550	23,750	18,350
55,000	36,200	23,900	18,400

Macrofossils should be stored with a small amount of water in a glass vial with a screw lid that has a foil liner and refrigerated. For all potential samples, organic consolidants, fungicides, etc. must be avoided.

Research continues to be undertaken on refining the chemical procedures used for preparing Pleistocene samples for radiocarbon dating. Ultrafiltration of gelatin extracted from bone, antler and ivory samples of this age is now routine (Brown et al. 1988; Jacobi et al. 2006), although other methods are also under development (Linscott et al. 2024; Deviese et al. 2018). Improved accuracy may also be obtained by implementing more complex pretreatment for charcoal samples (Bird et al. 1999; Ascough et al. 2009), and refined pre-screening and preparation methods for ornaments made from marine shell (Douka et al. 2010).

Materials selected for dating must not only contain sufficient carbon and be uncontaminated, but they must also have a secure association with the human activity or environmental event that is the target of the dating programme. Precision may be improved if sequences of related samples can be obtained (Bayesian Chronological Modelling). Given the technical difficulties of accurate radiocarbon dating in this period, replicate measurements should be undertaken where sufficient material is available. Suitable datable material is often scarce on Pleistocene sites, but it is essential that the reliability of the chronologies of this period are not undermined by dating unsuitable material simply through the lack of better samples.

The following information must be published for each radiocarbon measurement:

- details of the facility/facilities that produced the results and how samples were pretreated, prepared for measurement, and dated;

- details of the radiocarbon results and associated measurements and how these have been calculated;

- details of the material dated and the context from which it came.

Bayesian Chronological Modelling provides examples of the information that should be provided for each radiocarbon date. Note that at the limit of the technique some radiocarbon ages may be quoted with asymmetrical error terms (for example, GrN-12876 from Lynford Quarry, which produced an age of $35{,}710 \pm^{930}_{830}$ BP); others may produce minimum ages (for example OxA-11572 also from Lynford Quarry, which produced an age of >49,700 BP).

Radiocarbon calibration is now undertaken using a set of internationally-agreed calibration curves that extend back to 55,000 cal BP. Terrestrial samples from the northern hemisphere should use IntCal20 (Fig. 11; Reimer et al. 2020) and marine samples should be calibrated using Marine20 (Heaton et al. 2020) with an appropriate local ΔR (‘Delta R’) correction (*see* Bayliss and Marshall 2022, section 1.6). All radiocarbon results within this range should be calibrated, and details published of the calibration protocols used, including any reservoir corrections employed. Calibration in this period is, however, likely to be subject to significant refinement over the coming decades, so it is essential that laboratory codes and uncalibrated radiocarbon ages are also published to enable them to be recalibrated with new calibration curves in due course.

Where Bayesian Chronological Modelling is employed, calibration is simply part of the modelling process and it may be more appropriate to quote posterior density estimates rather than simple calibrated date ranges.

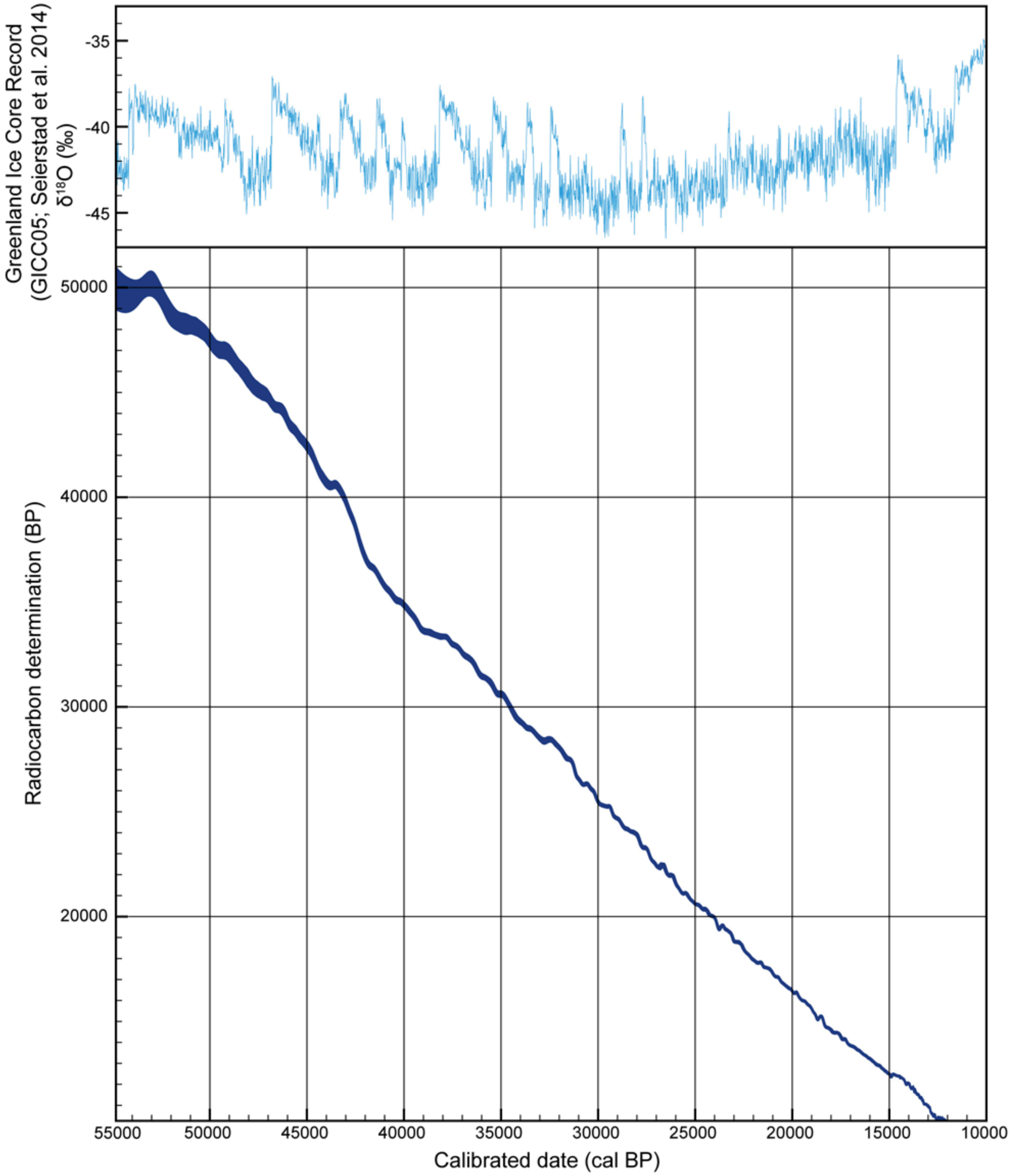


Figure 11: Radiocarbon calibration curve for atmospheric samples from the northern hemisphere, IntCal20 (Reimer et al. 2020), plotted against the Greenland Ice Core record.

4.2 Uranium-Thorium dating

Alistair Pike

Uranium-Thorium (U-Th) dating exploits the build-up of the isotope ^{230}Th (itself radioactive) from the decay of ^{238}U to ^{234}U to ^{230}Th, within the Uranium-series radioactive decay chain. Over time, the activity ratio $^{230}Th/^{238}U$ builds up until radioactive equilibrium is reached, which gives a practical older limit to the method of around 500 ka. The younger limit is constrained by our ability to measure low abundances of ^{230}Th. This depends on the sample size and its Uranium concentration, but dates typically can be produced on samples a few centuries old.

The technique is suitable for calcium carbonate (calcite) precipitates such as stalagmites, stalactites and flowstones (collectively known as speleothems), and for travertines and tufa (for example Richards and Dorale 2003). Speleothems can occur associated with archaeology in cave deposits, and travertine and tufa occasionally in open air sites.

The error on a U-Th date depends on its age. Under ideal circumstances, measurements of the isotopic ratios using modern mass spectrometric methods can be made to less than ±0.5% (at 2σ), which can lead to uncertainties of less than 100 years in 10 ka. But as the sample age approaches the limit of the method, the errors can get far larger. For example, a 0.5% measurement error (on each isotopic ratio) translates to errors of ±1.2 ka at 100 ka and of $\pm^{40}_{31}\,\mathrm{ka}$ at 400 ka. Note that the errors are noticeably asymmetrical towards the limit of the technique.

Problems are commonly encountered from detrital contamination of the calcite (for example by cave sediments and particulates). Not correcting for such contamination would lead to older apparent dates. The level of detritus is monitored by measurement of the common isotope of Thorium, ^{232}Th, usually expressed as the activity ratio $^{230}Th/^{232}Th$. High values (for example >100) indicate low levels of contamination, whereas values <5 indicate severe contamination.

For low and moderate levels of contamination a correction can be applied using an assumed $^{230}Th/^{232}Th$ ratio for the detritus with a large uncertainty propagated to the calculated date. For highly contaminated samples, the errors on corrected ages may become so large that the dates are not useful. An alternative strategy is to take multiple same-age samples (for example from a single growth layer of speleothem) to construct an ‘isochron’ to correct for detritus. Again, the errors will increase, sometimes drastically.

An additional, though apparently rare, problem is the leaching of Uranium or Thorium from the calcite (open-system behaviour), which can give older or younger apparent dates. Where this is suspected, speleothems can be sampled sequentially along their growth axis. U-Th dates not conforming to their stratigraphic order may indicate open-system behaviour.

When selecting samples, it is worth noting that dates on calcite are only indirect dates for the associated archaeology, but can provide maximum, minimum or bracketing ages for archaeological deposits (Table 3). Securely demonstrating the stratigraphical relationship between the samples dated and the archaeology is of utmost importance.

When taking samples, it is worth considering the worst-case scenario: that the samples will be detritally contaminated and possibly be open system. Samples should be taken that are suitable for multiple sub-sampling in the laboratory. This will enable the construction of an isochron and/or checks for any open system behaviour, even if these steps are not eventually required.

An ideal sample would be the complete sequence of growth layers of a flowstone floor that formed directly over or between two archaeological layers. These can be detached as a block, cut with a grinder or cored with a coring drill (Fig. 12). Photographic and other documentation of the position of the sample, and especially its relation to archaeological layers, is essential, as well as is indicating the uppermost (youngest) layer on the sample. Where speleothem formation is very active, long sequences of samples bracketing different layers can produce detailed chronologies for sites (for example Hoffmann et al. 2013). Sample storage is straightforward and can be in individual plastic bags, or for small samples, clean plastic tubes.

Occasionally, it is not possible to remove complete samples without undue damage to the archaeology or to the cave (for example in the case of calcite deposits on top of cave paintings; Pike et al. 2012). In these cases, the calcite should be sampled in situ. This provides fewer opportunities to control for open-system behaviour and increases the potential for contamination from the sampling equipment and other complexities, so it is best to consult with a specialist and arrange for them to take the samples.

The minimum required data for reporting a U-Th date are:

- sample code;
- laboratory code;
- U concentration;
- $^{234}U/^{238}U$ ± error;
- $^{30}Th/^{238}U$ ± error;
- $^{230}Th/^{232}Th$ ± error;
- uncorrected U-Th age ± error;
- corrected U-Th age ± error.

Table 3: Example of calcite sample suitable for U-Th dating.
For the hypothetical archaeological layers, A overlies B.

Type of sample	Date implications
Flowstone floor overlying layer A	Minimum age for layer A
Flowstone floor between layer A and B	Minimum age for layer B, maximum age for layer A
Flowstone floor underlying layer B	Maximum age for layer B and by implication layer A
Detached stalactites in layer B	Maximum age for layer B
Calcite encrustation on cave painting	Minimum age for cave painting
Calcite encrustation on human skull	Minimum age for skull
Stone tool embedded in travertine	Bracketing age for tool
Stalagmite growth on rock-fall blocking cave entrance	Minimum age of closure of cave

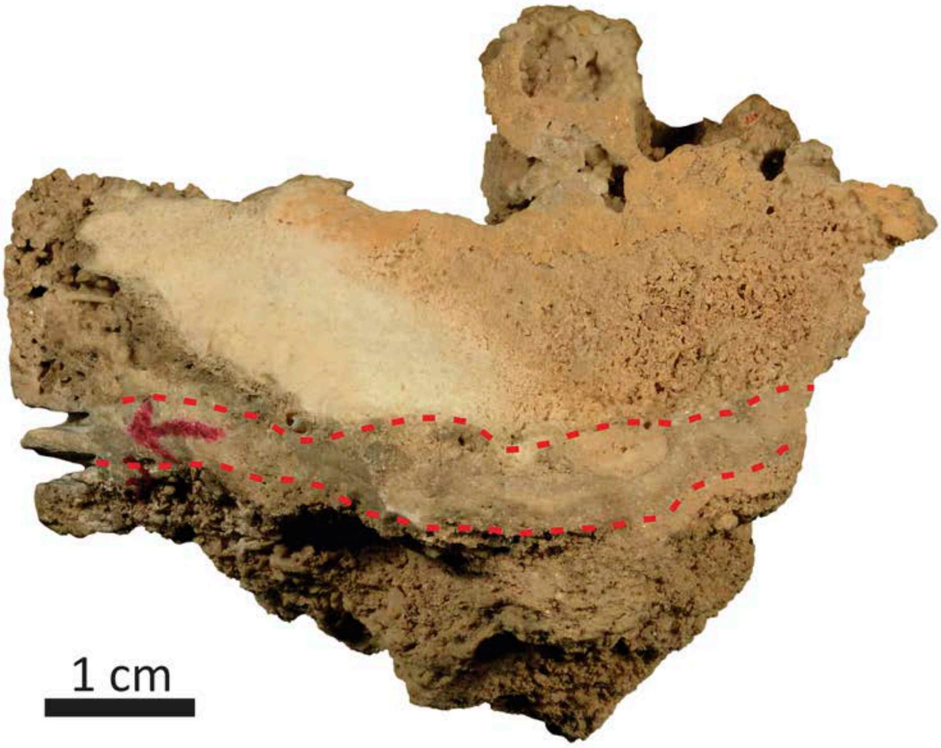


Figure 12: A block of breccia with flowstone removed from Church Hole Crypt, Creswell Crags.
The red lines show the approximate location of a relatively clean crystalline flowstone lying within breccia. Two samples were removed using a diamond cutting disk from layers at the top and bottom of the flowstone (left). The dates constrain the age of the archaeology found in the layers below. [Photograph by A Pike]

There is no convention on reporting ages relative to a datum, though BP (before AD 1950) has been used, as has b2k (before AD 2000), but most commonly no datum is stated and the date is assumed as years before the publication date. Dates are in calendar years and do not require further calibration. In addition, provide the half-lives used (or published source) for the date calculations, along with details of the method of correcting for detrital contamination and the ratios used.

If isochron dating is used, include a graphical plot of the isochron and associated statistics (as produced by software such as Isoplot), either in the publication or as supplementary information.

4.3 Luminescence dating

Geoff Duller

Luminescence dating methods use naturally occurring minerals to calculate the time since a sample was last exposed to daylight or was last heated above about 250°C (Duller 2008). It has become a key geochronological method for studies of the Middle Palaeolithic, especially in Africa, Australasia and Europe (for example Jacobs et al. 2008; Roberts et al. 2015).

When minerals such as quartz and feldspar are exposed to radioactivity from the natural environment, a small proportion of the energy is stored in the crystal structure. At some later date, the energy can be released and produces light; this is the luminescence signal used for dating (Fig. 13).

There are several luminescence dating techniques, based on different minerals and different signals. Quartz dating using optically stimulated luminescence (OSL) has been well established since 2000. Infrared-stimulated luminescence (IRSL) from feldspars has become established since 2008. This has led to the development of post-infrared IRSL methods (pIR-IRSL).

Other luminescence signals are also available, each with different strengths and weaknesses. For instance, infrared radiofluorescence (IR-RF) and infrared photoluminescence (IRPL) from feldspars have been developed, as has the use of the TL signal from biogenic calcite. These methods, however, are still in the early stages of development and application (e.g. Key et al. 2022; Duller and Roberts 2018). Advances in methodology are constantly being made and close collaboration with a laboratory is strongly recommended.

Luminescence methods can date the last time that the mineral grains in a sediment were exposed to daylight (optically bleached). This is normally when the sediments were deposited by a river, by the wind or by some other geomorphological process. When the mineral grains are exposed to daylight any energy stored in them is released, and this sets the 'clock' to zero. Once mineral grains are buried by further deposition energy starts to accumulate within them, and this continues until they are collected for measurement.

Sediments suitable for dating should contain either fine silt (4–11μm) or sand grains (90–300μm). Aeolian sediments are ideal (Text Box 5), but fluvial and some colluvial materials are also suitable, especially with the use of single-grain luminescence methods. The key consideration is whether there is a high probability that the mineral grains were exposed to daylight at or before deposition. Also consider the mixing of deposits through processes such as bioturbation or coversand reactivation.

The speed with which signals are bleached varies between different signals. Generally, the OSL signal from quartz bleaches the quickest and is therefore best suited to a situation where bleaching at deposition may have been limited. IRSL from feldspars bleaches more slowly; and pIR-IRSL and IS-RF signals bleach slower still.

Luminescence dating can also be used to date the last heating of stones and flints. Heating to more than about 250°C will release the energy stored in the mineral grains. Hearth stones, or flints that have been inadvertently burnt in hearths, have been targeted from Palaeolithic sites (for example Preece et al. 2007; Richter 2007).

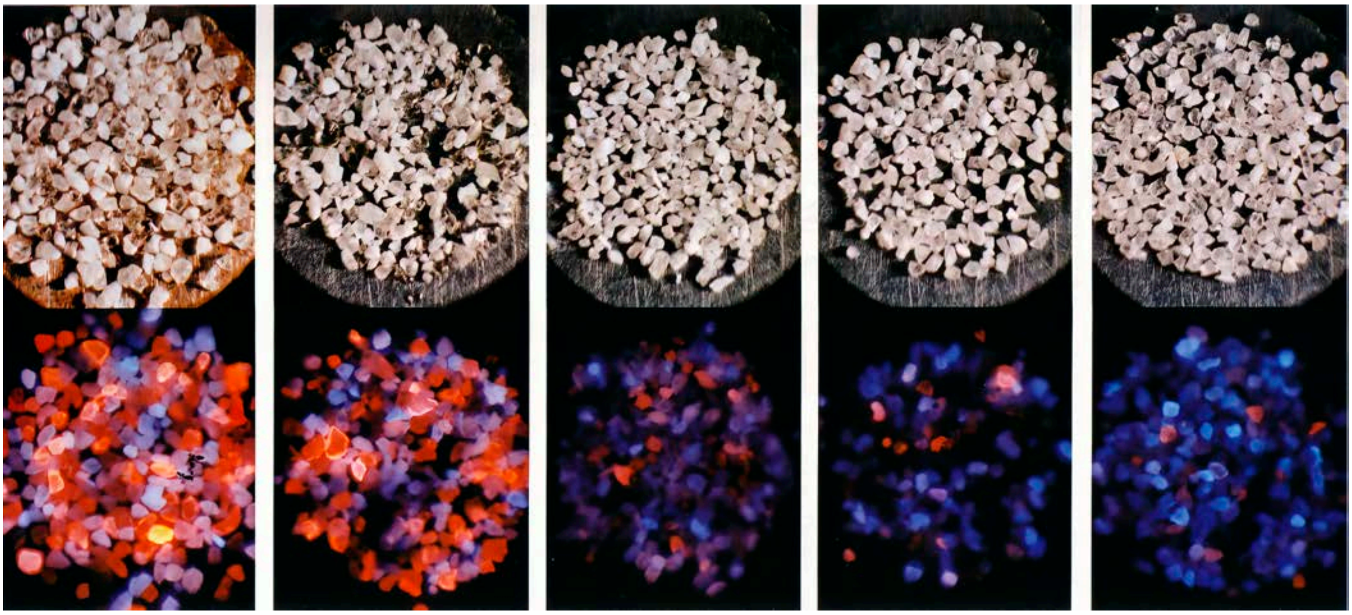


Figure 13: The upper row of photographs are sand-sized grains of quartz (*c.* 0.2mm in diameter). The lower row of photographs shows the luminescence signal emitted from these grains after they were exposed to radioactivity. [Photography by G Duller, © Aberwystwyth University]

Text Box 5: Aeolian deposits

Aeolian deposits are sands and silts that are eroded, transported and deposited by wind. Two main types of Pleistocene aeolian deposits are encountered in England: coversands and loess.

Coversands are Late Devensian periglacial aeolian sand deposits that form as relatively flat and thin mantles over older deposits. They are found predominantly in Lancashire, Yorkshire, North Lincolnshire and the Brecklands of East Anglia.

Loess is composed of the silt-sized component that was transported during periglacial conditions and deposited in cold steppe environments, and is found across southern and southeast England.

Brickearth is a third type of deposit commonly attributed to aeolian activity. It is a 19th century term relating to a fine-grained, largely stoneless superficial deposit usually with a silt-rich component, often reworked through colluvial, fluvial or solifluction processes. Brickearths are regularly found in river terraces, sometimes associated with rich Lower and Middle Palaeolithic sites.

Some aeolian deposits are formally recognised as sedimentary or stratigraphic units. Aeolian deposits are often well bleached at deposition and have grain sizes particularly suitable for luminescence dating. Studies show that these usually date from the Last Glacial Maximum (GS-2) and Younger Dryas (GS-1), though some pre-Devensian deposits are also known.

Some Late Devensian aeolian deposits seal palaeosols, peats or alluvial deposits from the pre-MIS 2 or Windermere Interstadial (GI-1). The Windermere Interstadial sometimes contains in situ Late Upper Palaeolithic open air sites, such as Farndon Fields in Nottinghamshire (Harding et al. 2014; Garton et al. 2020), Nea Farm in Hampshire (Barton et al. 2009) and Hengistbury Head in Dorset (Barton 1992).

Dating these archaeological sites has proven to be challenging, especially if there has been any post-depositional disturbance of the overlying aeolian deposit, which can produce a mixed assemblage of pre-burial, well-bleached grains alongside introduced younger grains, possibly due to bioturbation, pedoturbation or sand reactivation (Garton et al. 2020); such sites therefore require careful application of luminescence dating.

Samples for luminescence dating can be collected by non-specialists, but it is preferable for a luminescence practitioner to do this. The luminescence signals used for dating are sensitive to light, and thus samples must be collected in such a way that daylight is excluded. Red light, such as that from the LEDs used for rear bicycle lights, does not affect the signal, and can be used where limited illumination is needed during sampling.

For sediments a common method of sampling is to hammer a metal or plastic tube (typically 30–70mm in diameter and 150–200mm in length) into the sedimentary unit. The ends of the tube should be packed with plastic and sealed using tape to avoid movement of the sample during transportation to the laboratory, and to avoid moisture loss. If this way of collection is not possible an alternative method is to use a large sheet of black plastic to exclude daylight from the section and to collect the sample in an opaque bag using a trowel.

Intact borehole and vibrocore sequences can also be sampled for luminescence dating in the laboratory, as long as they have been retrieved and stored appropriately and sediment shielded from light is available.

Measurement of a luminescence signal from sediment can now be made with portable OSL instruments, which may enable differentiation of sediments of radically different ages. The equipment currently available is, however, unable to replicate the procedures undertaken in the laboratory. The signals obtained are complex to interpret and commonly need to be used in tandem with laboratory measurements.

To calculate an age, luminescence measurements are made to calculate the total dose received by the sample during burial (known as the equivalent dose (D_e) or palaeodose. Separate measurements are needed of the natural radioactivity at the site. This enables determination of the amount of energy delivered to the sample per year (known as the dose rate). The age is calculated by dividing the equivalent dose by the dose rate.

Some dose rate measurements can be made in the laboratory, but in situ measurements using a gamma spectrometer are preferable, especially where sediments of differing radioactivity occur (Fig. 14). Where in situ gamma spectrometry is not possible it is important to consider whether the nature of the sediments varies within 300mm of the sample. Where large variations are seen, sub-samples of the different sediments should be collected for dose rate measurements in the laboratory, and their location relative to the luminescence sample noted. These dosimetry samples can be exposed to daylight since they will not be used for luminescence measurements. In addition, the thickness of the overburden should be noted, and an estimate of the water content during burial will be required.

For burnt objects, shield the artefact from as much light as possible; complete exclusion of light is unnecessary, as the inside of the artefact is normally used for measurement. Collect a representative sample of the sediment surrounding the artefact along with the artefact. The same issues about measurement of the gamma dose rate apply for burnt samples as they do for sediments.

Luminescence can be used to date events from decades to more than 100 ka. The upper limit is determined by saturation of the luminescence signal — the point at which no additional energy can be stored in the mineral grains (Duller 2008). This varies from one sample to another, from one mineral to another, and is dependent on the dose rate.

It is common to be able to date to 100 ka, not unusual to be able to reach 200 ka, and ages of 400 or 600 ka are feasible. Feldspars are often able to date older samples than quartz, but this comes at the cost of greater methodological uncertainty as feldspar methods are more complex. Precision better than 5% (at 1σ) is normally unrealistic because of uncertainties in the dose rate. At ages of 100 ka and above, uncertainties of 10% are common.

Figure 14: Three samples for luminescence dating have been collected from this section at Broom using plastic tubes. On the right, a portable gamma spectrometer is measuring on-site radioactivity. [Photograph by R Hosfield]

Ages are normally given in kilo annum (ka) before the date of measurement. No agreed datum exists for luminescence ages, but it is good practice to report the date when a luminescence age was measured (Brauer et al. 2014). When reporting luminescence ages avoid using the term ‘BP’, which is used for radiocarbon ages.

Supporting information required for luminescence ages includes:

- the sample code;
- the laboratory code;
- the mineral and analytical method used for luminescence measurement;
- details of any statistical analysis of the luminescence data;
- the equivalent dose (D_e) for the sample.

Show on a radial or an Abanico plot if combining multiple D_e values to obtain the final age. It is also good practice to publish an example of the dose response curve (the growth of the luminescence signal with laboratory radiation) to illustrate whether the signal is close to saturation.

Include details of which methods were used to measure the dose rate, the water content used in calculation, the individual dose components (alpha, beta and gamma) and the cosmic dose rate.

4.4 Amino Acid Racemisation

Kirsty Penkman

Amino Acid Racemisation (AAR) dating relies on the time-dependent breakdown of proteins (and their constituent amino acids) in fossils such as shells. It covers the date range from 10 years ago up to as long ago as 3 Ma, and thus is applicable to the whole of the Quaternary. However, it is most useful in the British context for dating Palaeolithic sites and Pleistocene deposits older than *c.* 40 ka. A simplified overview of the technique is given below; further details can be found in Lowe and Walker (2015, 332–9).

Amino acids are the building blocks of proteins. They are found in all living tissues and can be preserved in fossil biominerals such as shells or coral. Most amino acids can exist in two forms, which are non-superimposable mirror images of each other (Fig. 15), and are designated left-handed (laevo, L-form) and right-handed (dextro, D-form). In living organisms, proteins are almost exclusively made from the L-form.

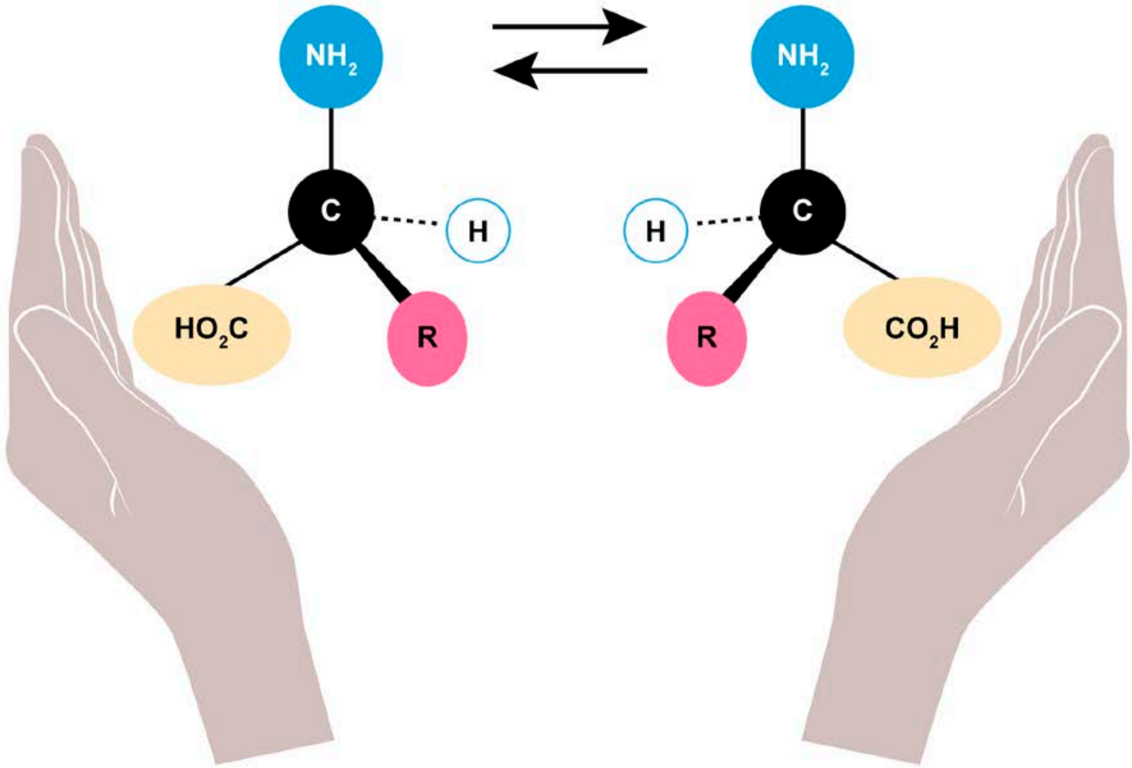


Figure 15: Most amino acids have no plane of symmetry, just like hands, so their mirror images are non-superimposable and therefore distinct. The breakdown of left-handed molecules to the right-handed form over time provides a mechanism for estimating the age of fossil material. [Modified from Crisp 2013]

After death, however, a spontaneous reaction starts called racemisation. This leads to a progressively increasing proportion of the D-form in direct relation to the time elapsed, until the D and L forms are present in equal quantities. Depending on the amino acid, this process can take thousands or millions of years and therefore is applicable over Quaternary timescales (Fig. 16a).

Different species break down at different rates, so analyses are undertaken on monospecific samples (usually individual mollusc shells, 1–5mg in weight). The extent of amino acid racemisation (AAR) in a sample is recorded as a D/L value, and its age can thus be determined based on (a) which amino acid it is, (b) the species (of mollusc or other biomineral) being analysed, and (c) a baseline reference framework of comparative data from independently dated sites (an aminostratigraphy).

Protein degradation consists of a series of chemical reactions that are dependent not only on time, but also on environmental factors (such as pH, availability of water), which can confound the time signal. These difficulties in AAR's early applications have led to a focus on analysing 'closed-system' protein from fossil samples (Towe 1980) — those where the fraction of protein analysed is physically or chemically shielded from the environment. The chemically isolated 'intra-crystalline' fraction found in some biominerals forms such a closed system, meaning that the AAR within this fraction is solely time and temperature dependent, and therefore predictable (Penkman et al. 2008; Dickinson et al. 2019; 2024). This technique has been particularly successful in dating carbonate and phosphate fossils (shells, tooth enamel, eggshells, foraminifera, ostracods, earthworm granules) and long-lived biominerals (corals). It can be used to provide age information within an individual sample (Hendy et al. 2012).

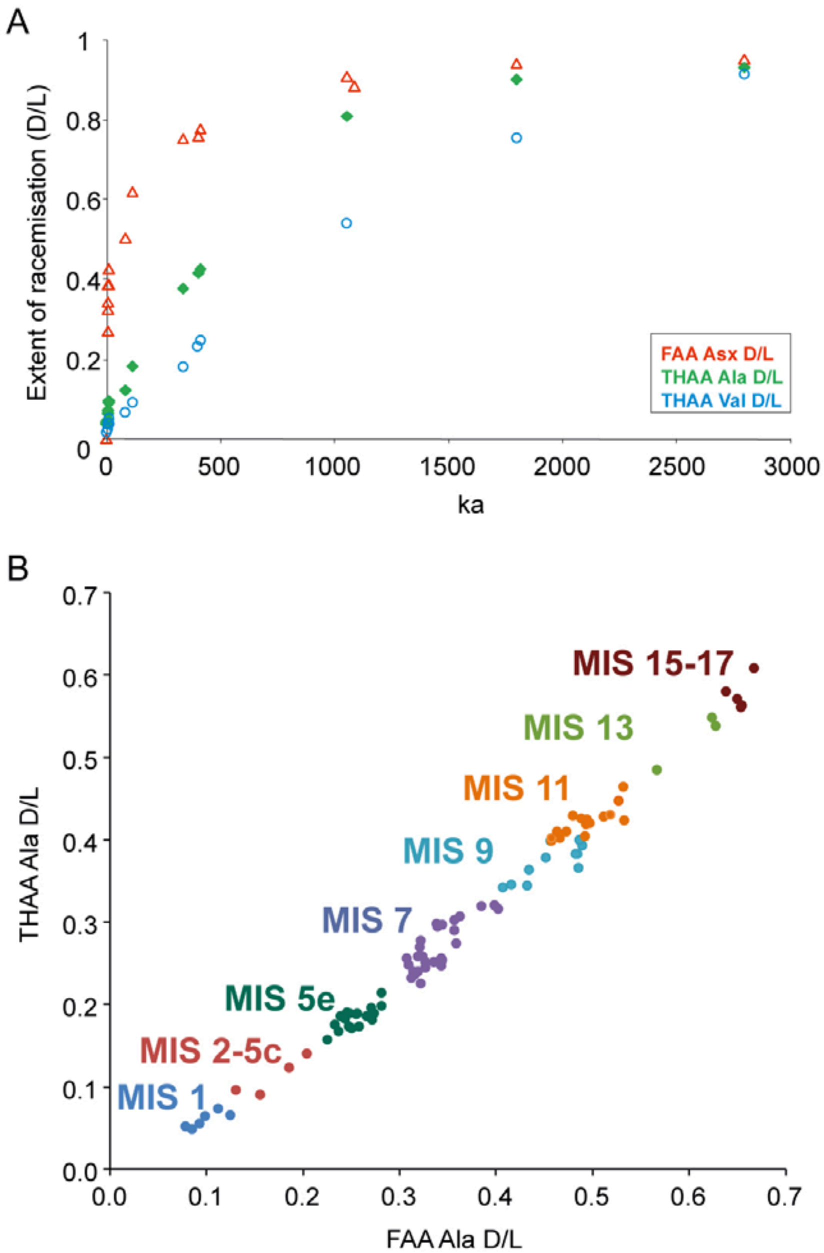


Figure 16: (A) The increase in racemisation in *Bithynia* opercula with age for the free amino acid (FAA) aspartic acid (Asx) and the total hydrolysable amino acids (THAA) valine (Ala) and alanine (Val); (B) mean THAA D/L vs FAA D/L for alanine in *Bithynia* opercula from British sites, with colours representing the independent evidence of age for each site. [Modified from Penkman et al. 2011]

AAR laboratories have developed dating frameworks for a large number of commonly-occurring ‘closed-system’ species, but tests can be undertaken on additional species to examine whether they would be suitable for AAR dating. In a British Palaeolithic context, the most suitable materials for AAR dating are tooth enamel, *Bithynia* opercula (Fig. 17) and *Bithynia*, *Valvata*, *Littorina*, *Nucella*, *Patella* and *Pupilla* shells. The crystal phase of calcite biominerals (such as opercula or eggshell) are more stable over longer timescales and are therefore preferred for sites of Early and Middle Pleistocene age.

The rate of breakdown towards D/L equilibrium in the intra-crystalline fraction is still affected by temperature, so comparative frameworks need to be applied from regions with a broadly similar temperature history. For instance, it is not appropriate to compare D/L results from tropical material to a framework based on sites from southern England, but any material from England can be interpreted within the same comparative framework. In Britain analysis of amino acids in *Bithynia* opercula can be used to correlate deposits with the Marine Oxygen Isotope stages (Fig. 16b), to a sub-MIS level for at least the Late Pleistocene (Penkman et al. 2011).

A non-specialist can collect material and/or sediment samples in the field. Sometimes molluscs, teeth or other suitable remains will be directly visible, but as it is not always possible to tell whether a sediment body contains suitable material for AAR dating, it may be necessary to collect a preliminary sample and then subsequently assess its potential for AAR dating.

Material for AAR dating is typically collected from wet-sieved residues of sediment samples. The only special sampling and pretreatment considerations are that the temperature-dependence of the racemisation reactions means it is important that any material submitted for dating has not been treated in any way that compromises its temperature history. For example, do not sieve with hot water or dry in an oven. Suitable material for AAR dating in the residues can be identified to species level (e.g. vertebrate or mollusc) by a faunal specialist or by the AAR laboratory.

Analyses are routinely undertaken on the total hydrolysable amino acid fraction (THAA, which includes both free and peptide-bound amino acids), and often also on the free amino acid fraction (FAA, produced by natural hydrolysis). AAR laboratories tend to issue results in a report, with laboratory codes identifying samples, the relevant D/Ls and concentrations where appropriate. These data should be included in any publications, and it is also important to publish full sample information (including species), provenance information on the dated material and the provenance of material contributing to the reference framework.

Figure 17: *Bithynia tentaculata* (L.) operculum. [Photograph by E. Nelson]

4.5 Palaeomagnetism

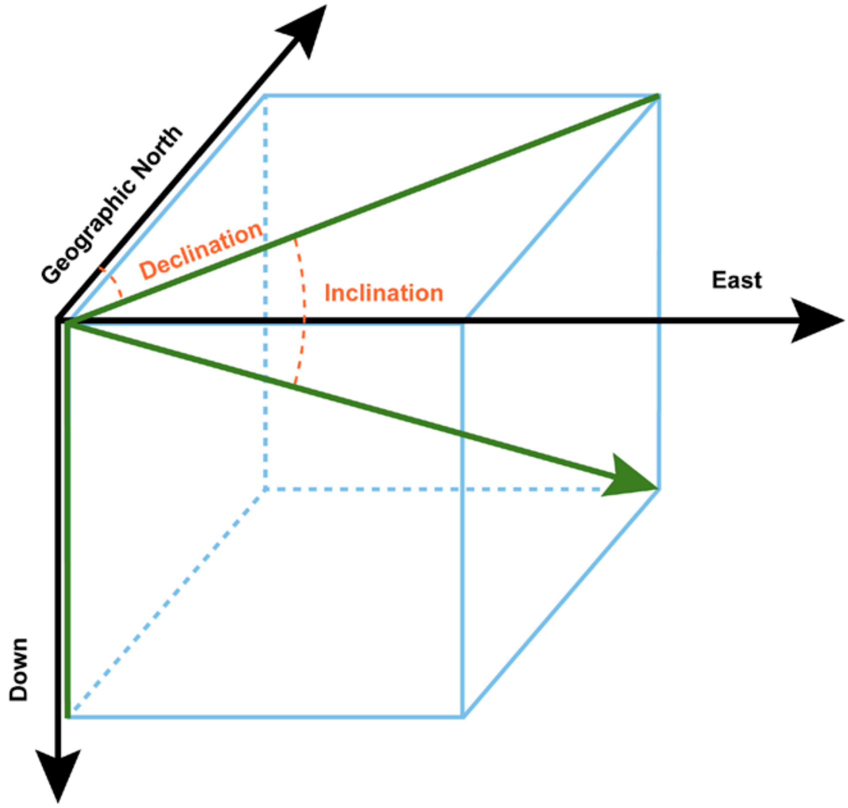
Chuang Xuan

The Earth's magnetic field intensity and direction are constantly changing at various temporal and spatial scales. Beyond historical observations of the last few hundred years, our knowledge of past field behaviour is mainly derived from natural remanent magnetisations (NRM) preserved in geological and archaeological archives. These archives record palaeomagnetic field information mainly through two mechanisms: igneous rocks (e.g. lava, volcanic glass) and fired archaeological features acquire NRM through thermal remanent magnetisation (TRM). This is when magnetic minerals cool from high temperatures to below the Curie point, locking in a magnetic signature. In contrast, sedimentary rocks formed in a marine or lake environment record palaeomagnetic field information through (post) depositional remanent magnetisation (DRM). This is when magnetic particles in the sediments align themselves to the ambient magnetic field during or shortly after sediment deposition.

Palaeomagnetism has been widely used for dating Pleistocene sedimentary sequences. The process typically involves the measurement of palaeomagnetic directions and/or intensity preserved within stratified samples, which are then compared to well-dated palaeomagnetic reference records (Hounslow et al. 2022).

Reversals in the Earth's magnetic polarity (swapping of north and south poles), referred to as chron and sub-chron boundaries, provide a key method for correlating and dating sedimentary sequences worldwide (e.g. Opdyke et al. 1966). Changes in polarity within a sedimentary sequence are identified by measuring the NRM directions: declination and inclination (Fig. 18). The measured chron pattern of a sedimentary sequence is then compared with a geomagnetic polarity time scale (GPTS) which provides ages for when corresponding reversals occurred.

Figure 18: Definition of declination and inclination of a remanent magnetisation signal.



Interpretation of a magnetic polarity record often requires verification from other independent dating methods (e.g. biostratigraphy, Marine Oxygen Isotope curves; Happisburgh 3), especially when the top of a sequence does not have a modern age, or when a sequence contains a hiatus. Any significant geological rotation or tilting caused by tectonic events should also be considered, but these are usually negligible for Pleistocene-aged sequences. The resolution and accuracy of palaeomagnetic dating based on geomagnetic polarities is determined by the number of reversals available and on uncertainties associated with the age of these reversals in the GPTS. For the Pleistocene, the major reversal is between the Matuyama and Brunhes chrons (*see* Fig. 19). Subchrons represent shorter-term reversals lasting tens or hundreds of thousands of years. GPTS ages for all Pleistocene reversals have been calibrated by astrochronology (*see* Ogg 2020) and should have uncertainties of less than 10–20 ka.

The more frequent geomagnetic excursions are defined as brief (<10 ka) events during which geomagnetic poles significantly deviate (up to 45°) from the background pole positions (Fig. 19), though high-resolution studies indicate that at least some excursions are associated with 180° directional changes that lasted a few hundred to a few thousand years (Laj and Channell 2015).

Polarity reversals and geomagnetic excursions provide detailed insights into the Earth's magnetic field behaviours and offer valuable opportunities for correlation and the establishment of isochrons for Pleistocene sedimentary sequences around the globe. NRM preserved in sediments records not only reversals and excursions, but also detailed changes in field strength and directions. These can be reconstructed through estimates of relative palaeointensity (RPI) and through palaeo-secular variations (PSV).

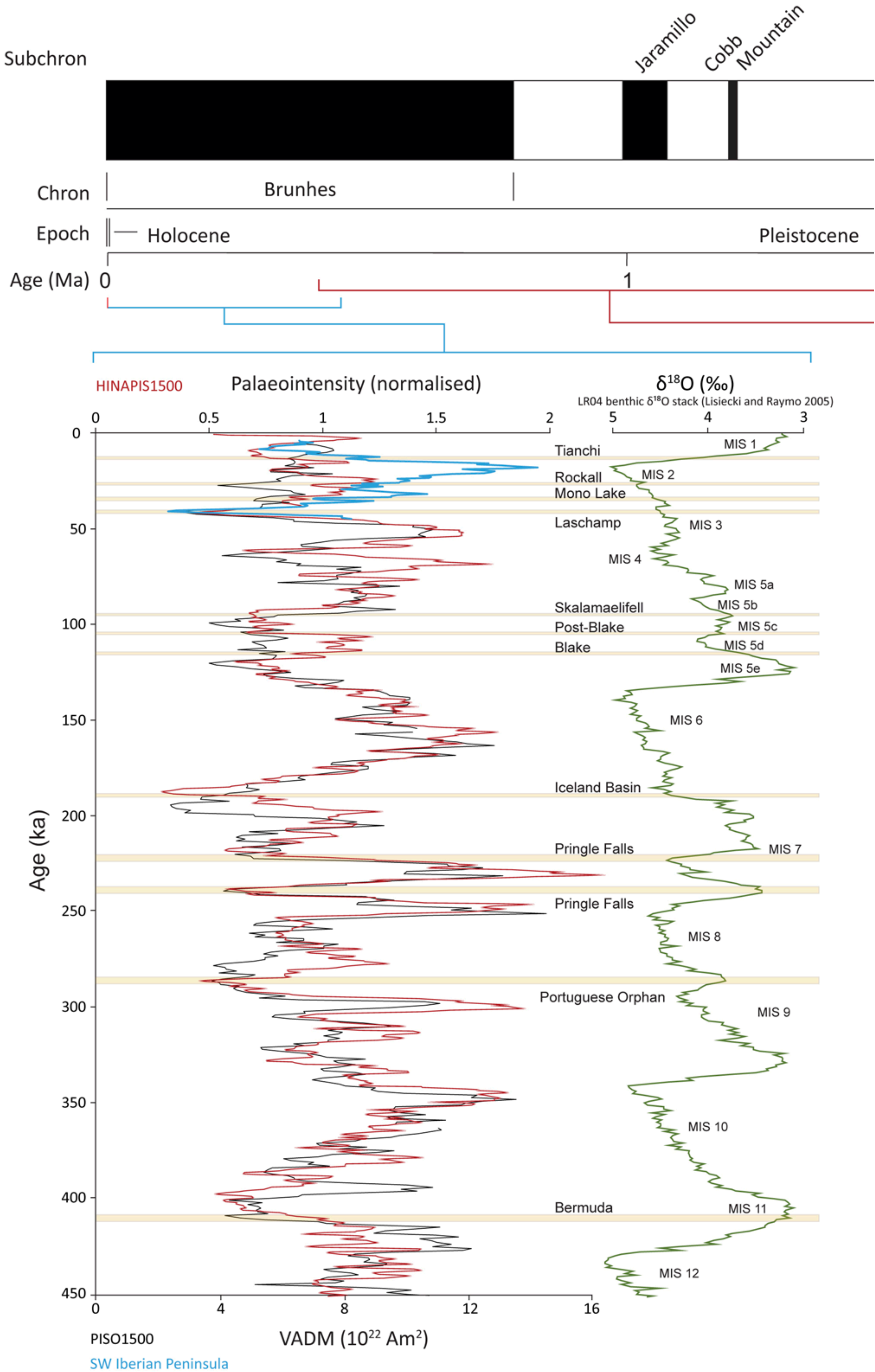
RPI records are usually constructed by normalising NRM of a sample by laboratory-introduced magnetisation to compensate for the ability of the sample to acquire magnetisation. Various criteria have been proposed to ensure the quality of the RPI records (e.g. Tauxe 1993). RPI records constructed from different worldwide sedimentary sequences appear to record a dominantly dipolar geomagnetic signal and are generally coherent at a scale of a few tens of thousands of years. These RPI records can also be correlated to palaeointensity changes estimated using other methods, such as cosmogenic nuclides (e.g. Simon et al. 2016; Text Box 3) and marine magnetic anomaly profiles (Gee et al. 2000). Geomagnetic polarity reversals and excursions are usually associated with dominant lows in RPI records.

The use of RPI to constrain the chronology of a sedimentary sequence is usually referred to as palaeointensity-assisted chronology (PAC). Detailed RPI stack records that can be used as global or regional templates now span the entire Pleistocene (e.g. Valet et al. 2005; Yamazaki and Oda 2005; Channell et al. 2009) (*see* Fig. 19, bottom). In addition, PSV (i.e. declination and inclination) records have also been widely used to provide centennial-millennial scale age constraints, especially for late Pleistocene and Holocene sequences. These usually compare the PSV records to a regional reference curve or geomagnetic field model prediction for a location (e.g. Avery et al. 2017).

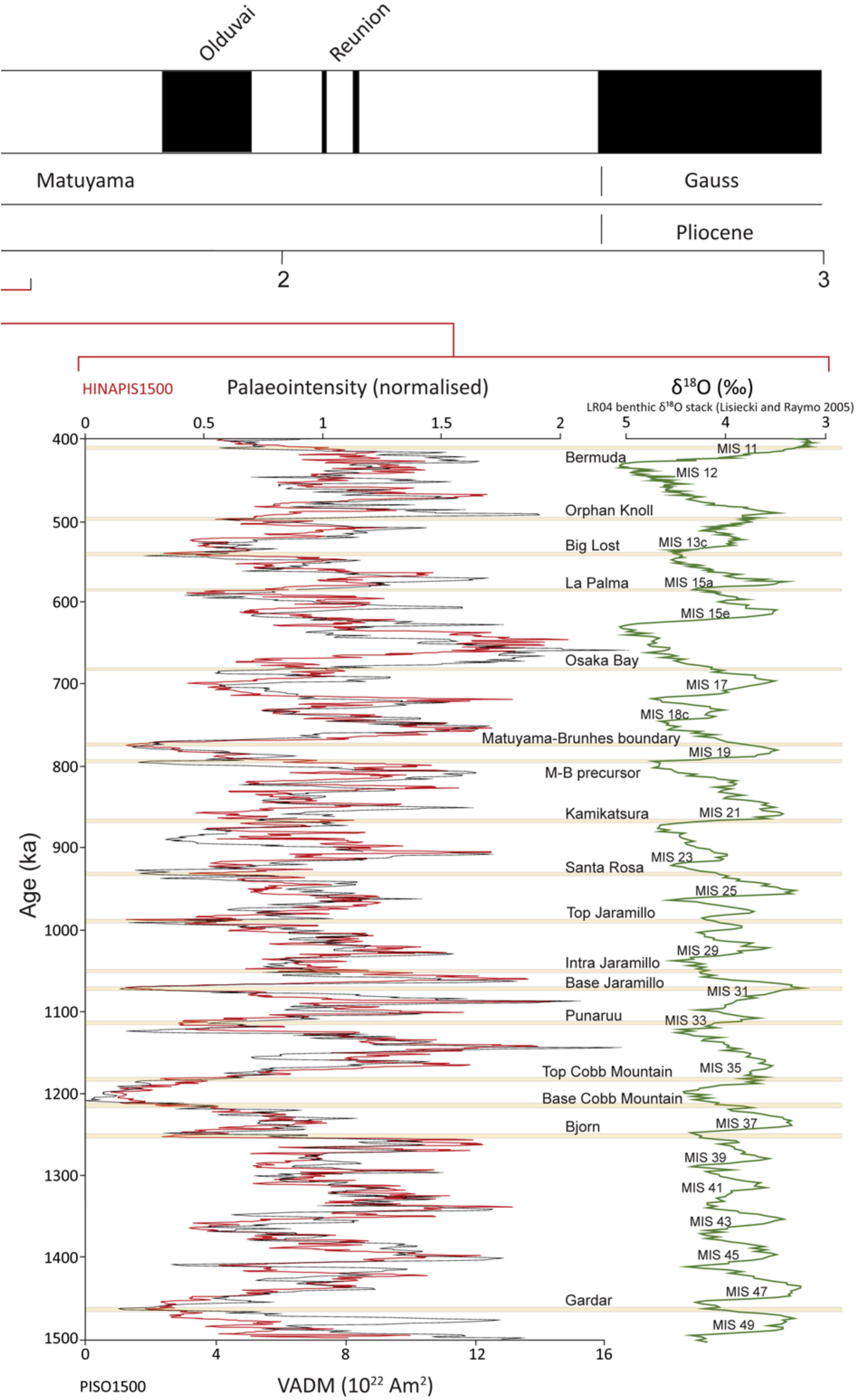
Samples used for palaeomagnetic dating are typically oriented according to their dip and strike directions (i.e. deviation and angle from horizontal plane). Samples are taken as discrete cubes or cylinders (Fig. 20a), or as continuous U-channel sections (Fig. 20b) marked with a reference orientation (true north, direction of top of sample). For core samples where orientation is difficult to track during coring, a straight reference line should be marked on the core liner to guide subsequent cutting and splitting of the core and to facilitate declination corrections later on. Sediment samples are typically enclosed in plastic containers and stored in a fridge (set to ~4°C) away from strong magnetic sources to suppress any physical or chemical alternations.

Measurement of NRM and laboratory-introduced magnetisations of the samples are often conducted on a superconducting rock magnetometer capable of resolving weak magnetisations (i.e. 10-5 A/m level) (Fig. 20c). Samples are usually measured before and after stepwise heating or alternating field (AF) demagnetisation treatment to remove secondary magnetisations presumably carried by magnetic minerals with lower blocking/unblocking temperatures or lower coercivity.

Figure 19 (pages 47–48): Palaeomagnetic polarity for the Pleistocene, showing the named chrons and subchrons indicated by black and white bars. The relative paleointensity record is shown below it, expressed as virtual axial dipole moment (VADM) or normalised palaeointensity, for the last 1.5 Ma, with geomagnetic excursions indicated by horizonal lines (from Channell et al. 2020 and Ogg 2020). Reference records for the palaeointensity-assisted chronology profiles shown are PISO1500 (Channell et al. 2009), HINAPIS1500 (Xuan et al. 2016) and NW Iberian Curve (Channell et al. 2018), plotted against the Marine Oxygen Isotope record.



Subchron
Jaramillo
Cobb Mountain
Chron
Brunhes
Epoch
Holocene
Pleistocene
Age (Ma)
0
1
HINAPIS1500
Palaeointensity (normalised)
δ18O (‰)
LR04 benthic δ18O stack (Lisiecki and Raymo 2005)
Tianchi
Rockall
Mono Lake
Laschamp
Skalamaelifell
Post-Blake
Blake
Iceland Basin
Pringle Falls
Pringle Falls
Portuguese Orphan
Bermuda
MIS 1
MIS 2
MIS 3
MIS 4
MIS 5a
MIS 5b
MIS 5c
MIS 5d
MIS 5e
MIS 6
MIS 7
MIS 8
MIS 9
MIS 10
MIS 11
MIS 12
Age (ka)
VADM (10²² Am²)
PISO1500
SW Iberian Peninsula


Olduvai
Reunion
Matuyama
Gauss
Pliocene
2
3
HINAPIS1500
Palaeointensity (normalised)
δ18O (‰)
LR04 benthic δ18O stack (Lisiecki and Raymo 2005)
Age (ka)
Bermuda
Orphan Knoll
Big Lost
La Palma
Osaka Bay
Matuyama-Brunhes boundary
M-B precursor
Kamikatsura
Santa Rosa
Top Jaramillo
Intra Jaramillo
Base Jaramillo
Punaruu
Top Cobb Mountain
Base Cobb Mountain
Bjorn
Gardar
MIS 11
MIS 12
MIS 13c
MIS 15a
MIS 15e
MIS 17
MIS 18c
MIS 19
MIS 21
MIS 23
MIS 25
MIS 29
MIS 31
MIS 33
MIS 35
MIS 37
MIS 39
MIS 41
MIS 43
MIS 45
MIS 47
MIS 49
PISO1500
VADM (10²² Am²)

Although geomagnetic polarity chrons, excursions, and RPI and PSV have become widely used for dating Pleistocene sequences, the detailed mechanism through which sediments acquire magnetisation is still poorly understood. The sediment magnetisation 'lock-in' process may introduce a smoothing effect and centennial- to millennial-scale Epoch offsets to sedimentary palaeomagnetic records (*see* Roberts et al. 2013). Such offsets might define the ultimate resolution of palaeomagnetism dating for Pleistocene sequences.

Figure 20: (A) Discrete and (B) continuous sampling using a U-channel of sedimentary sequences for palaeomagnetic dating; (C) Superconducting Rock Magnetometer used for measuring remanent magnetisation. [Photographs by C. Xuan]

4.6 Tephrochronology

Rupert Housley and Ian Matthews

When volcanoes erupt, they disperse ash over thousands of kilometres in a matter of days or months. When identified in Pleistocene deposits they provide time-parallel marker horizons called isochrons. Tephrochronology is the use of these volcanic ash layers (tephras) to infer the age of associated sediments. The detection of tephra layers is achieved by extracting the volcanic material from the host sediments – usually the glass fraction – and then classifying it chemically. This chemical dataset is then matched to a particular eruption (a correlative) by comparing its chemical signal with those from previously recorded eruptions in an international database (Fig. 21 and Fig. 22; for a full review *see* Lowe 2011).

Tephra research is primarily stratigraphic, but calendar dating for Pleistocene sequences can be acquired by two methods: direct dating of the tephra itself or dating of associated material.

Direct dating of volcanic deposits using Argon-Argon, Uranium-series or fission track methods, requires large amounts of material (Walker 2005). However, such quantities are usually not available in areas distant from the source volcano. England receives ash from Iceland and from Continental Europe, but the ash concentrations are too low and they lack the relevant mineral material to be directly dated.

Tephras are more commonly dated by determining the age of the layer in which they are found. The layer can be directly dated using datable material within it, or by obtaining a series of dates from a stratigraphic sequence of deposits — for example using age-depth Bayesian modelling of a series of radiocarbon dates (*see* Gransmoor). In some cases, the date of the layer can be estimated directly by counting annual laminations in lakes and in ice cores. Tephra isochrons allow this calendar dating to be transferred to deposits wherever the ash is detected.

Tephrochronology is a viable dating technique for the entire Pleistocene period and is only limited by the reference datasets available for comparison. So far, there have been only a limited number of studies applying tephrochronology to English archaeological sites. However, distribution maps of ash fall suggest there is good potential to apply tephra studies to sites across the entire country (Fig. 21).

Tephra studies in Europe have focused on the Late Pleistocene. There is, a robust tephrochronology for northern Europe consisting of *c.* 20 tephras between 15 and 11.5 ka. A developing tephrochronology of *c.* 58 tephras has been established for the remaining Late Pleistocene (*c.* 120–15 ka) (Blockley et al. 2014; Davies et al. 2014). There is no reason why tephras should not be detected in Early or Middle Pleistocene deposits but these earlier periods have not received the same level of research. One example has been identified in the Middle Pleistocene West Runton Freshwater Bed in Norfolk (Brough et al. 2010).

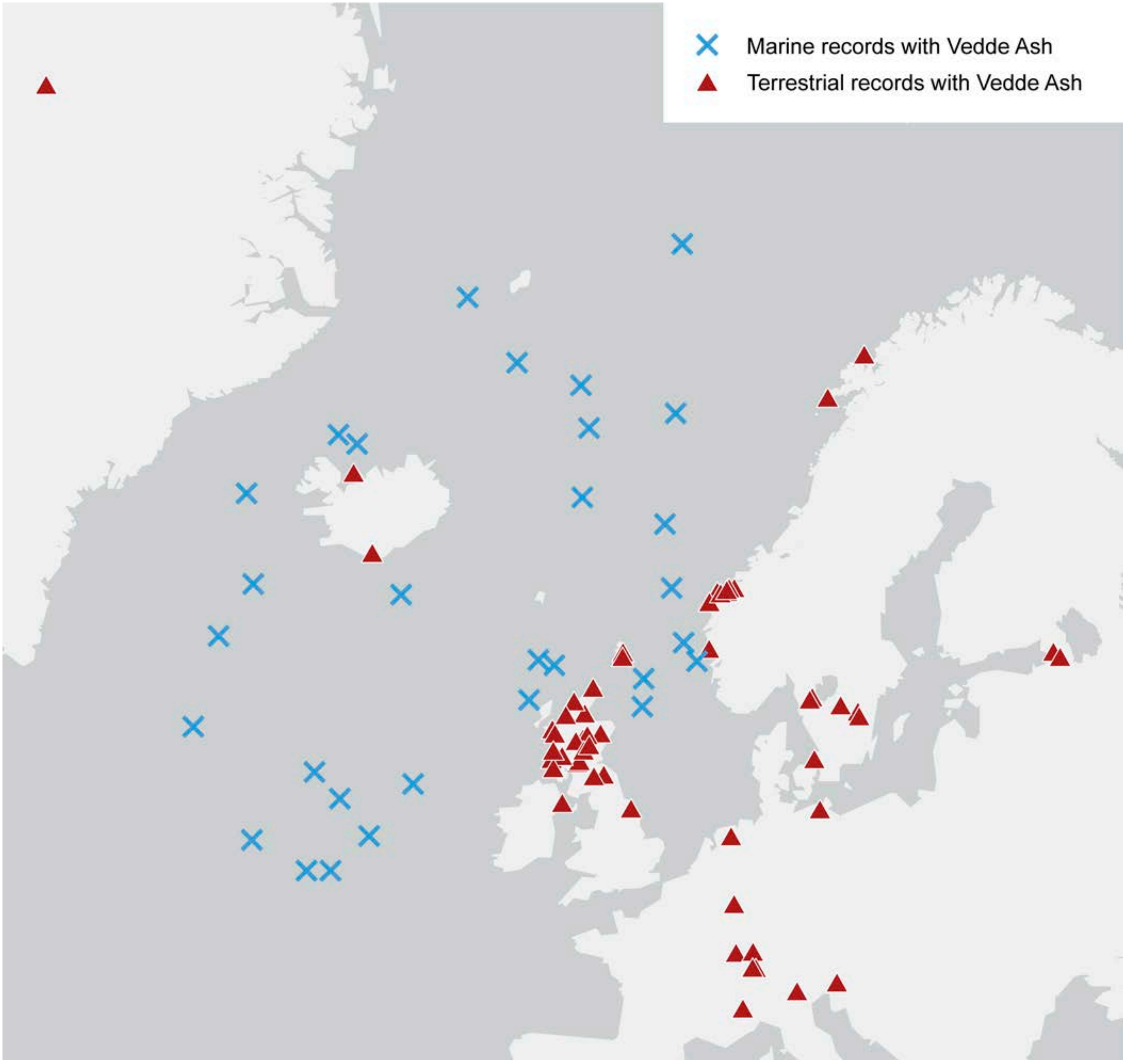


Figure 21: Distribution of sites where the Vedde Ash eruption of Katla, Iceland has been identified, and dated to *11,925–12,075 cal BP (95% probability; Vedde;* Bronk Ramsay et al. 2015a, recalculated using IntCal20) (Vedde Ash distribution from Blockley et al. (2007), Alloway et al. (2013), Timm et al. (2019), Tephrabase (Newton et al. 2007), RESET (Bronk Ramsey et al. 2015b) and Davies et al. (2022)).

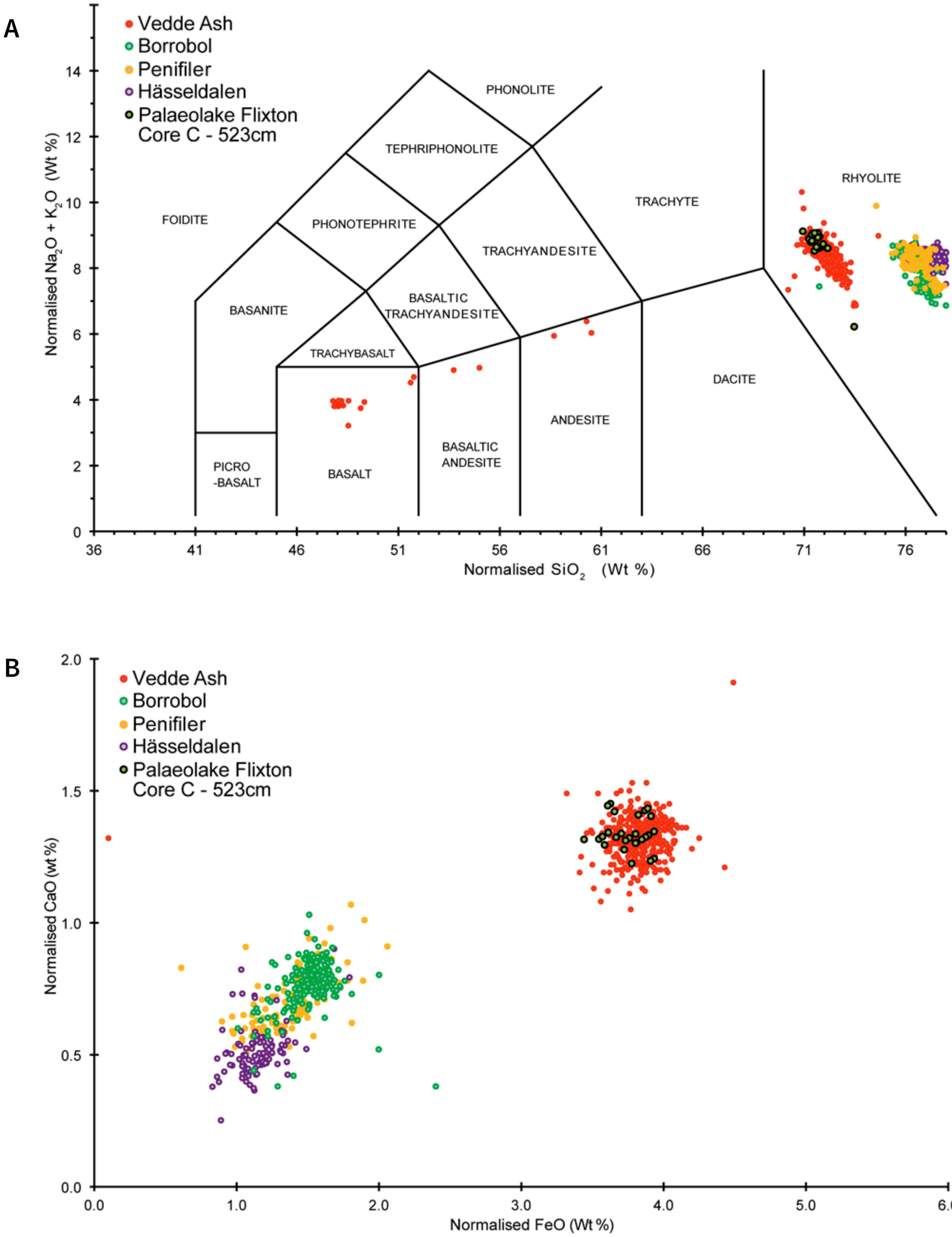


Figure 22: (A) total alkali vs silica (TAS); (B) iron oxide vs calcium oxide bi-plots of the geochemical composition of tephra shards from palaeolake Flixton, Yorkshire, compared to those from the Vedde Ash and other Lateglacial eruptions (geochemical comparison data from Blockley et al. (2007), Alloway et al. (2013), Timm et al. (2019), Tephrabase (Newton et al. 2007), RESET (Bronk Ramsey et al. 2015b) and Davies et al. (2022)).

The precision and accuracy of tephra ages are limited by the dating techniques and age models used for the type sites. During the Late Pleistocene, precision can be as good as 1–2% of the determined age (Bronk Ramsey et al. 2015a). You should provide the following information when reporting tephra data:

- the tephra counts;
- the chemical data and the chemical standards;
- the analytical conditions used;
- the proposed correlative;
- how the age estimate is derived.

Ash layers — called cryptotephra — are usually of shards less than 125µm and therefore invisible to the naked eye. In England, it is likely that any tephras encountered will not be visible in the field owing to their small shard sizes.

Sampling for cryptotephra on archaeological sites requires the collection of a continuous sediment record covering the entire studied sequence (Fig. 23). Tephra are often unevenly represented on a site so it is advisable to sample two or more sections.

In fine-grained sediments, take the samples using overlapping monolith tins. Where coarse clastic material predominates, collect samples in clean small bags from an exposed face, in contiguous 10–20mm intervals working from the section base upwards. In exceptionally clastic-rich sediments taking a full sample may not be possible; or a lower resolution (such as 50–100mm) must be accepted.

The relationship of the samples to geological layers and the archaeology must also be recorded.

Cryptotephra processing (Lane et al. 2014) in the laboratory involves (Fig. 23):

- screening of samples *c.* 300mm^3 in size from 50–100mm contiguous sediment blocks;
- if tephra is present, a series of contiguous 10mm samples are processed to pinpoint the highest concentration, often interpreted as the isochron;
- separating sufficient vitreous tephra shards for major (using EPMA (Electron Probe Microanalyser)) and trace element (using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) or SIMS (Secondary Ion Mass Spectrometry)) chemical analysis;
- compare these chemical results with databases of chemical signatures of known tephra horizons (Tephrabase: Newton et al. 2007; RESET: Bronk Ramsey et al. 2015b).

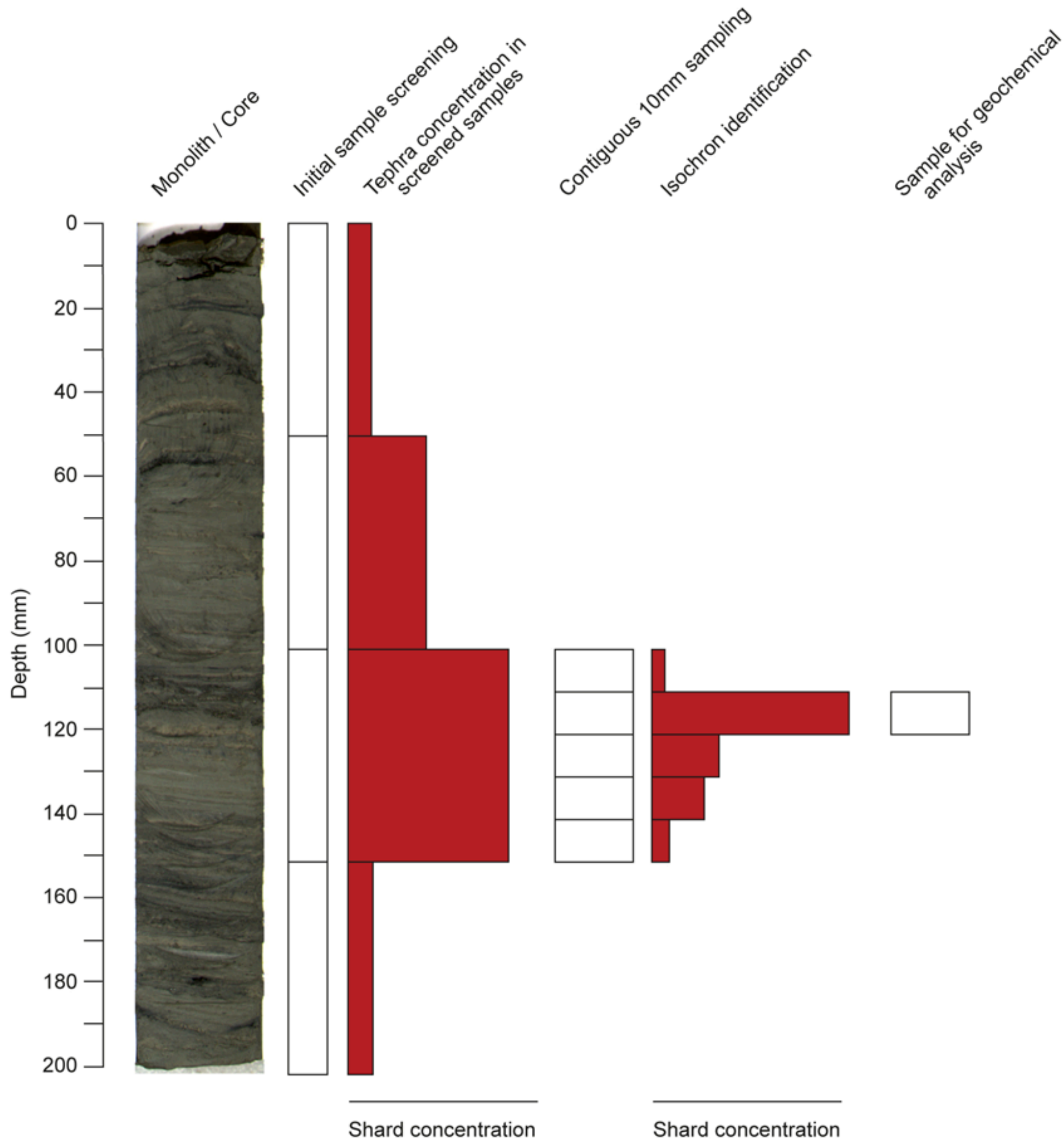


Figure 23: Steps in locating a tephra horizon, from left to fight: collected sediment sequence, sub-sampling, tephra counts from 50–100mm samples, tephra counts from 10mm samples.

The current application of tephrochronology to archaeology can be classified into three categories: (1) wetland archaeology; (2) open-air 'dry' sites; and (3) rock shelters and caves. No formal assessment has been made of the likelihood of finding tephras in any of these kinds of deposits in Britain, but Housley et al. (2015) demonstrated that 22% of open-air 'dry' sites and 34% of rock shelters and caves produced tephras in Continental Europe.

To summarise: successful tephrochronological dating is dependent on the presence of an eruption coincident at the time the sediment accumulated. Longer records are more likely to include tephra and/or cryptotephra, so undisturbed deposits are preferable. Even if tephra shards are isolated on a site, they can only be assigned to an isochron if suitable dated geochemical reference data is available. Currently, these criteria are more likely to be met in the Late Pleistocene than in earlier periods.

4.7 The 'Vole Clock'

Danielle Schreve

The recovery of small vertebrate remains is now a routine procedure when investigating sites of Quaternary age. Any calcareous fine-grained deposits may be suitable for sampling (sands, silts and clays, or seams of these within coarser gravel bodies).

Excavation with a trowel will often damage fragile specimens, so it is best to collect bulk samples of sediment, either as a column (to investigate any change up through a sequence) or as block samples around particular features of interest.

The samples should be wet-sieved individually through a half-millimetre mesh size before the residue is dried and then scanned under a low-power binocular microscope, extracting bones and teeth using foil tweezers. Clay-rich sediment samples should be air-dried or soaked with a dispersant such as 1% sodium hexametaphosphate before wet-sieving. This procedure will help to weaken the hydrophilic bond of the clay particles and enable easier processing.

Small vertebrate remains can offer highly detailed insights into many aspects of past environments and climates, food webs and evolutionary trends. In particular, the vertebrate fauna in Britain have been profoundly affected by Late Pleistocene long-term glacial to interglacial climate change and the succession of abrupt (decadal to centennial) climatic changes (Schreve 2001).

These cycles have influenced vertebrate species' biogeographical ranges and have driven evolutionary trends and extinction events (Lister 1992). Taken together, these changes can be used to establish the relative ages of fossil assemblages — their biostratigraphy.

One notable example of a biostratigraphically-significant evolutionary trend is that seen in the water vole lineage, sometimes referred to as The 'Vole Clock'. Remains of fossil water voles are common in Quaternary deposits, thereby providing a large sample of teeth through which quantifiable changes can be observed. This is important because morphological change is often small over Quaternary timescales and tooth morphology between individuals can be highly variable. Large samples are required to capture variation within a population accurately.

The genus *Mimomys* appeared in Europe about 4 million years ago and evolved through several species. The genus survived until about 600 ka, when the final representative, *Mimomys savini*, was replaced by the modern genus *Arvicola*.

The key dental features of interest reside in the first lower molar (m1) — a 'cloche-hat-shaped' anterior loop (the anteroconid complex, ACC) and a series of three closed interlocking triangles and a posterior loop (Fig. 24).

In the transition from *Mimomys* to *Arvicola* during the early Middle Pleistocene (late Cromerian Complex), an important change occurred in the switch from rooted teeth to permanently-growing molars (Fig. 25). This apparently rapid change provides a significant biostratigraphic marker throughout western Eurasia.

In Britain, this dental transition shows a clear separation of older and younger sites. An 'old' group of early Middle Pleistocene sites are characterised by *Mimomys* (e.g. West Runton, Norfolk and Pakefield, Suffolk) and a 'young' group of early Middle Pleistocene sites have *Arvicola* (e.g. Westbury-sub-Mendip, Somerset and Boxgrove, West Sussex) (Preece and Parfitt 2012). This advantageous mutation provided *Arvicola* with extra tooth life, allowing them to extend their life span and breeding opportunities, thus perpetuating the mutation.

Within the genus *Arvicola*, further trends have been noted over the last half million years. There were two subspecies in Britain: *Arvicola terrestris cantian*a (also known as *Arvicola mosbachensis*) and the modern *Arvicola terrestris terrestris* (also known as *Arvicola amphibius*). The m1 lengthened and there was an increase in the ratio of the ACC to overall tooth length. The *Mimomys* fold, an archaic feature in the ACC, also became progressively uncommon in younger samples until finally disappearing (Fig. 24).

The key trend, however, are differences in enamel thickness on the leading and trailing edges of the molars. *Mimomys* and early forms of *Arvicola* have thicker enamel on the trailing edges of the lower molars than on the leading edges. Over time, this trend reverses, so that in modern populations of *Arvicola terrestris terrestris* from Western Europe, the enamel is thicker on the leading edges of the lower molars (Fig. 24) (Hinton 1926).

A method known as the *Schmelzband-Differenzierungs-Quotient* (SDQ or enamel differentiation ratio) was proposed by Heinrich (1982) to quantify this progressive trend. The method uses measurements of the combined trailing edge thickness from established points on the molar, divided by the combined leading-edge thickness, multiplied by 100.

The SDQ can then be compared with those of different *Arvicola* populations to establish the relative age of the sample. This technique has been widely applied in Britain to provide an independent chronology for many Quaternary sites (for example Schreve 2001; Roe et al. 2009).

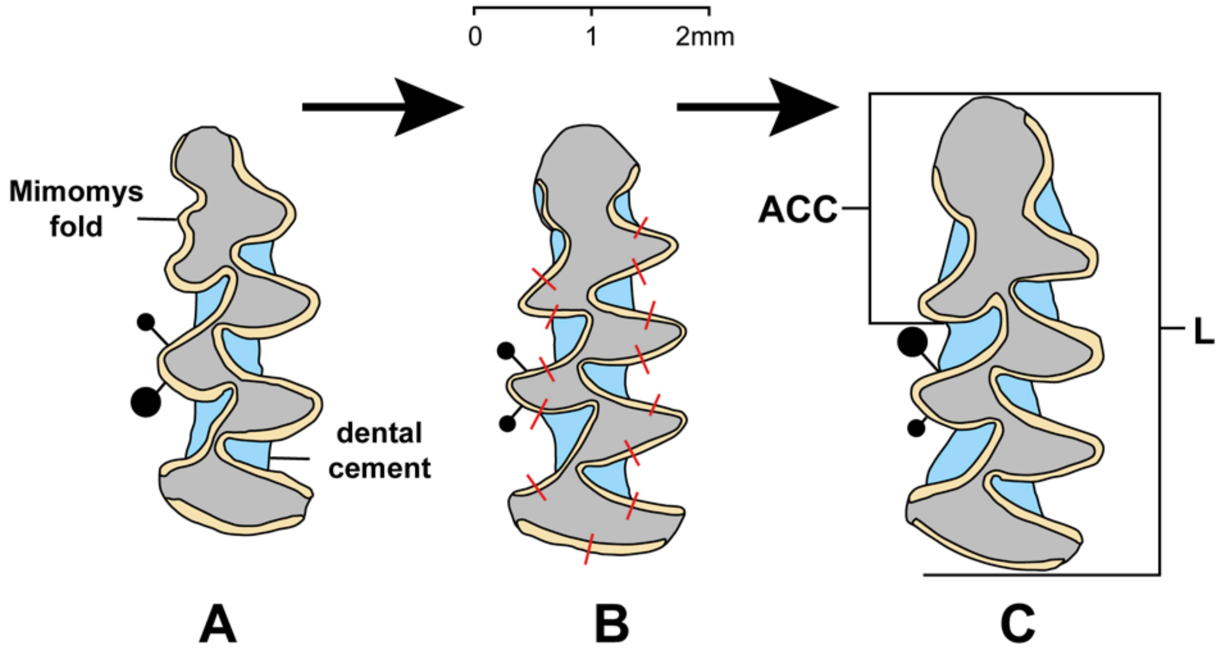


Figure 24: Evolutionary trends in *Arvicola* from the early Middle Pleistocene to the present day: (A) *Arvicola terrestris cantiana*; (B) transitional form; (C) *Arvicola terrestris terrestris* – arrows indicate the direction of evolution; ACC anteroconid complex; L length. Red lines on B indicate point of measurement for SDQ calculations. [After Sutcliffe and Kowalski 1976]

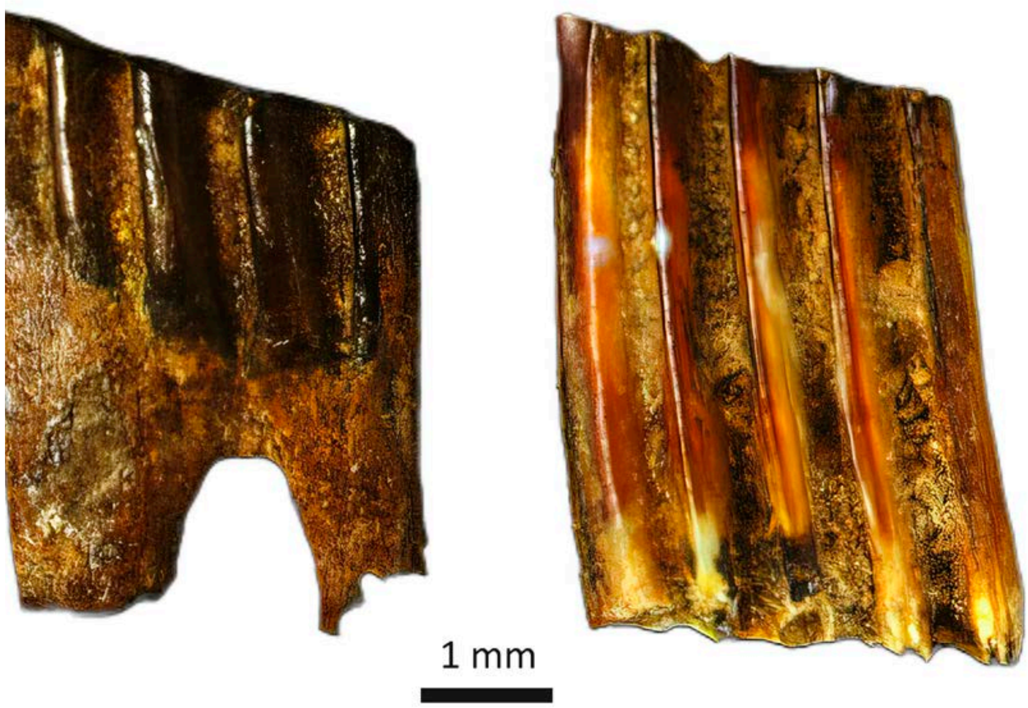


Figure 25: Lateral views of rooted first lower molar in *Mimomys savini* (left) compared to unrooted molar of *Arvicola cantiana*. [Photograph by D Schreve]

5. Case Studies

5.1 Happisburgh, Site 3, Norfolk

Zoe Outram and Peter Marshall

The Cromer Forest-bed Formation can be found along the coast of Norfolk and Suffolk. It formed between 2 and 0.5 million years ago and is famous for its rich flora and fauna. Mammoth, rhinoceros and hippopotamus remains have been discovered over the last 250 years. Despite such a long history of investigation it has only recently yielded evidence for hominin presence.

Excavations at Happisburgh Site 3, Norfolk (*see* front cover), recovered an assemblage of 78 flint artefacts from the fills of a series of stacked, overlapping channels (Parfitt et al. 2010). The deposits contained a remarkable range of remains for a Pleistocene site, including stone tools, and floral and faunal remains (Fig. 26). These provided the opportunity for a detailed study of hominin activities and the environment that they occupied.

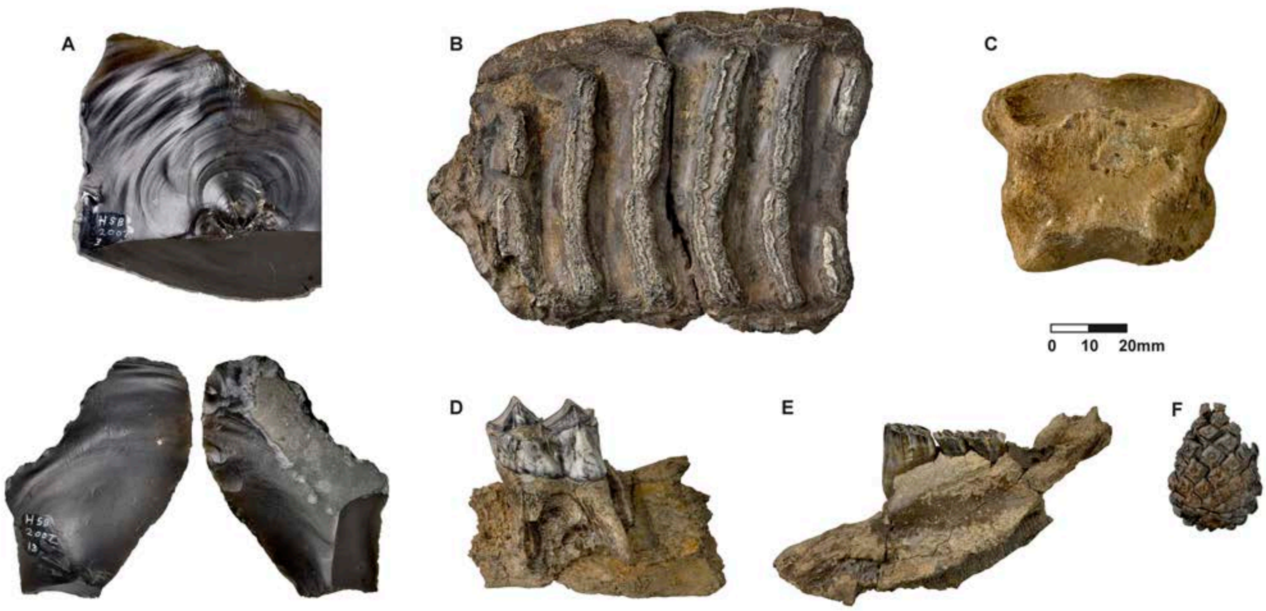


Figure 26: Artefacts and biological remains from Happisburgh 3: (A) hard hammer flake artefacts; (B) *Mammuthus* cf. *meridionalis* (mammoth) upper second molar; (C) *Equus* cf. *sussenbornensis* (horse) phalanx; (D) *Cervus latifrons* (elk) lower molar; (E) *Trogontherium cuvieri* (giant rodent) mandible; (F) *Pinus mugo* (dwarf mountain pine) cone. [Photographs by P Crabb, © Trustees of the National History Museum]

Stratigraphic evidence indicates that the site was older than MIS 12 (450 ka), when the marine and freshwater deposits associated with Cromer Forest-bed Formation ended and sediments associated with the Anglian glaciation were laid down. Determining more precisely the age of the hominin activities at the site was essential to understand their significance and to place them into a broader context.

Samples for palaeomagnetic dating (*see* Palaeomagnetism) were obtained from a stratigraphic sequence of deposits below, within and above the artefact-bearing gravels. The sediments all displayed a reversed polarity, placing their deposition in the Matuyama chron (2.52–0.78 Ma). Biostratigraphic evidence, including the presence of key plant taxa identified from the pollen spectra, suggested that the age of the site was towards the end of the Early Pleistocene. Plant taxa identified include *Tsuga* (hemlock) and *Ostrya*-type (hop-hornbeam type), which are unknown in northern Europe after the Early Pleistocene. Extinct mammals identified included mammoths, equids and voles (genus *Mimomys*; *see* The 'Vole Clock'). Taken together, these biostratigraphic and palaeomagnetic data indicate that the hominin occupation at Happisburgh occurred towards the end of the Mutuyama chron, placing the deposits between 990 and 780 ka (Parfitt et al. 2010).

Further evidence of this hominin occupation is provided by the palaoebotanical record, which indicates that it occurred during a phase of climatic cooling in the second half of an interglacial cycle (Fig. 27). Using this evidence, Parfitt et al. (2010) suggest that the site was occupied at the end of either MIS 25 (970–936 ka) or MIS 21 (866–814 ka).

Westaway (2011) proposes a younger date of MIS 15c (*c.* 600 ka), based on reinterpretation of the palaeomagnetic evidence and the suggestion that the pollen and faunal remains on the site are reworked from earlier deposits.

Parfitt et al. (2010, supplement) assign the sediments, based on their composition, to an Early Pleistocene extended Thames. By MIS 15, the northern part of East Anglia, within which Happisburgh 3 is located, was now within the River Bytham catchment, with the Thames positioned further south. Accepting Westaway's (2011) interpretation would therefore throw into doubt the current understanding of the River Thames and Bytham catchments at this time (White et al. 2018).

If Westaway's later dating is correct, Happisburgh Site 3 is much in keeping with other indications from the European Continent of the date when the first hominins occupied this part of north-west Europe. If Parfitt et al.'s earlier dating is accepted, then Happisburgh Site 3 has yielded the oldest hominin occupation north of Iberia and the first occupation within the northern boreal zone. This earlier dating has important implications for our understanding of populations, in terms of their migrations and movements, their behaviour, and their ability to adapt and survive different environments, such as the cooler climates recorded towards the end of an interglacial.

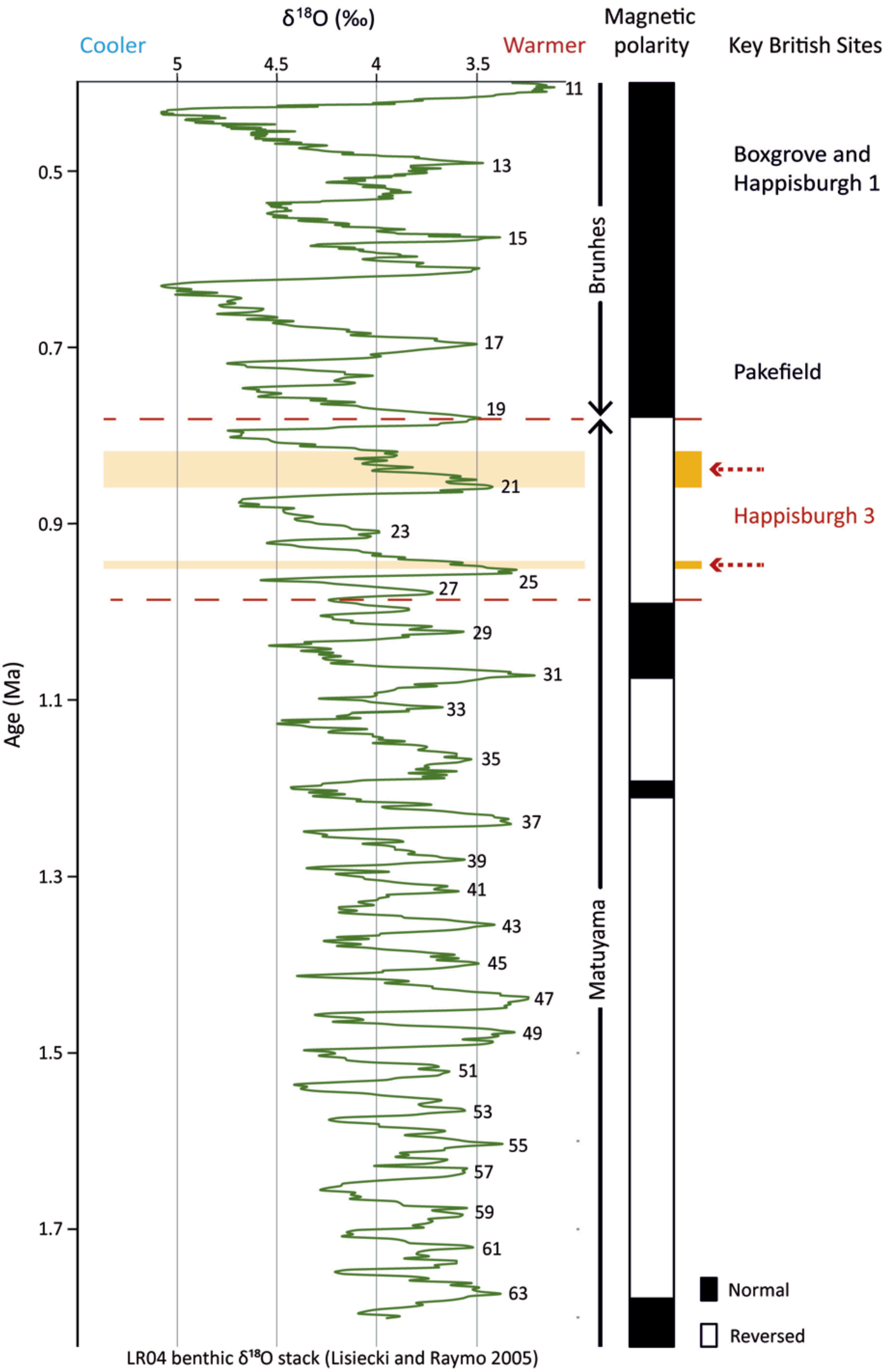


Figure 27: Suggested age of the Happisburgh 3 site, showing correlation with the Marine Oxygen Isotope and magnetic polarity records, and likely age of other key English Early Palaeolithic coastal sites.

These different interpretations of the evidence for the age of Happisburgh 3, which fundamentally depends on the production of an accurate chronology for the site, highlights the importance of scientific dating techniques in the Pleistocene. Nonetheless, the evidence from Happisburgh Site 3 has redefined our understanding of the earliest known occupation of Britain.

5.2 Boxgrove, West Sussex

Danielle Schreve

The site of Boxgrove is located in West Sussex, 12km north of the English Channel coast. Its modern position is significant, as the Pleistocene deposits of archaeological and palaeontological interest lie on top of a wave-cut platform in the Cretaceous Upper Chalk bedrock, indicating that the site once lay at the northern edge of a large marine embayment (Fig. 28). The marine beach associated with the platform reaches a maximum height of 43.5m OD, highlighting considerable tectonic uplift since the deposits were laid down. The site forms the highest (and oldest) of a flight of four marine terraces that represent former sea-level high stands, which extend down to modern sea-level on the West Sussex Coastal Plain.

Excavated between 1984 and 1996, Boxgrove is internationally renowned for its spectacular Lower Palaeolithic archaeological record. This includes several hundred ovate bifaces (handaxes) made of flint sourced from the nearby Chalk cliff, its rich and diverse fossil vertebrate assemblage, and the presence of hominin remains (two incisors and a tibia) attributed to *Homo heidelbergensis*. More than 100 species of vertebrate fauna, together with invertebrates such as molluscs, ostracods and foraminifera were recovered (Roberts and Parfitt 1999).

The deposits at the site were laid down on the wave-cut platform and consist of a sequence of marine sands (the Slindon Sands) laying beneath a series of lagoonal deposits (the Slindon Silts) upon which a stable land surface developed. Palaeoclimatic conditions remained temperate throughout this period. The Slindon Silts and overlying land surface are the source of the majority of the archaeological and faunal remains (Fig. 29). The fine-grained nature of the sediments is such that individual episodes of handaxe knapping can be identified and the flakes refitted to reveal the process of manufacture. Bone and antler hammers used for handaxe manufacture were also recovered, and part of the site contains evidence for the presence of spring-fed pools surrounded by open grassland, which appear to have acted as a focal point for human activity.

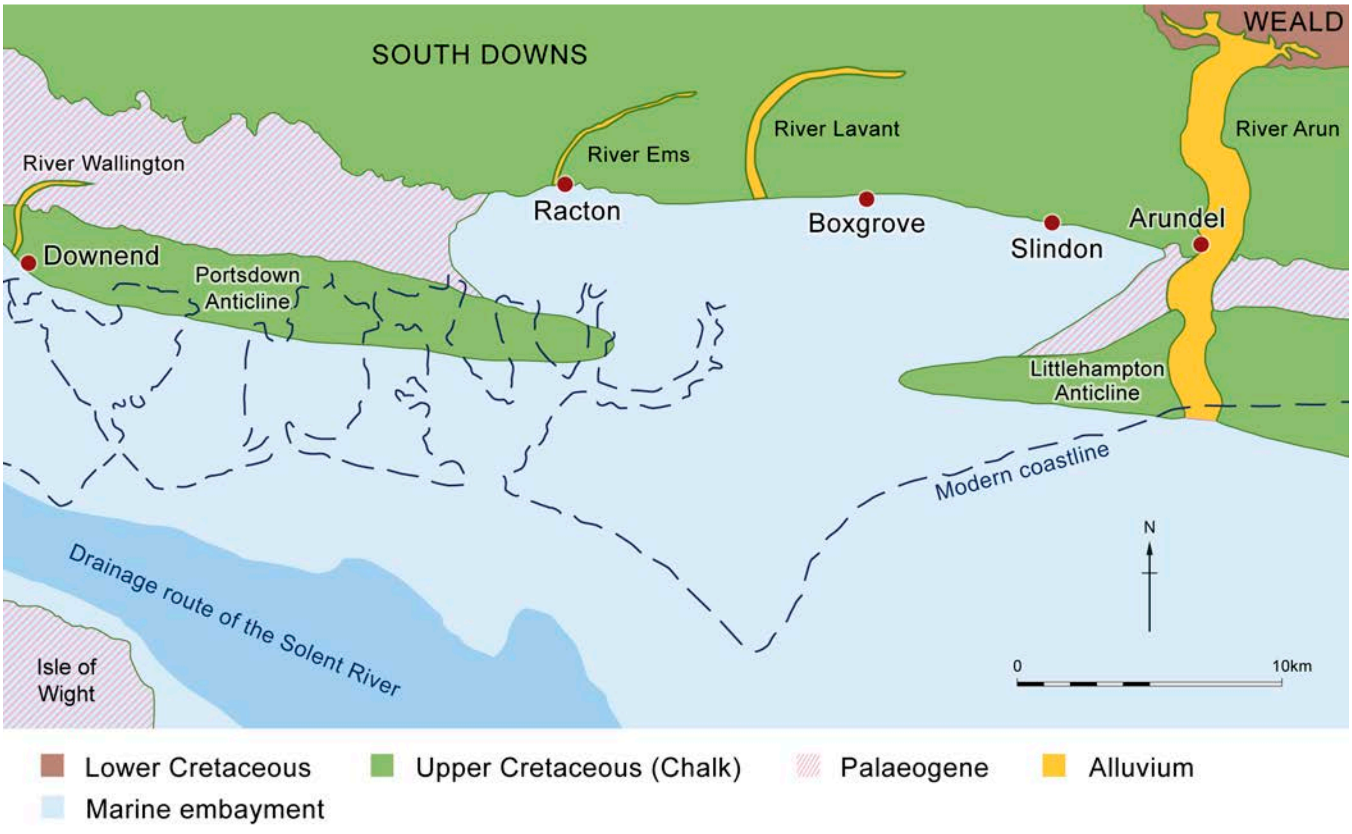


Figure 28: The position of Boxgrove relative to the contemporary coastline at the end of MIS 13. [After Roberts and Pope 2009, fig. 6.4]

Figure 29: Excavation of flint scatter from the Slindon Silts (Unit 4b). [© Boxgrove Project]

This Pleistocene land surface was subsequently covered by silty brickearth and gravels (the Eartham Formation), which were deposited as climate deteriorated and vegetation cover became sparse. This transition to cold climate conditions is supported by the kinds of ostracod and mammal remains found in the upper part of the Slindon Silts and the basal sediments of the overlying Eartham Formation (Roberts and Pope 2009).

Boxgrove has also yielded extensive proof for large mammal butchery, including evidence for the dismemberment of wild horse, red deer, giant deer, bison and three Hundsheim rhinoceroses. The carcasses of these animals are littered with cutmarks from stone tools, indicating a complete process from skinning to the removal of the major muscle blocks and tendons. Where present, carnivore gnaw-marks overlie anthropogenic cut-marks, indicating that humans had first access to the carcasses and to the complete range of body parts.

Pathological evidence for a trauma wound to the shoulder blade of the butchered horse is consistent with impact damage from a large projectile, such as a wooden spear (Roberts and Parfitt 1999). In combination, all the evidence provides a strong indication of hominin hunting capabilities in the Lower Palaeolithic. The large size of the prey tackled and the concomitant meat yield (700kg in the case of a rhinoceros) have implications for palaeo-demography, with groups of up to 50 individuals in the immediate area.

A range of techniques have been used to date Boxgrove since it was first discovered. As with many Palaeolithic and Pleistocene sites, the establishment of a robust chronology has been problematic, particularly in the absence of suitable materials for geochronological techniques at the time of excavation, or indeed methods that extend far enough back in time or provide sufficient resolution (Fig. 9). When the site was first discovered, only three interglacials were formally recognised in the Middle and Late Pleistocene in Britain: the Cromerian, Hoxnian and Ipswichian (Mitchell et al. 1973). However, the unusual character of the mammalian assemblage, containing both post-Cromerian and pre-Hoxnian species, was first detected by Currant (in Roberts 1986), suggesting that Boxgrove might date to a previously unrecognised intermediate episode. Later palaeomagnetic dating (*see* Palaeomagnetism) analysis of the Slindon Sands in the 1990s confirmed that the sediments have normal polarity and are therefore younger than 780 ka old but could not provide any further resolution (David and Linford 1999).

The age of the Boxgrove deposits is debated. Different authors suggest pre- and post-Anglian (MIS 12) ages. The evidence for a post-Anglian age can now be questioned, however, based on scientific advances since the original studies were undertaken. For example, Amino-Acid Racemisation put forward as the strongest evidence for later dating (Bowen and Sykes 1999) was not undertaken on the intra-crystalline fraction of the shells. The mammalian biostratigraphy from the site, in particular the presence of a large number of taxa, strongly implies that the Boxgrove temperate climate sediments must pre-date, rather than post-date, MIS 12. This evidence includes the shrew *Sorex* (*Drepanosorex*) *savini*, the vole *Pliomys episcopalis*, the cave bear *Ursus deningeri*, the rhinoceros *Stephanorhinus hundsheimensis* (Fig. 30) and the giant deer *Praemegaceros dawkinsi* and *Praemegaceros* cf. *verticornis* that became extinct in Britain during the Anglian glaciation. This evidence strongly implies that the Boxgrove temperate climate sediments must pre-date, rather than post-date, MIS 12.

Further resolution of the likely date of the Boxgrove deposits is provided by The 'Vole Clock'. The Cromerian Complex interglacials can be divided into an older group, characterised by the presence of the archaic water vole, *Mimomys savini*, and a younger group characterised by its descendant, *Arvicola cantiana terrestris*. The presence of the latter at Boxgrove therefore implies a younger age within the Cromerian Complex. Furthermore, the presence of a more derived (i.e. advanced) form of narrow-skulled vole, *Lasiopodomys gregalis*, suggests a more recent age for Boxgrove within the early Middle Pleistocene *Arvicola* group.

The preferred position of the Boxgrove Slindon Formation is therefore right at the end of the early Middle Pleistocene, correlated with MIS 13, and with the cold-climate Eartham Formation correlated with MIS 12 (Roberts and Parfitt 1999; Roberts and Pope 2009). The attribution of Boxgrove to MIS 13 also helps to more firmly establish the timing of the earliest Acheulean in Britain, as handaxe sites are currently only known in association with *Arvicola* (Candy et al. 2015).

These conclusions reinforce the importance of the vertebrate fossil record for chronological determination at Pleistocene sites.

Figure 30: Upper fourth premolar of the biostratigraphical indicator *Stephanorhinus hundsheimensis*. [© Boxgrove Project]

5.3 The Axe Valley at Broom, Devon/Dorset border

Peter Marshall

The sand and gravel exposures at Broom, on the River Axe along the Devon/Dorset border, are of considerable significance in the context of the Lower Palaeolithic and the fluvial terrace stratigraphy of south-west England (Fig. 31).

The deposits exposed in three working pits have yielded at least 2,300 Palaeolithic artefacts, an assemblage dominated by handaxes. Like most of England's river-terrace Palaeolithic archaeology, the contextual information for the assemblage is incomplete. The physical condition of the stone tool assemblage suggests a mixture of locally derived artefacts and pieces that had been transported farther by the river during the Middle Pleistocene. The archaeology is of both regional importance for the understanding of the Lower Palaeolithic occupation of south-west England and of national significance with respect to the use of chert in the manufacture of the majority of the lithic assemblage (Hosfield and Green 2013).

The traditional model of sediment accumulation at Broom emphasises a tripartite sequence of lower gravels (Holditch Lane Gravel Member); an intervening unit comprising sands, silts and clays (Wadbrook Member); and an upper gravel unit (Fortfield Farm Gravel Member). This sequence resonates with Bridgland's (1996) model of the typical aggradational terrace. The model's framework associates major fluvial aggradations and incisions with the cyclical shifts from interglacial to glacial recorded in the Marine Oxygen Isotope record (Text Box 1). However, the age of the sediments remained unknown.

The *Archaeological Potential of Secondary Contexts* project (Hosfield et al. 2007) assessed the interpretative potential of the secondary context archaeological resource for the Lower and Middle Palaeolithic in England. It included excavations at Broom that built on a long history of research to contextualise the artefact collections and date the fluvial sediments. Eighteen OSL samples (*see* Luminescence dating) were dated (Table 4; Toms 2013; Toms et al. 2005) to provide an absolute chronology for the Middle Pleistocene terrace succession and the artefacts at Broom, and to assess whether the River Axe's fluvial record matches the classic Bridgland model.

The OSL age estimates from the Wadbrook Member and the Fortfield Farm Gravel Member were combined with relative dating information provided by the stratigraphic relationships between the samples to create a Bayesian chronological model (Fig. 32). Age estimates from the Wadbrook Member come from a single section and were therefore defined sequentially (GL02084<GL03011<GL02083) as their relative stratigraphic position was unambiguous. The Fortfield Farm Gravel Member age estimates derived from several separate sections, and therefore formed part of a Fortfield Farm Gravel phase.

Figure 31: Fluvial gravels and sands (Fortfield Farm Gravel Member), Pratt's New Pit, Broom.
[Photograph by R. Hosfield]

Table 4: Broom quartz Optically Stimulated Luminescence dates (Toms 2013).

Laboratory Code	Depth (m)	Palaeodose (Gy)	Total dose rate (Gy ka^{-1})	Mean Age (ka)	Minimum Age (ka)	*Highest Posterior Density Interval – ka (95% probability)*
GL02082	5.1	503.4±27.8	1.72±0.11	293±24	-	*301–237*
GL02083	15.6	461.5±28.0	1.61±0.08	287±22	-	*319–283*
GL02084	16.5	483.0±21.0	1.73±0.10	279±20	-	*341–290*
GL02085	2.78	353.4±21.4	1.27±0.08	279±24	-	*290–254*
GL03001	1.65	274.3±18.5	0.60±0.03	460±38	215±13	*233–182*
GL03002	2.12	367.8±39.0	0.50±0.03	739±89	275±21	*254–206*
GL03003	2.68	449.8±33.3	0.52±0.02	870±76	326±53	*252–131*
GL03004	2.66	288.3±19.1	1.08±0.05	268±22	107±8.1	*273–227*
GL03005	2.95	326.8±17.3	1.45±0.07	226±16	-	*263–220*
GL03006	2.81	375.9±27.1	1.36±0.08	277±25	-	*284–241*
GL03007	2.96	324.0±20.8	1.19±0.06	271±22	-	*298–253*
GL03008	0.95	352.8±18.9	1.45±0.07	244±18	-	*269–205*
GL03009	1.09	343.0±18.6	1.27±0.06	270±19	-	*294–238*
GL03010	15.0	380.6±28.0	1.61±0.12	237±25	-	*281–187*
GL03011	16.2	546.0±44.8	1.84±0.10	297±29	-	*329–283*
GL03057	10.43	39.8±1.7	2.01±0.12	24±2	-	-
GL03058	10.65	39.6±2.7	2.47±0.17	20±2	-	-
GL03059	10.81	57.5±3.6	1.98±0.11	34±2	-	-

The model provides an estimate for the timing of the transition from the Wadbrook Member to the Fortfield Farm Gravel Member of *311–270 ka* (*95% probability*; *Wadbrook/Fortfield Farm Member*; Fig. 32) and probably *300 ka–280 ka* (*68% probability*).

These results indicate that the Wadbrook Member formed between mid-MIS 9 (interglacial) and early MIS 8 (glacial), and that the Fortfield Farm Gravel Member formed between MIS 8 (glacial) and MIS 7 (interglacial). Combined with the stratigraphic and sedimentary evidence at Broom, these dates show that the Axe valley's terrace stratigraphy does not fit exactly into existing models of terrace formation. This is a valuable reminder that not all rivers respond in the same way to variations of climate, geology and base level.

These age estimates also provide a chronology for the prolific assemblage of Acheulean (biface) artefacts recovered from the Wadbrook Member. They are notable because they clearly indicate that the Acheulean-dominated assemblage at Broom was deposited at a time when evidence in south-east England suggests the beginning of a shift towards using Levallois prepared-core dominated technologies (e.g. at Purfleet, Essex).

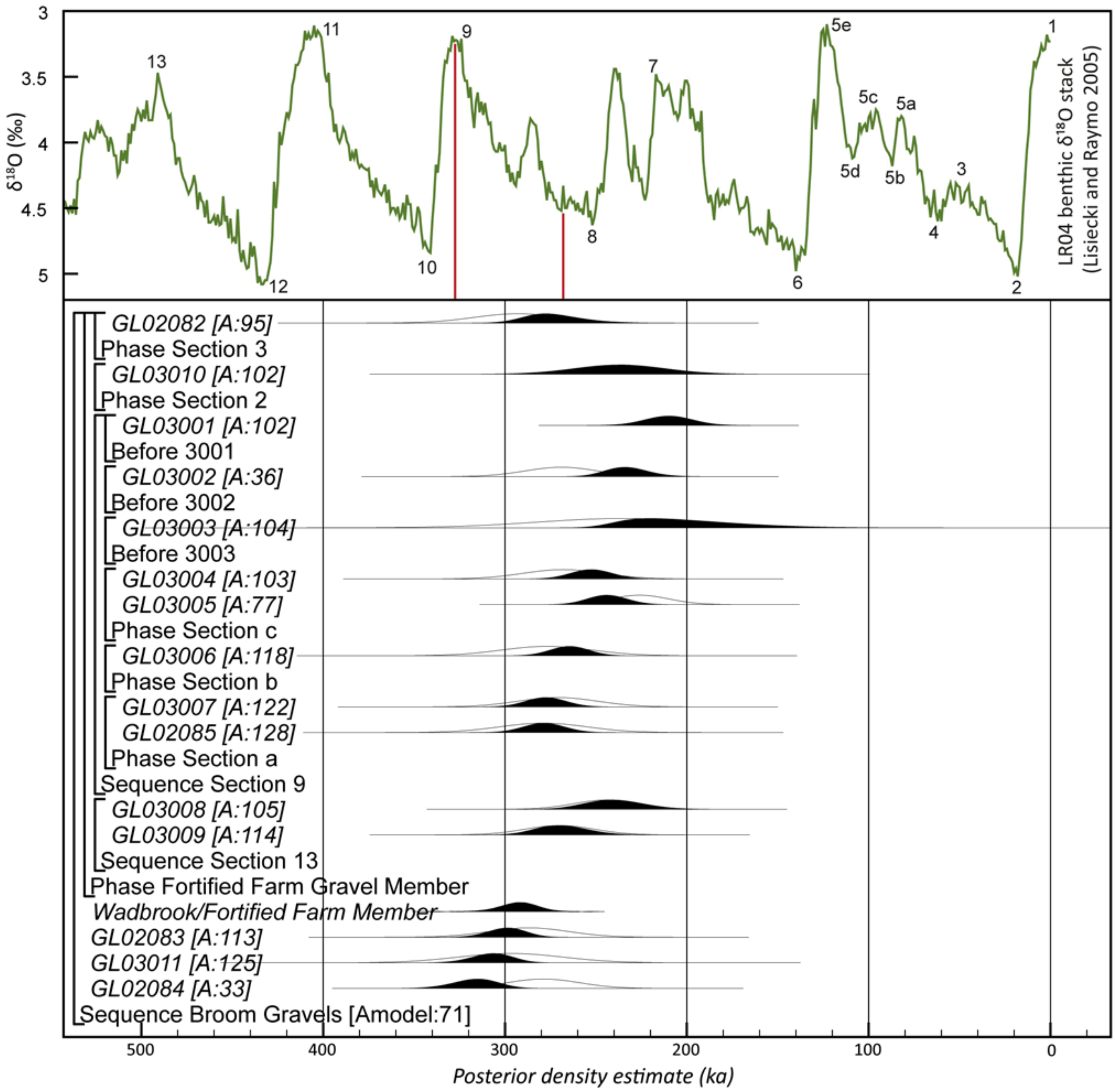


Figure 32: Probability distributions of dates from Broom, Devon. The large square brackets down the left-hand side of the diagram, along with the OxCal keywords define the overall model exactly. The upper panel shows the Marine Oxygen Isotope record.

5.4 Marine Aggregate Licence Area 240, North Sea off Great Yarmouth, Norfolk

Peter Marshall

Between December 2007 and February 2008 gravel extraction 11km off the coast of East Anglia in Marine Aggregate Licence Area 240 (Fig. 33) produced an important collection of Middle Palaeolithic artefacts (Fig. 34) and faunal remains: 88 worked flints, including 33 handaxes, plus woolly mammoth, rhinoceros, bison, reindeer and horse (Tizzard et al. 2014; 2015). The unweathered nature of many of the handaxes indicates they probably derived from an in situ or a near in situ context before being dredged from the seabed. Although prehistoric material has been recovered since the 1930s from the North Sea through fishing and dredging, the material from Area 240 came from known dredging lanes within it. Thus, unlike many chance finds, the Area 240 material offered the opportunity to establish the geological and geomorphological context of the material and to provide an estimate of the age of the deposits.

Area 240 is in the lower reaches of the Palaeo-Yare river system and for most of the last 1 Ma it has been part of a coastal or inland environment due to lower sea-levels. From 2008 to 2011 the geophysical and geotechnical data were re-examined, and a new geophysical survey undertaken of the area from which the artefacts and faunal remains came. The deposits were also cored to obtain material for OSL dating (*see* Luminescence dating) and for reconstructing past environmental conditions (Tizzard et al. 2015; Fig. 33).

A Bayesian chronological model was constructed using the OSL dates and the stratigraphic sequence (Fig. 35). The model suggests that Unit 3b, from which many of the artefacts and faunal material are thought to derive, started to form in *275–192 ka* (*95% probability*; *start_unit_3B*; Fig. 36), probably in *244–204 ka* (*68% probability*), and ended in *223–161 ka* (*95% probability*; *end_unit_3B*; Fig. 36), probably in *210–180 ka* (*68% probability*). The dating suggests that Unit 3b most likely dates to MIS 7 or possibly the beginning of MIS 6.

The material from Area 240 can now be included in the corpus of archaeological sites dated to MIS 7 within the British Palaeolithic record (White et al. 2006). The archaeological record of MIS 7 is important as it represents the final phase of Middle Palaeolithic occupation of Britain before the *c.* 120 ka hiatus between MIS 6–3, when hominins were absent.

Bayesian chronological modelling of the OSL dates from Area 240 (Table 5) enables us to correlate the key depositional unit thought to have contained the flint artefacts with the sequence of MIS stages (most probably MIS 7); something that could not have been achieved without the dating programme. Together with other investigations in Area 240 (Tizzard et al. 2014; 2015) the results confirmed that submerged landscapes have the potential to preserve in situ Middle Palaeolithic artefacts.

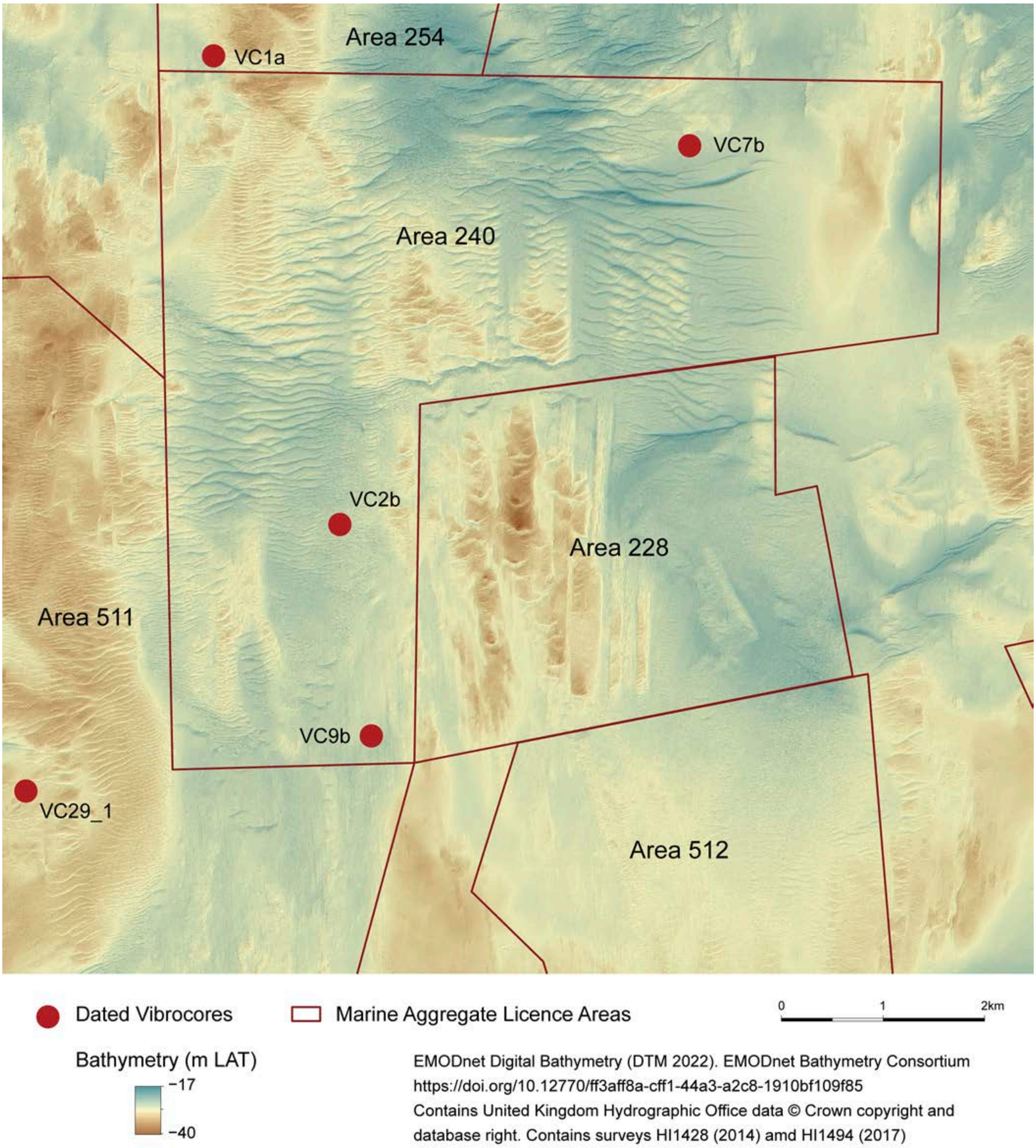


Figure 33: Bathymetry of Aggregate Licence Area 240 and locations of vibrocores mentioned in the text.

Table 5: Quartz Optically Stimulated Luminescence dates from in and around Area 240 (Toms 2011, Wessex Archaeology 2008 and Limpenny et al. 2011). Note that full details for the samples dated from VC1a and VC29 are not published and could not be traced in the laboratory or archaeological archives.

Laboratory Code	Field Code	Elevation (m OD)	Palaeodose (Gy)	Total dose rate (Gy ka^{-1})	Age (ka)
GL10037	VC7b 1.32–1.42m	−28.6	105.6±6.2	0.96±0.08	109±11
GL10038	VC2b 0.85–0.95m	−28.7	230.1±16.7	0.95±0.11	243±33
GL10039	VC2b 3.1–3.2m	−31.0	326.1±53.4	0.78±0.11	418±78
GL10041	VC7b 0.45–0.55m	−27.8	125.3±8.5	1.31±0.12	96±11
GL10042	C7b 2.5–2.65m	−29.8	92.5±0.04	0.45±0.04	207±24
GL10043	C9b 4.51–4.61m	−31.5	313.1±47.6	1.11±0.14	283±56
GL10044	C9b 1.45–1.55m	−28.5	31.3±1.5	0.86±0.07	36±3
GL10045	C9b 0.7–0.8m	−27.7	21.2±2.3	0.59±0.05	36±5
	VC1a: 1.14	−28.8			17±2
	VC1a: 1.92	−29.6			167±11
	VC1a: 3.3	−40.0			176±23
	VC1a: 3.7	−31.4			577±65
	VC29_1	−33.4			207±30
	VC29_2	−32.5			222±29
	VC29_3	−31.5			188±19
	VC29_4	−30.9			57±6

Figure 34: Small cordate handaxe (top) and Levallois flake (bottom) from Area 240. [© Wessex Archaeology]

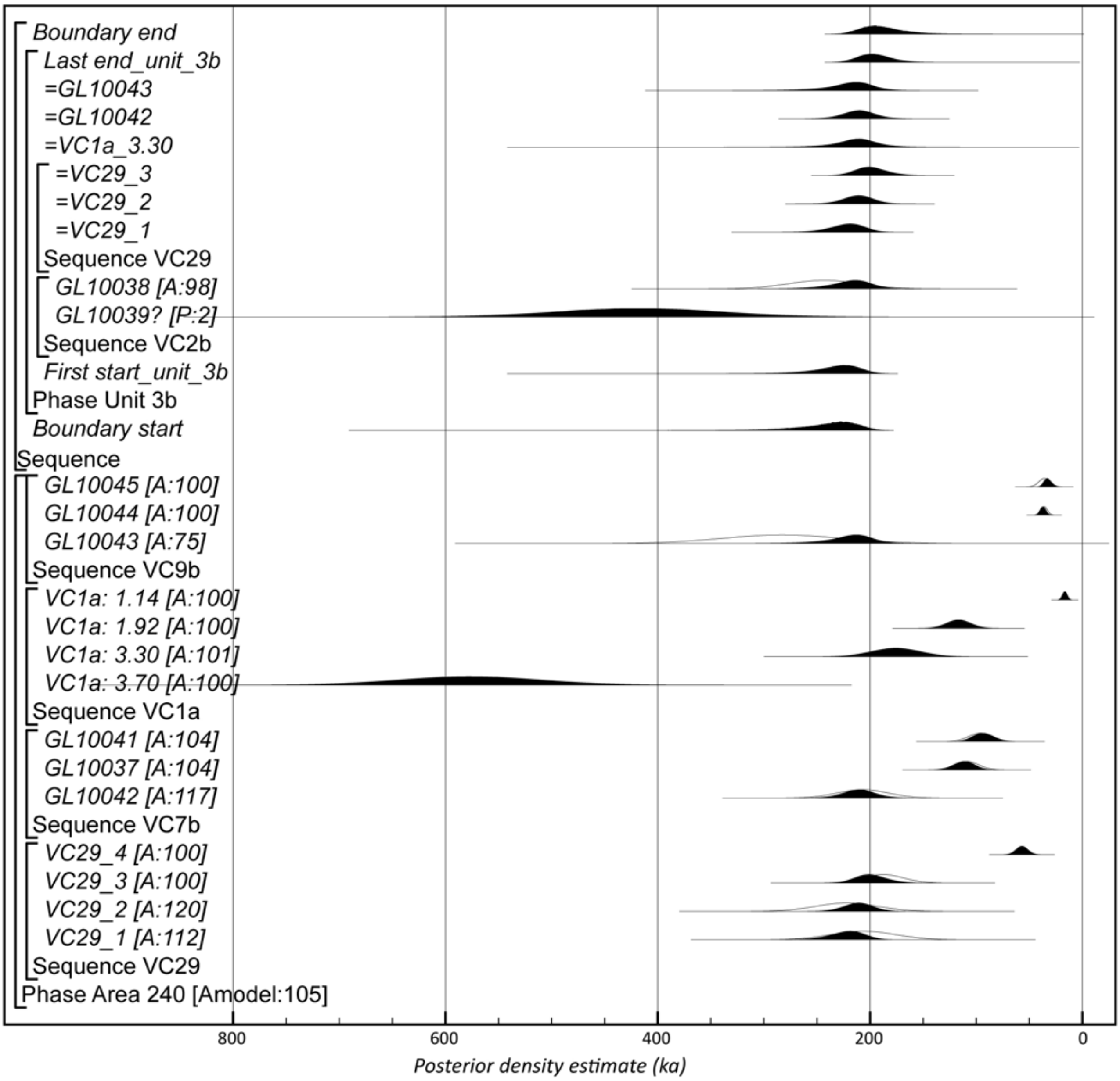


Figure 35: Probability distributions of dates from vibrocores in and around Area 240 (locations shown in Fig. 33). The large square brackets down the left-hand side of the diagram, along with the OxCal keywords define the overall model exactly.

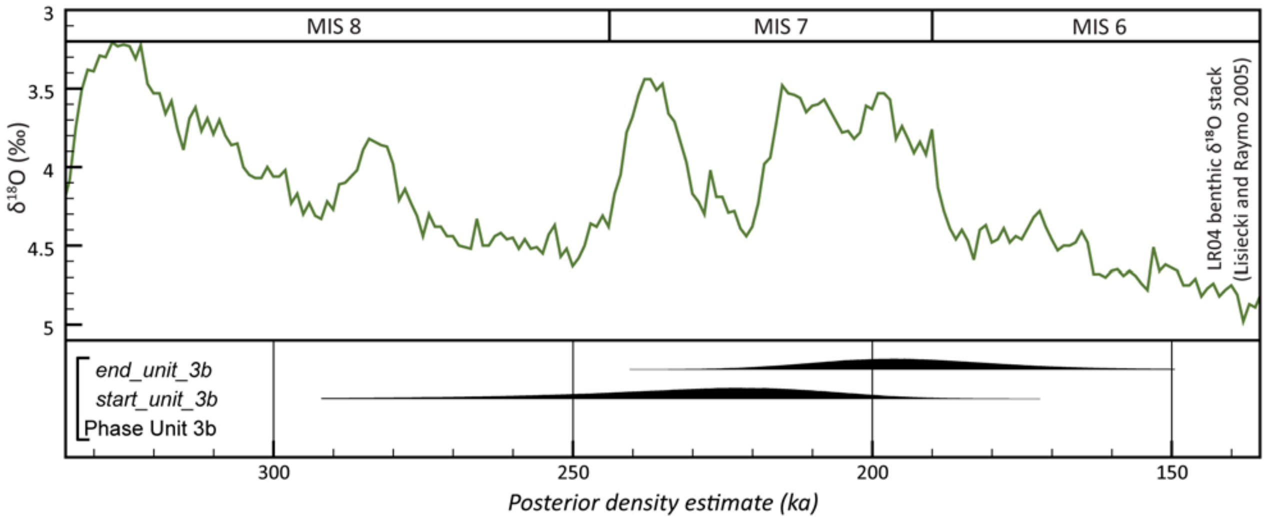


Figure 36: Probability distributions for the beginning and end of the formation of Unit 3b in and around Area 240 (derived from the model shown in Fig. 35). The upper panel shows the Marine Oxygen Isotope record.

5.5 Pin Hole, Creswell Crags, Derbyshire

Alistair Pike

In ideal circumstances samples for Uranium-Thorium dating would be collected during controlled excavation. Many archaeologically important cave sites were excavated, however, in the 19th or early 20th century using now-outdated excavation methods and recording. This means that caves containing intact and undisturbed Pleistocene deposits are rare in England.

Age constraints for the museum collections derived from these excavations, however, can be obtained if flowstones were left in situ in the excavated cave. These can be sampled and related to the excavated assemblage within the museum collection. Flowstones collected as part of the archaeological assemblage can also be sampled for dating.

For example, during excavations at Pin Hole, Creswell Crags, Derbyshire, in 1925, flowstones were collected (Fig. 37). Leslie Armstrong, the excavator, collected stalactites and stalagmites (collectively known as speleothems) believing them to be tools (Armstrong 1932). The three-dimensional position of the bones and artefacts, including the calcite, were recorded, enabling us to reconstruct the stratigraphy (Fig. 38). This consists of two units: an upper layer containing Upper Palaeolithic or Mesolithic flint blades and a lower layer containing Mousterian non-flint artefacts along with fauna (including reindeer, spotted hyaena, woolly rhinoceros and horse) and datable speleothems (Jacobi et al. 1998).

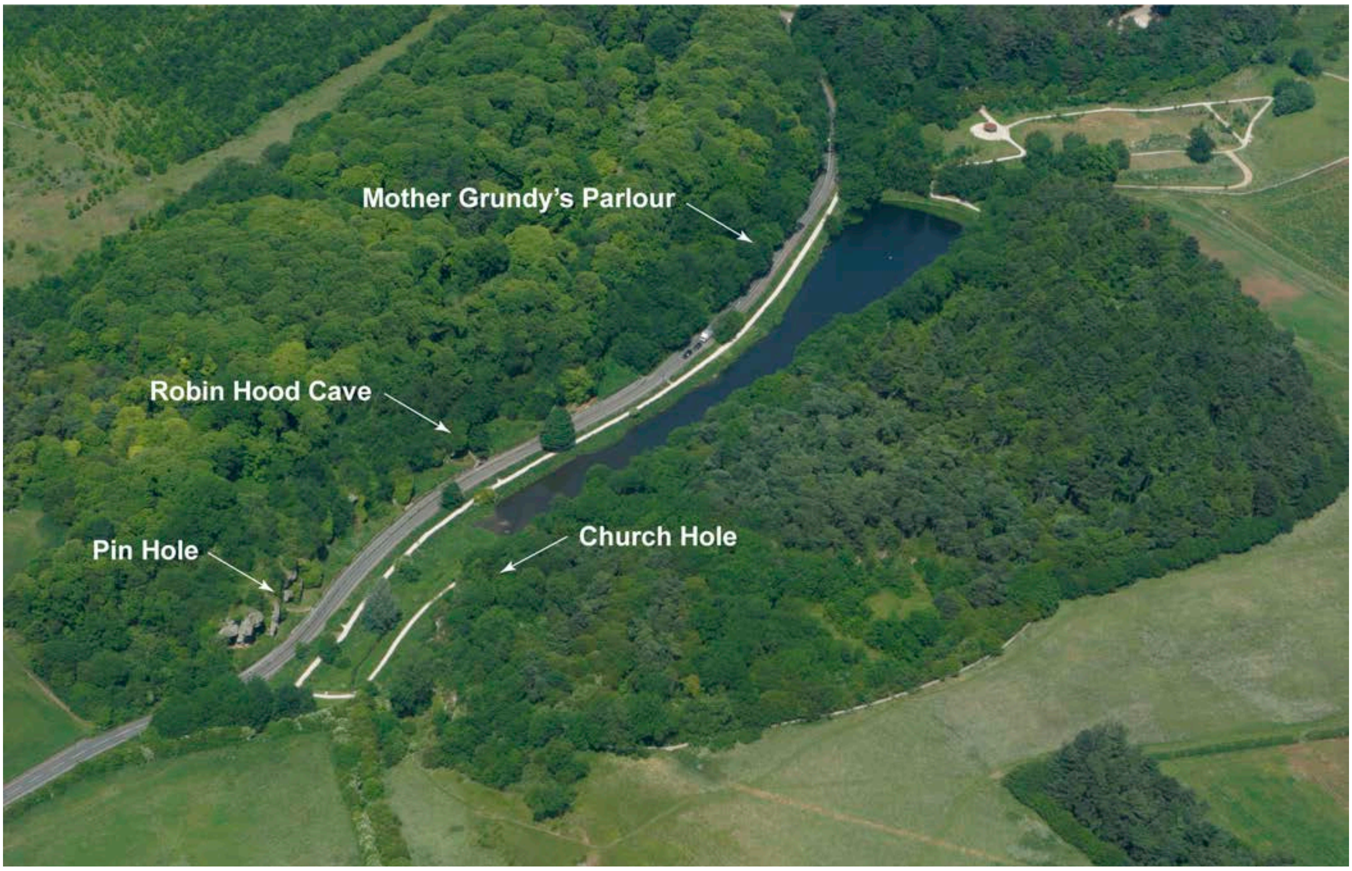


Figure 37: Aerial photograph of Creswell Crags showing the location of Pin Hole and other caves. [20276_013 © Historic England Archive]

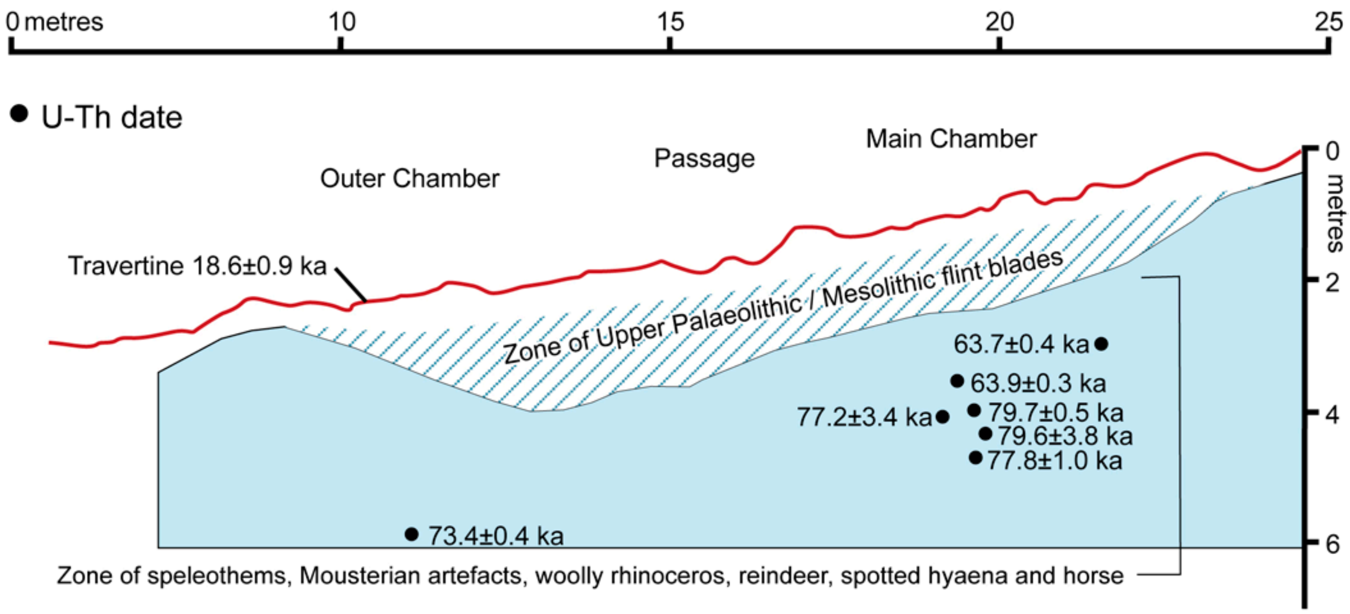


Figure 38: The reconstructed stratigraphy of Pin Hole cave showing artefact zones and dated calcite samples. [after Jacobi et al. 1998]

The Uranium-Thorium ages are scattered (Table 6), reflecting the variable ages of the speleothems before they became incorporated in the archaeological layer. However, the youngest age (64 ka) provides a maximum age (*terminus post quem*) for the fauna and Middle Palaeolithic artefacts with which they are associated, and also a maximum age for the archaeological assemblages in the level immediately above.

This study is important because the maximum age of 64 ka supported the idea that hominins were absent in Britain during the preceding interglacial (Ipswichian; MIS 5e) but returned at the end of MIS 4. Additionally, the distinctive fauna at Pin Hole, chronologically constrained by these Uranium-Thorium dates and additional Electron Spin Resonance (*see* Text Box 4) and Radiocarbon dating, is critical in defining a stage in the formal mammalian biostratigraphy for the Late Pleistocene of Britain (Currant and Jacobi 2001).

Table 6: Uranium-Thorium TIMS data. Sample number is Armstrong's find co-ordinate. Mid and Upp refer to middle and upper layers, respectively, of calcites with more than one growth phase, separated by hiatuses.

Sample number	^{238}U (μg g^{-1})	$^{230}Th/^{232}Th$	$^{234}U/^{238}U$	$^{230}Th/^{238}U$	$^{230}Th/^{234}U$	Age (ka)
32/5'	0.105	376±4	1.154±0.002	0.683±0.001	0.592±0.005	94.8±1.3
36/12'	0.120	26.6±0.2	1.212±0.001	0.605±0.005	0.499±0.002	73.4±0.4
51/8'	0.105	2625±7	1.219±0.001	0.715±0.003	0.587±0.002	92.8±0.4
59/11' Upp	0.063	98±3	1.075±0.001	0.619±0.022	0.576±0.020	92.1±5.0
63/8' Upp	0.121	523±2	1.195±0.001	0.539±0.003	0.451±0.003	63.9±0.3
64/10P	0.087	25.0±0.1	1.183±0.001	0.625±0.004	0.528±0.002	79.7±0.5
64/12P Mid	0.098	98±1	1.191±0.001	0.619±0.009	0.519±0.005	77.8±1.0
64/12P Upp	0.051	11.9±0.9	1.135±0.003	0.553±0.034	0.487±0.036	71.5±7.7
69/7'	0.116	2340±13	1.227±0.001	0.699±0.007	0.569±0.003	88.5±0.7
70/8'	0.094	95±3	1.190±0.002	0.534±0.003	0.449±0.002	63.7±0.4
12/Pii	0.060	87±2	1.140±0.002	0.544±0.002	0.477±0.002	69.4±0.4

5.6 Lynford Quarry, Mundford, Norfolk

Peter Marshall and Zoe Outram

In 2002 a palaeochannel was observed during archaeological monitoring at Lynford Quarry, Mundford, Norfolk. The palaeochannel had a dark organic fill containing mammoth remains and associated Mousterian stone tools in situ, as well as debitage buried under 2–3m of bedded sands and gravels (Fig. 39). Well-preserved in situ Middle Palaeolithic open-air sites are unusual in Europe and exceedingly rare in England, so this site is of international importance.

The palaeochannel and associated deposits with archaeological remains were subsequently excavated and recorded by the Norfolk Archaeological Unit (Boismier et al. 2012). This provides a range of spatial, palaeoenvironmental and taphonomic information about the deposits and their formation. It also provides information on the associated hominin activity, including for investigating questions of diet, land use and habitat.

Figure 39: Excavation of mammoth tusk and associated flint tools at Lynford Quarry. [AA028489 © Historic England Archive]

The lithic assemblage was dominated by Mousterian tools — handaxes and bifacial scrapers characteristic of the Late Middle Palaeolithic, *c.* 59–38 ka. The handaxes are of a form frequently associated with Neanderthals. Reliable dating evidence for this activity is important to better understand when England was re-occupied by hominins after the cold stage of MIS 4.

Biostratigraphic evidence from the faunal remains suggested that the site was older than 30 ka and probably older than *c.* 41 ka, based on the known presence of woolly mammoths (*Mammuthus primigenius*), woolly rhinoceros (*Coelodonta antiquitatis*) and spotted hyena (*Crocuta crocuta*).

Seventeen OSL dates (Table 7; *see* Luminescence dating) and eight radiocarbon dates (Table 8; *see* Radiocarbon dating) from the site are incorporated into a Bayesian chronological model (Fig. 40). Amino Acid Racemisation analysis failed because of poor preservation of shells. Prior information about the relationship between samples is derived from direct stratigraphic relationships and from the sedimentological model for the formation of the site.

The model establishes a chronological framework for fluvial activity with the infilling of the channel (Association B) estimated to have started in *76–60 ka* (*95% probability*; *First association_B*; Fig. 40) and probably in *72–63 ka* (*68% probability*). Fine-grained organic sediments continued to be deposited in the channel until *65–52 ka* (*95% probability*; *OxL-1340*; Fig. 40) and probably *62–54 ka* (*68% probability*) when beds of laminated sands began to accumulate.

Radiocarbon measurements from two mammoth bones recovered from the Association B channel organic sediments are close to the reliable limits of the technique (*see* Radiocarbon dating) and suggest that the true age of the faunal material is probably in excess of 50 ka. The model suggests this dating and highlights one of the challenges faced when investigating Middle Palaeolithic sites: that the earlier part of the period is beyond the range of radiocarbon dating.

The hominin activity recorded at Lynford can therefore be dated to late MIS 4 and/or MIS 3 as Neanderthals re-occupied England after a long hiatus during the cold stage of MIS 4.

Table 7: Lynford Quarry quartz Optically Stimulated Luminescence dates (Schwenninger and Rhodes 2005).

Age estimate code	**Field code**	**Lab. code**	**Facies unit**	**Height (m OD)**	**Context (*contained lithic artefacts)**	**Palaeodose (Gy)**	**Total dose rate (Gy ka^{-1})**	**In situ γ-ray spectrometry**	**Age (ka)**	***Highest Posterior Density Interval – ka (95% probability)***
OxL-1337	LYN03-01	X1098	A	6.102	20327	47.90±2.80	0.610 ± 0.04	Yes, but poor geometry	78.6±6.7	*93–70*
OxL-1490	LYN03-02	X1099	B-ii:03	8.362	20003*	56.55±2.51	0.87 ± 0.06	Yes	64.8±5.5	*76–60*
OxL-1338	LYN03-03	X1100	B-ii:03	8.532	20003*	60.86±3.83	1.04±0.07	Yes	58.3±5.6	*69–56*
OxL-1491	LYN03-04	X1101	B-ii:05	8.655	20002*	66.84±2.93	1.20±0.06	No	55.9±3.9	*63–52*
OxL-1492	LYN03-05	X1102	B-ii:05	8.752	20005*	67.64±2.65	1.27±0.05	Yes	53.4±3.3	*59–49*
OxL-1339	LYN03-06	X1103	B-iii	8.723	20015*	41.30±1.83	0.86±0.04	Yes	48.0±3.2	*55–46*
OxL-1340	LYN03-07	X1104	B-ii:05	9.107	20002*/20003*	72.50±3.10	1.19±0.06	Yes	60.7±4.3	*65–52*
OxL-1493	LYN03-08	X1160	?B-ii:02	7.750	20357	60.00±3.38	0.92±0.08	Yes	65.0±6.9	*80–61*
OxL-1494	LYN03-09	X1161	B-ii:02	7.700	20390*/20403*	47.88±2.20	0.69±0.05	No	69.9±6.1	*75–57*
OxL-1495	LYN03-10	X1162	B-ii:02	8.000	20371*	45.86±1.61	0.77±0.05	Yes	59.5±4.9	*67–49*
OxL-1496	LYN03-11	X1163	B-ii:01	7.614	20254*	45.82±2.25	0.80±0.04	Yes, but poor geometry	57.4±4.2	*54–43*
OxL-1497	LYN03-12	X1164	D	9.908	20205	15.23±0.98	0.44±0.02	Yes	34.7±2.9	*41–28*
OxL-1498	LYN03-13	X1165	E (Holocene)	11.04	20317	0.68±0.04	0.70±0.03	Yes	0.97±0.08	-
OxL-1499	LYN03-14	X1166	E (Holocene)	11.481	20285	0.90±0.09	0.83±0.04	Yes	1.08±0.12	-
OxL-1500	LYN03-15	X1167	D	10.656	20305	23.12±0.78	0.71±0.04	Yes	32.4±2.2	*37–27*
OxL-1501	LYN03-16	X1837	Pre-A	*c.* 12.56	Test pit 15	115.93±9.20	0.65±0.09	No	175.6±27.7	-
OxL-1502	LYN03-17	X1838	Pre-A	*c.* 17.30	Test pit 17	131.35±14.20	0.78±0.09	No	169.2±26.9	-

Table 8: Lynford Quarry radiocarbon and associated stable isotope measurements.

Laboratory Code	Sample number	Material and context	Radiocarbon Age (BP)	$\delta^{13}C_{IRMS}$ (‰)	*Highest Posterior Density Interval – cal BP (95% probability)*
GrN-28399	30085	Bulk sediment, humin from the basal unit of the Holocene deposits of Association E	1050±110	−28.2	—
GrN-28400	30085	Bulk sediment, humic – as GrN-28399	1310±80	−29.2	
GrN-28395	30377	Peat, humin from the base of a palaeochannel cut by the east-facing section at the western edge of the quarry, *c*. 118m west of the excavation area	$35{,}710 \pm^{930}_{830}$ BP	−28.0	*41,800–38,900*
GrN-28396	30377	Peat, humin – as GrN-28395	$35{,}800 \pm^{1200}_{1050}$ BP	−25.8	
GrN-28397	30378	Peat, humin from the upper fill of a palaeochannel cut by the east-facing section at the western edge of the quarry, *c*. 118m west of the excavation area	30,340±350	−28.3	*35,000–33,900*
GrN-28398	30378	Peat, humic – as GrN-28398	$30{,}690 \pm^{620}_{570}$ BP	−27.8	
OxA-11571	50137	Tooth, *Mammuthus primigenius*, anterior fragment of molar DM3 or M1	53,700±3100	−21.2	—
OxA-11572	50000	Animal bone, *Mammuthus primigenius*, part of mandible attached to molar DM3	<49,700	−21.1	—

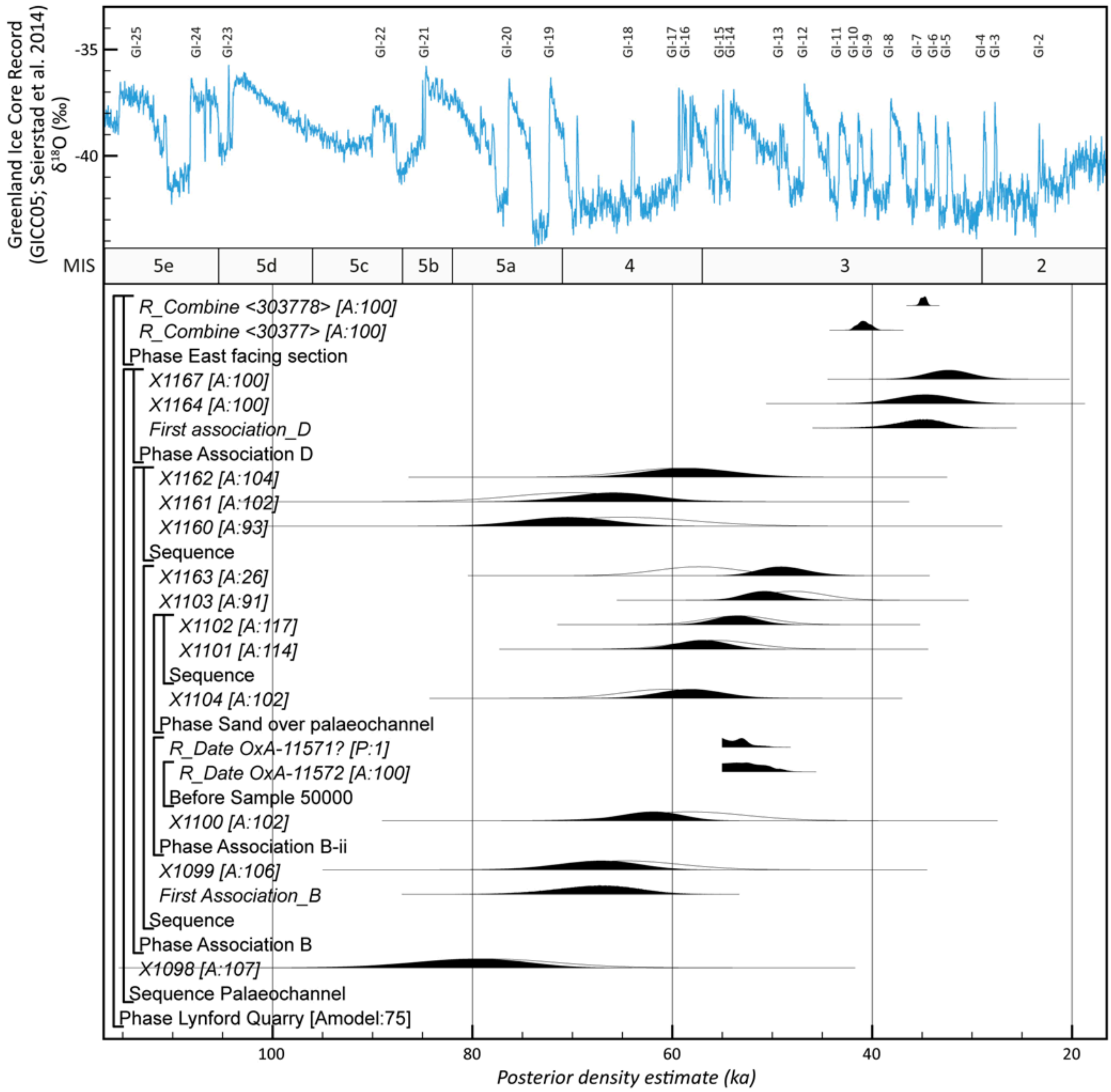


Figure 40: Probability distributions of dates from Lynford Quarry. The large square brackets down the left-hand side of the diagram, along with the OxCal keywords, define the overall model exactly. The upper panel shows the Greenland Ice Core record.

5.7 Gransmoor, East Yorkshire

Peter Marshall

A working sand and gravel quarry about 1km west of the village of Gransmoor, East Yorkshire, exposed Lateglacial sediments that had accumulated in a kettle hole within fluvio-glacial deposits laid down at the end of the Late Devensian. The most complete and comprehensively studied sequence came from more than 2m of aquatic and semi-terrestrial deposits that overlay several metres of glacial sands in a working face on the north side of the quarry (Fig. 41). Palynological, coleopteran, molluscan and geochemical studies of samples from this sequence enables a detailed reconstruction of environmental and climatic change during the Lateglacial period (Walker et al. 1993; Lowe et al. 1995).

Figure 41: The Lateglacial sequence exposed at Gransmoor.
The light coloured sediments at the base are the non-polleniferous sands and silts; the Lateglacial interstadial/Loch Lomond stadial boundary coincides with the thin white band within the centre of the darker organic clays. [Photograph by M Walker]

Age-depth models (Parnell et al. 2011) are crucial for establishing the temporal framework of paleoenvironmental archives such as those from Gransmoor. Twenty-five radiocarbon measurements (*see* Radiocarbon dating) are available from the site (Table 9). The samples were processed according to methods outlined in Mook and Waterbolk (1985). The acid-insoluble, alkali-soluble ('humic acid') and the alkali- and acid-insoluble ('humin') fractions were dated. Radiocarbon measurements from six samples (SRR-) were determined by liquid scintillation spectrometry (Harkness and Wilson 1972), although 19 samples produced insufficient carbon dioxide for conventional dating, and so sub-samples were sent for graphitisation and dating by accelerator mass spectrometry (AA-), as described by Slota et al. (1987) and Linick et al. (1986).

The two measurements from 1.70m are statistically inconsistent at the 5% level (T'=44.5, T'(5%)=3.8, ν=1; Ward and Wilson 1978) and we have preferred the terrestrial macrofossil sample (AA-12004) over the humic fraction of the bulk sediment sample (SRR-3875) for the age of this horizon, as the macrofossil date shows better agreement (cf. Blockley et al. 2004). The four basal samples have elevated $\delta^{13}C$ values consistent with a hard-water reservoir effect (Bayliss and Marshall 2022, section 1.6), which would make their dates anomalously old. They have therefore been excluded from the age-depth model shown in Figure 42.

Age-depth modelling was implemented with rBacon version 3.2.0 (Blaauw and Christen, 2011) in R (R Core Team, 2021) using IntCal20 (Reimer et al. 2020). The accumulation rate prior was set at 10 yr/cm as a gamma distribution (Fig. 42 – upper middle). A second parameter (acc.shape), which controls how much influence the accumulation rate has on the model, was set at the default 1.5 recommended by Blaauw and Christen (2011).

Radiocarbon age distributions in rBacon are derived from the Student's-t distribution, which produces calibrated distributions with longer tails than the Normal model (Christen and Pérez 2009). The longer tails on radiocarbon dates, and a prior assumption of unidirectional sediment accumulation, mean in most cases excluding outliers is not necessary when using rBacon. Thus, unlike previous attempts to produce age-depth models for Gransmoor using OxCal (e.g. Blockley et al. 2004; Elias and Matthews 2013), no radiocarbon dates, apart from SRR-3875 and those with a hard water offset, were excluded from the rBacon model.

Figure 42 shows the resulting age-depth model. The sequence from Gransmoor is estimated to span the period from *14,170–13,630 cal BP* (*95% probability*; *2.35m*; Fig. 40) to *11,910–11,380 cal BP* (*95% probability*; *0.23m*; Fig. 42), with deposition of sediments occurring in the Windermere interstadial (GI-1) and Loch Lomond stadial (GS-1; *see* Fig. 8). Age-depth modelling allows 'events' in a sedimentary sequence that have not been directly dated to be plotted against time, as opposed to depth, with quantified estimates of their chronological uncertainties (Blaauw et al. 2007).

Table 9: Gransmoor Quarry radiocarbon and associated stable isoptope measurements (Lowe et al 1995; Walker et al 1993).

Laboratory code	Material and depth	$\delta^{13}C_{IRMS}$ (‰)	Radiocarbon Age (BP)
AA-13299	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 0.4m	−28.6±0.1	10,150±80
AA-13298	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 0.5m	−29.5±0.1	10,215±90
AA-13297	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 0.6m	−29.0±0.1	10,355±75
AA-13296	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 0.7m	−27.5±0.1	10,835±80
AA-13295	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 0.85m	−29.2±0.1	10,340±85
AA-13294	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 0.95m	−28.9±0.1	9745±85
AA-13293	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 1.01m	−28.8±0.1	10,565±75
AA-13292	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 1.15m	−29.7±0.1	10,385±75
SRR-3873	Bulk sediment, humic fraction from 1.20m	−27.8±0.1	11,715±45
AA-13291	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 1.35m	−29.2±0.1	10,275±90
SRR-3874	Bulk sediment, humic fraction from 1.38m	−28.0±0.1	11,530±50
AA-13290	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 1.42m	−29.5±0.1	10,575±80
AA-12005	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 1.60m	−25.6±0.1	11,335±80
SRR-4920	Wood, from 1.69m	−27.2±0.1	11,475±50
AA-12004	*Carex* fruits, from 1.70m	−25.5±0.1	11,195±80
SRR-3875	Bulk sediment, humic fraction from 1.70m	−29.2±0.1	11,820±45
SRR-3876	Bulk sediment, humic fraction from 1.74m	−28.9±0.1	12,340±45
AA-12003	*Carex* fruits, from 1.78m	−26.2±0.1	10,905±75
AA-12002	*Carex* fruits, from 1.88m	−25.8±0.1	11,300±80
SRR-3877	Bulk sediment, humic fraction from 1.95m	−30.1±0.1	12,790±45
AA-12001	*Carex* fruits, from 2.05m	−24.8±0.1	11,565±85
AA-12000	Aquatic macrophytes from 2.14m	−12.5±0.1	15,060±100
AA-11999	Aquatic macrophytes from 2.17m	−11.5±0.1	13,375±90
AA-11998	Aquatic macrophytes from 2.24m	−9.9±0.1	13,160±90
AA-11997	Aquatic macrophytes and sedge remains from 2.26m	−10.2±0.1	12,445±90

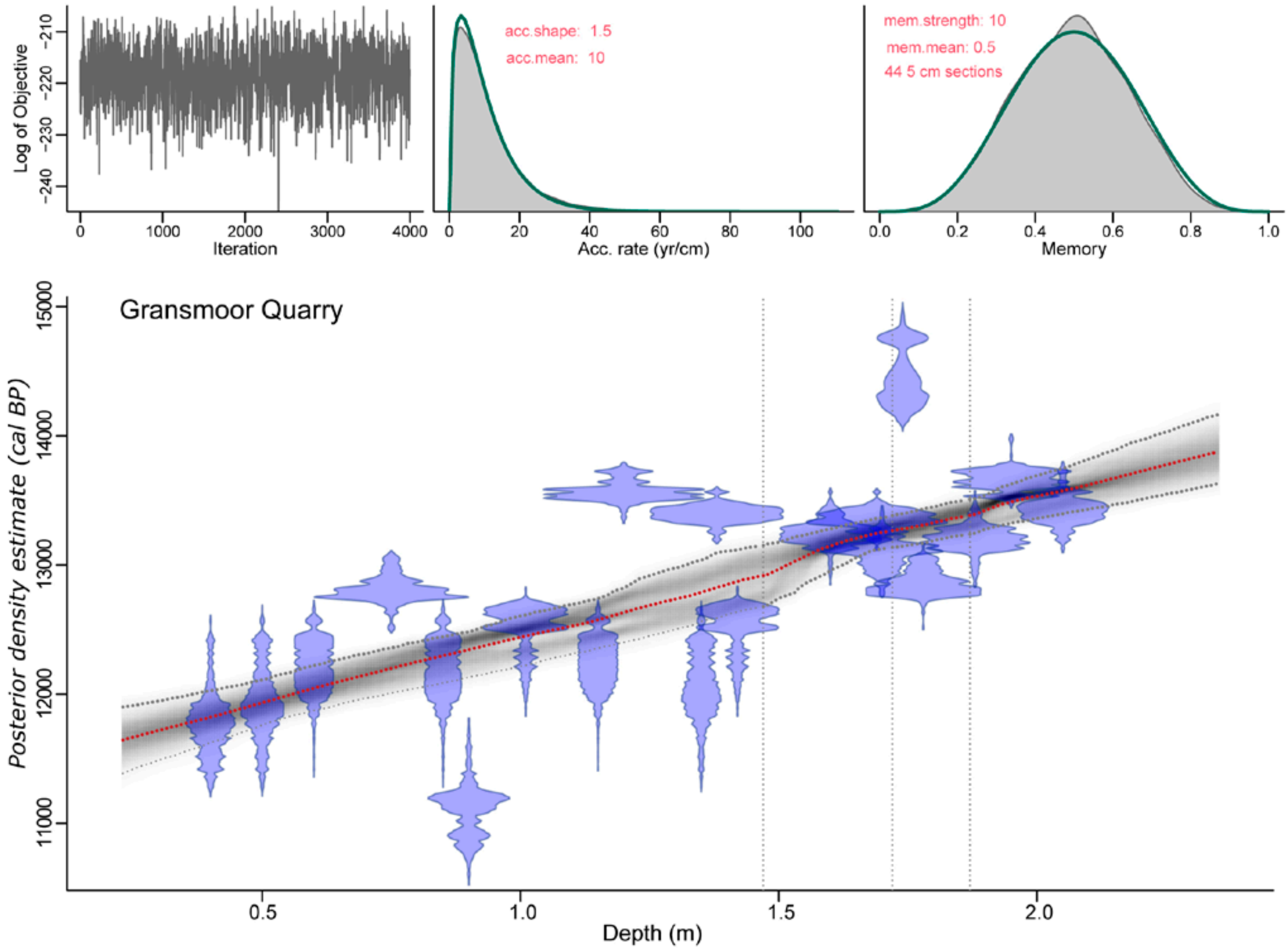
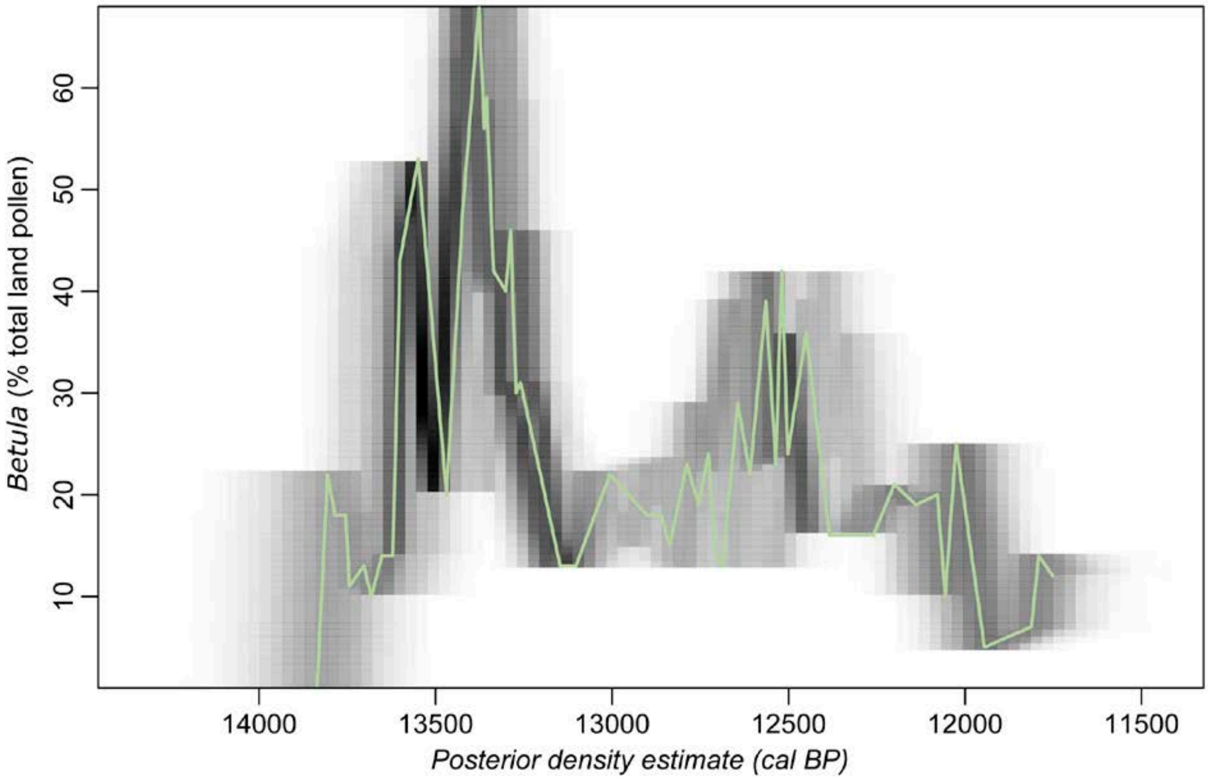
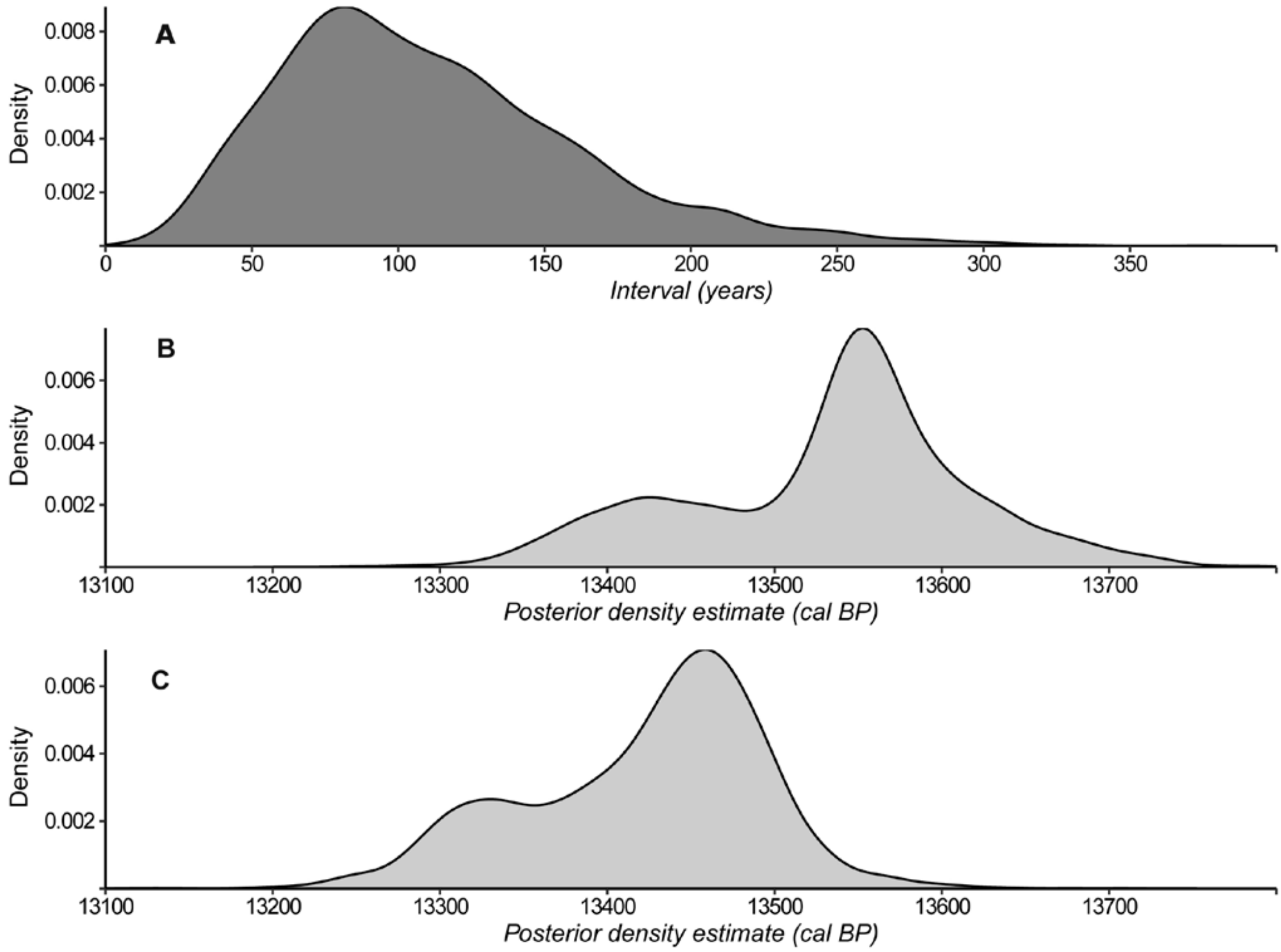


Figure 42: Gransmoor sequence based on rBacon (Blauuw and Christen 2011). The three panels depict: MCMC iterations (top-left panel; a stationary distribution with little structure among neighbouring iterations = good run); the prior (green curve) and posterior (grey histogram) distributions for the accumulation rate (top-middle panel); and the prior (green curve) and posterior (grey histogram) distributions for memory (top-right panel). The main bottom panel shows the calibrated radiocarbon dates (transparent blue), and the age-depth model (darker greys indicate more likely calendar ages. Grey stippled lines show 95% Highest Posterior Density intervals and the red curve shows the single 'best' model) based on the weighted mean age for each depth. The dashed lines denote the position of major boundaries in the stratigraphic record.

Figure 43 (top, page 86): Gransmoor *Betula* (% total land pollen) proxy.ghost graph that shows the entire MCMC run output from Figure 42. The less certain sections are lighter grey than more certain sections and the median age is shown in green.

Figure 44 (bottom, page 86): Posterior density estimates for the length of time (A) between 2.0m and 1.9m at Gransmoor, and the end (B) and start (C) of fluctuations in the percentage values of *Betula.*


Betula (% total land pollen)
10
20
30
40
50
60
14000
13500
13000
12500
12000
11500
Posterior density estimate (cal BP)


A
Density
0.008
0.006
0.004
0.002
0
50
100
150
200
250
300
350
Interval (years)
B
Density
0.006
0.004
0.002
13100
13200
13300
13400
13500
13600
13700
Posterior density estimate (cal BP)
C
Density
0.006
0.004
0.002
13100
13200
13300
13400
13500
13600
13700
Posterior density estimate (cal BP)

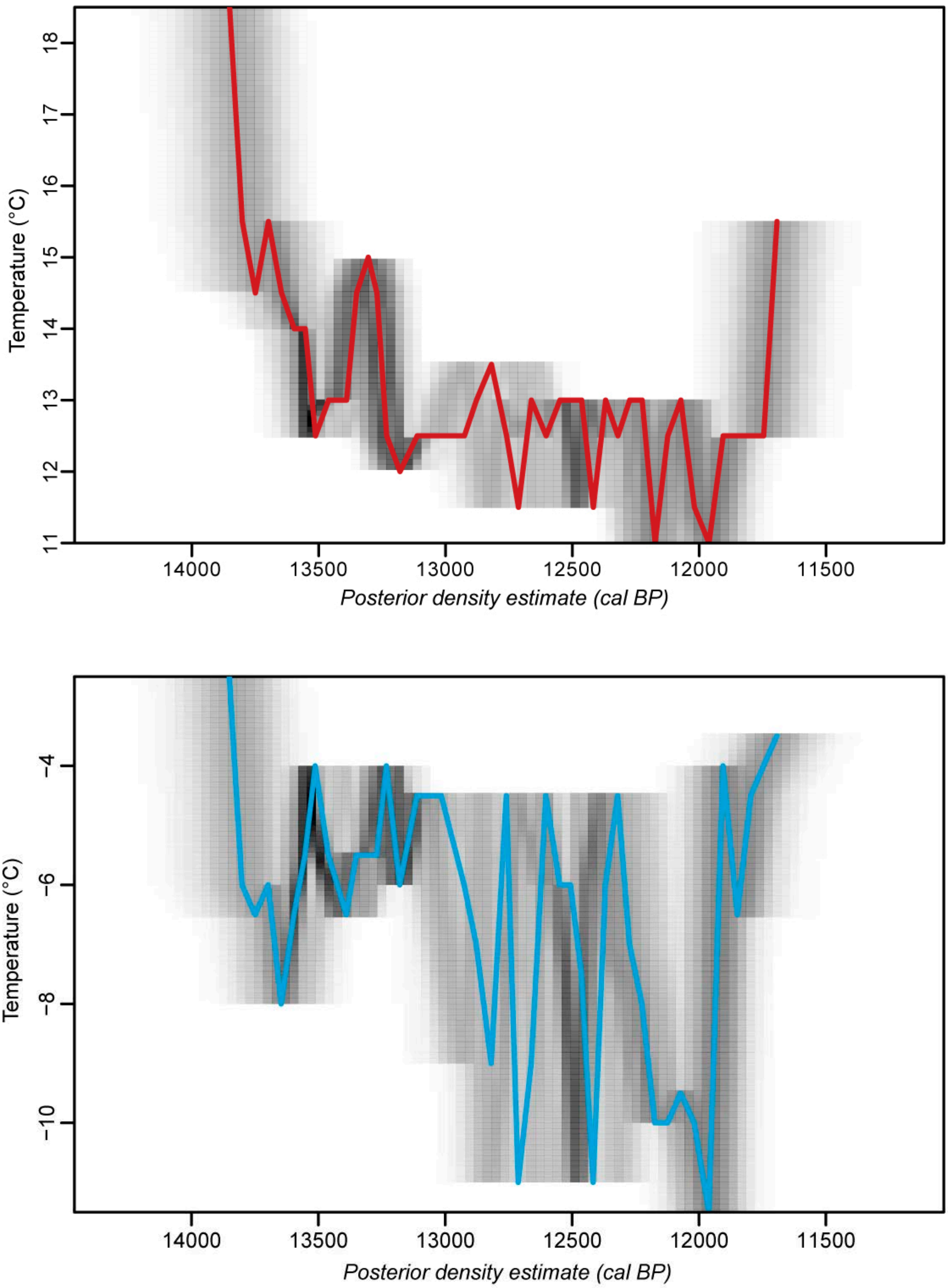


Figure 45: Lateglacial temperature changes from Gransmoor through time (data from c14.arch.ox.ac.uk.intimate; Elias and Matthews 2013) proxy.ghost graph that shows the entire MCMC run output from Figure 42. The less certain sections of the chronology are lighter grey than more certain sections; the red line (top) indicates reconstructed temperature in the warmest month; and the blue line (bottom) indicates reconstructed temperature in the coldest month.

To illustrate this, a feature of the pollen record from Gransmoor is the decline and subsequent recovery of *Betula* values that follow an initial abrupt rise for the genus (Sheldrick et al. 1997, fig 3). The decline from >60% to below 20% total land pollen in less than 100mm can be estimated from the age-depth model (Fig. 43) to have taken place between *13,690–13,350 cal BP* (*95% probability*; Fig. 44a) and *13,540-13,270 cal BP* (*95% probability*; Fig. 44b) over an interval of *30–240 years* (*95% probability*; Fig. 44c).

The age-depth model can also be used to provide a chronology for the reconstructed temperature changes derived from the fossil insect assemblage (Atkinson et al. 1987; Elias and Matthews 2013). Figure 45 illustrates that Late Pleistocene temperatures at Gransmoor oscillated rapidly on a large scale.

Finally, an Upper Palaeolithic antler barbed point embedded in a piece of wood was recovered at a depth of 1.69m in the sediment sequence (Sheldrick et al. 1997; Fig 46). This artefact was not directly dated as it was considered too valuable to be sub-sampled. The age-depth model suggests that this artefact was deposited in *13,360-13,110 cal BP* (*95% probability*; *1.69m*).

The sequence provided by the stratigraphy at Gransmoor assures strong prior beliefs for the construction of the age-depth model and highlights the importance of sequence in the construction of Bayesian models.

Figure 46: The barbed point recovered from Gransmoor, showing two intact barbs and criss-cross markings. [P Gentil © Hull and East Riding Museum: Hull Museums]

6. Practicalities

6.1 Project organisation and planning

Peter Marshall

Government guidance set out in the National Planning Policy Framework (NPPF) (Department for Communities and Local Government 2024) enshrines the principle of sustainable development in the planning process. Where archaeological projects are commissioned to inform the planning process the information sought should be proportionate to the significance of the heritage asset and to the potential impacts of the proposed development.

Assessments of heritage assets in advance of determinations of planning applications should therefore be sufficient to provide an understanding of the significance of heritage assets and their settings, affected either directly or indirectly by the development proposals (e.g. desk-based assessment or field evaluation where appropriate).

Specifications/briefs

These guidelines apply to all archaeological projects, but are aimed primarily at those undertaken as part of the planning process. To facilitate early identification of potential Pleistocene deposits, a comprehensive desk-based assessment is critical. This should include consultation with local planning archaeologists, the Historic England regional science advisor and Palaeolithic archaeologists/Quaternary scientists with knowledge of the area (*see* Historic England 2023, section 3.1.2). Regional/period research frameworks, Historic Environment Records (HER) and British Geological Survey (BGS) mapping can also aid in establishing the potential to encounter Pleistocene deposits (*see* Historic England 2023, section 2).

Historic England's *Curating the Palaeolithic* guidance (Historic England 2023, section 7) outlines the key Pleistocene deposits within which Palaeolithic remains can be found. Many of these deposits are suitable for scientific dating. The selection of appropriate techniques is key, given the available types of datable material, its taphonomic relationship to the archaeological objectives of the project, and the expected time-range of the site (Fig. 9).

Identifying the potential for encountering such deposits early in project planning is critical to enable inclusion of realistic costings and programming for scientific dating in fieldwork specifications. This is particularly important for Pleistocene sites because many of the available scientific dating techniques require specialist on-site sampling.

Curators who need further advice on the potential for using scientific dating on specific Pleistocene sites can obtain independent non-commercial advice from Historic England (*see* section 6.3). Where advice is obtained from a commercial contractor, it is the responsibility of the commissioning body to ensure that vested interests are openly declared, and that subsequent competition is fair (CIfA 2022).

Specifications and briefs should state that scientific dating on Pleistocene sites is to be carried out in accordance with these guidelines. Strategies for dating Pleistocene deposits should be included in Project Designs and in Written Schemes of Investigation. Definitions of briefs, specifications and project designs can be found in the Association of County Archaeological Officers' (1993) Model Briefs and Specifications for Archaeological Assessments and Field Evaluations and in the CIfA's Standard and Guidance series (CIfA 2020a–c; 2023a–f). Named specialists should be included in such documents and curators should, if necessary, ask for details of relevant experience (published papers, reports, etc.).

Chronology is the framework for understanding all archaeological sites, including sites with Pleistocene deposits. When planning archaeological projects, full use should be made of all available sources of information on scientific dating potential. Construction of reliable chronologies should form an integral part of the initial project specification. It should not be simply seen as a contingency or luxury.

Accurate prediction of the presence of Pleistocene deposits and their suitability for different scientific dating techniques can be difficult. Further potential may become apparent during site investigations or in post-excavation assessment. Therefore, the identification of 'contingency funds' within the overall budget would be prudent (Brunning and Watson 2010).

Desk-based assessment

Desk-based assessment is critical in establishing whether Pleistocene deposits are present at a site (Historic England 2023, section 3). This will identify at an early stage the likelihood that scientific dating will be required.

The purpose, definition and standard for desk-based assessment are given in CIfA (2020a). Specialists can contribute to desk-based assessments with information and evaluation of existing scientific dating evidence from previous investigations, and the potential for scientific dating to contribute to the aims and objectives of the project. Such information can be used to inform where to excavate and the scientific dating strategy.

Field evaluation

The purpose, definition and standard for evaluations are given in CIfA (2023a–b). Evaluation to inform planning decisions and mitigation strategies is crucial to understand the nature of the archaeological resource. In some situations, an evaluation might be the only intervention undertaken. Where the potential for encountering Pleistocene deposits is uncertain, preliminary studies such as a geoarchaeological borehole or trial trenching may be appropriate (Canti and Corcoran 2015; Historic England 2023, section 3.4).

As part of the evaluation, scientific dating can make an important contribution to identifying and understanding the potential significance of the Pleistocene archaeological resource.

Examples of the types of questions scientific dating might be used to answer as part of evaluations include:

- Are the deposits suitable for scientific dating?
- What is the age of unexpected discoveries?
- What is the age of the deposits?
- What is the date of the archaeological remains?

Archaeological monitoring and recording

The purpose, definition and standard for archaeological monitoring and recording is given in CIfA (2023c–d). Scientific dating undertaken on samples collected during archaeological monitoring would only be expected in exceptional circumstances (e.g. completely unexpected archaeological finds).

Excavation

Where pre-determination field evaluation (Historic England 2023, section 3.4.3) identifies archaeological and/or palaeoenvironmental deposits with high Palaeolithic potential, further works may be recommended to mitigate their loss (Historic England 2023, section 4.2). The purpose, definition, and standard for excavation is given in CIfA (2023e–f).

Excavation presents better opportunities for the recovery of samples (e.g. Campbell et al. 2011) for scientific dating, and for better understanding their archaeological context. For many dating techniques employed on Pleistocene deposits, specialist on-site sampling can be essential (e.g. Luminescence dating and Palaeomagnetism), and should be stipulated in the Written Scheme of Investigation. Where in situ specialist sampling is not required (e.g. Amino Acid Racemisation or Radiocarbon dating), specialist handling procedures, including packaging and storage, can still apply.

Post-fieldwork assessment

The purpose of post-excavation assessment is to determine the suitability of the available samples for scientific dating and then to design a cost-effective sampling strategy for full analysis.

Analysis of a small number of 'range-finder' samples may be used to establish:

- the broad age of the deposits;
- whether a technique can be used successfully on the site;
- how best to employ a technique.

The selection of samples for range-finder dating will be determined by the nature of the deposits, sample taphonomy, previous successful and unsuccessful dating studies in the area, and the relative ordering of samples as determined through deposit modelling (Historic England 2020) or stratigraphy. On Pleistocene sites, replicate dating using different techniques should be used whenever possible.

For example, at Lynford Quarry, OSL of quartz was successful, radiocarbon dating was at or beyond the limit of detection, and AAR failed because of poor preservation of shells. If dating of this site had relied solely on one of the dating techniques, the site chronology may not have been established.

In some areas of England, previous studies have shown that successful luminescence dating may depend on the local geology (e.g. Bridgland and Long 2011). On some sites, incomplete bleaching or mixing may require single grain, rather than aliquot, analysis to provide a viable chronology (*see* Luminescence dating). Some sites may be at, or exceed, the maximum age limit of OSL, requiring an alternative trapped charge dating technique, such as ESR or pIR-IRSL to be used instead (e.g. Voinchet et al. 2015).

Radiocarbon dating of organic deposits may confirm their suspected Pleistocene age, although the potential for older samples to give finite radiocarbon ages — because they contain low-level recent contamination — should be noted (*see* Table 2). The compatibility, or otherwise, of replicate determinations on different bulk organic fractions will indicate whether an organic deposit can be robustly dated, and thus whether further work on the environmental remains is merited (Bayliss and Marshall 2022, section 3.2).

Once a pool of potential samples that are viable for scientific dating has been identified, a sampling strategy for analysis is needed. This strategy should address the aims and objectives of the project. It needs to combine effectively the results of the scientific dating with other information (such as relative dating provided by site/regional stratigraphy and mapping), to produce a robust and accurate chronology.

The following information is required by the specialist to devise an effective strategy for scientific dating:

- brief account of the nature and history of the site;
- aims and objectives of the project;
- access to the (geo)archaeological results;
- context types and stratigraphic relationships;
- sample locations;
- assessment reports from other relevant specialists, including range-finder dating.

A cost-effective sampling strategy should maximise the relative dating information among the analysed samples. Within this framework, the number of samples that should be dated can be assessed through simulation and Bayesian Chronological Modelling (*see* Bayliss and Marshall 2022, section 3.3.1).

The resultant assessment report should contain:

- statement of potential — how scientific dating can contribute to site, specialist, and wider research questions;
- a list of samples recommended for full analysis;
- justification of the techniques used and number of measurements required;
- details of dating specialists/facilities to be used;
- tasks, time and costings (analysis and publication).

Given the technical complexity of using scientific dating on Pleistocene sites, and the potential expense of scientific dating programmes, a staged approach may be appropriate.

Post-excavation analysis

During post-excavation analysis, the work specified and agreed in the post-fieldwork assessment should be undertaken. Scientific dating specialists will need to work closely with other specialists throughout the analysis stage.

A full technical report should be produced for all the scientific dating undertaken on the site and, where appropriate, for the Bayesian chronological modelling.

This report should include:

- objectives of the study;
- sampling strategy, (including discussion of the selection of scientific dating techniques employed, the available samples, the available prior information, the results of any simulation models, and the rationale by which these elements have been combined into a strategy;
- statements on the methods for the scientific dating techniques employed;
- details of scientific dating results, reported according to established standards for each technique (e.g. Bayliss and Marshall 2022, section 3.6.1);
- chronological model definition and description, including references to relevant software and discussion of the scientific dates and prior information included in the model and their strengths and weaknesses;
- sensitivity analyses, presenting the results of alternative chronological models, if undertaken;
- how these results contribute to regional or period-specific research frameworks;
- recommendations for further work, if appropriate.

Dissemination and archiving

Historic Environment Records (HER)

Current best practice is to report any archaeological intervention, even if only an evaluation. Any report should be deposited with the local HER as quickly as possible after the work is completed. It should also be added to the Online Access to the Index of Investigations (OASIS).

Chronological information may form a component of these reports and results from scientific dating methods should be recorded in HERs.

Publication

Where possible, full details of the methods used and the results generated from each scientific dating technique should be included in the publication. This information can be in the main body of the publication, in an electronic supplement, or deposited in an accessible open-access repository, signposted in the publication. As Pleistocene deposits often require multidisciplinary analyses, the scientific dating results can also be published in dedicated archaeological, Quaternary science and other specialist journals.

Archiving

The scientific dating specialist reports should be included in the material deposited with the other project publications, in accordance with their standards. For guidelines on archive deposition *see* Brown (2011), Longworth and Wood (2000), Museum and Galleries Commission (1992), Walker (1990), Archaeology Data Service (2015) and Archaeology Data Service and Digital Antiquity (2011).

Physical samples are usually stored with the rest of the physical archive (e.g. bones, shells, etc.) and do not require specialist archiving. Package and store them in accordance with current best practice. Sediment samples usually do not form part of the physical archive, unless retention is specified by the curator. Where retention is required, these should be deposited in specialist long-term storage facilities.

6.2 Laboratories

An essential part of the successful application of any dating strategy is early discussion between the field project director and the specialist(s) undertaking the analysis. Note that not all laboratories undertake all forms of analysis, nor do they all provide commercial services. Historic England regional science advisors can provide contact details for specialists and laboratories who may be able to provide scientific dating support.

Radiocarbon dating

All radiocarbon dating laboratories will be happy to advise on the technical aspects of radiocarbon dating that affect the selection of suitable samples, on suitable storage and packaging, and on the methods of sample preparation and dating used in their facility. Some will also be able to advise on the archaeological and statistical aspects of sample selection.

A full list of radiocarbon laboratories is maintained by the journal *Radiocarbon* (https://radiocarbon.org/laboratories).

Uranium-Thorium dating

U-Th dating facilities are common in universities with large geochemistry, oceanography or geology departments. Historic England regional science advisors can provide contact details if required.

Luminescence dating

There are a number of luminescence dating facilities in the UK, largely based in universities, which offer research and, in some cases, commercial services, including on-site sampling. Historic England regional science advisors can provide contact details if required.

Amino Acid Racemisation (AAR)

The main facility in the UK for AAR dating is NEaar (North East Amino Acid Racemization) based at the University of York.

Palaeomagnetism

Palaeomagnetism dating requires specialist laboratory facilities based within university departments. These might be able to undertake work on a commercial basis. Historic England regional science advisors can provide contact details if required.

Tephrochronology

The chemical analysis of tephra shards requires an Electron Probe Microanalyser (EPMA) for major elements and either Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) or Secondary Ion Mass Spectrometry (SIMS) for trace elements. These are hosted by earth science or geography departments in several UK universities, which might also be able to undertake tephra extraction on a commercial basis. Historic England regional science advisors can provide contact details if required.

Biostratigraphy and the 'Vole Clock'

The identification and analysis of Pleistocene biological remains for biostratigraphic purposes, including the 'Vole Clock', requires a specialist. Historic England regional science advisors can provide contact details if required.

7. Where to get advice

A. Historic England (HE)

The first point of contact for general archaeological science enquiries is the HE science advisors, including advice on scientific dating and Bayesian chronological modelling. HE science advisors can provide independent, non-commercial advice. They are based in the HE local offices.

For contact details *see* https://historicengland.org.uk/advice/technical-advice/archaeological-science/science-advisors/

Specific advice on scientific dating and Bayesian chronological modelling can be sought from the Historic England Scientific Dating Team:

Historic England
Cannon Bridge House
25 Dowgate Hill
London EC4R 2YA

Email: c14@historicengland.org.uk

B. Scientific dating laboratories

All laboratories will be happy to advise on the technical aspects of applying their technique to Pleistocene deposits. They can advise on the retrieval and selection of suitable samples, suitable storage and packaging, and the methods of sample preparation and dating used in their facility.

Laboratories put a great deal of skill and effort into dating the samples sent to them accurately. They welcome the opportunity to provide guidance on sample selection to ensure that together you achieve the best dating possible for your samples.

C. On-line resources

Radiocarbon dates

The Project Radiocarbon on-line database at https://doi.org/10.5284/1118748 contains details of many measurements undertaken on archaeological samples from England, Wales, Scotland, and the island of Ireland.

Basic information on 30,517 measurements from England, Wales, Scotland and Ireland gathered by Bevan et al. (2017) can be found at http://dx.doi.org/10.14324/000.ds.10025178.

Basic information on 45,495 measurements from England, Wales, Scotland and Ireland gathered by Bird et al. (2022) can be found at https://github.com/people3k/p3k14c.

Details of measurements undertaken by the Oxford Radiocarbon Accelerator Unit can be found in their on-line database at http://c14.arch.ox.ac.uk/results, and published in a series of datelists in the journal Archaeometry.

Other datelists, particularly for measurements undertaken before *c.* 1980, can be found in the journal Radiocarbon (https://www.cambridge.org/core/journals/radiocarbon).

Radiocarbon calibration databases

The calibration curves that are currently internationally agreed are available at (https://www.intcal.org/); and the data included in them is available at https://www.intcal.org/data.html.

A database of marine reservoir values is provided by the ^{14}CHRONO Centre, Queen's University, Belfast at http://calib.org/marine.

Palaeomagnetism

GEOMAGIA50 — a database providing access to published archaeomagnetic/volcanic and sediment palaeomagnetic and chronological data for the past 50 ka. It is available at http://geomagia.gfz-potsdam.de/

PINT — the Absolute Palaeointensity (PINT) Database, a catalogue of all absolute palaeointensity data with ages > 50 ka that have been published in the peer-reviewed literature. It is available at http://www.pintdb.org/

MagIC — Magnetic Information Consortium (MagIC), an open community digital data archive for rock and palaeomagnetic data. It is available at https://www2.earthref.org/MagIC

Tephrochronology

Resources containing geochemical data associated with tephra are available on-line. No single resource is comprehensive and access to original published datasets, such as within journal articles, is often required to supplement these resources.

RESET — Derived from the 'Response of Humans to Abrupt Environmental Transitions' (RESET) project, a database has been made available containing information on occurrences and chemical compositions of glass shards from tephra and cryptotephra deposits found across Europe. The data include information from the RESET project itself and from the published literature. In addition to these data, RESET also contains a series of tools for the analysis of these data, including statistical approaches to evaluate the likelihood of tephra compositions matched. The database is available at http://c14.arch.ox.ac.uk/reset/; described in Bronk Ramsey et al. (2015b).

Tephrabase — a database focused on providing geochemical, chronological and spatial data for tephra sites, predominantly for sites in Iceland and north-west Europe. The database is available at https://www.tephrabase.org/

EarthChem — a community-driven project facilitating the compilation and dissemination of geochemical data of all types, including tephra. It is a global database and therefore has much broader coverage than RESET. EarthChem is available at https://www.earthchem.org/

GVP — The Smithsonian Institution's Global Volcanism Program (GVP) contains a comprehensive database of global volcanic activity, cataloguing Holocene and Pleistocene volcanoes, and eruptions. It is available at https://volcano.si.edu/

Relevant software

Radiocarbon dating calibration

A variety of freely downloadable software is available for radiocarbon calibration:

Calib — on-line and downloadable versions are available at http://calib.org/calib/ (described in Stuiver and Reimer 1993).

IOSACal — open-source radiocarbon calibration; available at https://iosacal.readthedocs.io/en/latest/index.html

MatCal — open-source Bayesian ^{14}C age calibration in Matlab; available at https://github.com/bryanlougheed/MatCal/ (described in Lougheed and Obrochta 2016).

rcarbon — downloadable software for the calibration and analysis of radiocarbon dates, which runs in the R software environment (http://www.r-project.org/); available at https://cran.r-project.org/package=rcarbon

Trapped charge dating calculations

The online Dose Rate and Age Calculator (DRAC; https://www.aber.ac.uk/alrl/drac) is widely used by the luminescence dating community and is described by Durcan et al. (2015).

Chronological modelling

A variety of freely downloadable software is available for chronological modelling. Some packages enable the construction of a wide range of models; others are more specialised.

a) Flexible Bayesian Chronological Modelling

BCal — online program available at http://bcal.shef.ac.uk/ (described in Buck et al. (1999).

OxCal — online and downloadable versions available at https://c14.arch.ox.ac.uk/OxCal (described in Bronk Ramsey 1995, 1998, 2001, 2008, 2009a–b, 2017; Bronk Ramsey et al. 2001; 2010; and Bronk Ramsey and Lee 2013).

b) Specialist Bayesian Chronological Modelling

rBacon — downloadable package for flexible Bayesian age-depth modelling, which runs in the R software environment (http://www.r-project.org/); available at https://cran.r-project.org/package=rbacon (described in Blaauw and Christen 2011).

Bchron — downloadable package for calibration of radiocarbon dates together with routines for age-depth modelling and relative sea level rate estimation, which runs in the R software environment (http://www.r-project.org/); available at https://CRAN.R-project.org/package=Bchron (described in Haslett and Parnell 2008; and Parnell and Gehrels 2015).

ChronoModel — an open-source downloadable application that provides tools for constructing chronologies, available from https://chronomodel.com (described in Lanos and Dufresne 2024; and Lanos and Philippe 2017; 2018).

Coffee — downloadable package that uses Bayesian methods to enforce the chronological ordering of radiocarbon dates, which runs in the R software environment (http://www.r-project.org/); available at https://cran.r-project.org/package=coffee

c) Classical statistical modelling

Clam — downloadable software for 'classical', non-Bayesian, age-depth modelling, which runs in the R software environment (http://www.r-project.org/); available at https://CRAN.R-project.org/package=clam (described in Blaauw 2010).

8. References

Alley, R. B. 2000 'Ice-core evidence of abrupt climate changes', *Proceedings of the National Academy of Sciences*, 97, 1331–4; https://doi.org/10.1073/pnas.97.4.1331

Alloway, B. V., Lowe, D. J., Larsen, G., Shane, P. A. R., and Westgate, J. A. 2013 'Tephrochronology', in Elias, S. A., and Mock, C. J., eds, The Encyclopaedia of Quaternary Science, 2nd edn., 4, (Amsterdam), 277–304; https://doi.org/10.1016/B0-44-452747-8/00075-2

Archaeology Data Service 2015 *Guidelines for Depositors* (v3); https://archaeologydataservice.ac.uk/advice/guidelinesForDepositors.xhtml (acc. September 2024)

Archaeology Data Service and Digital Antiquity 2011 *Guides to Good Practice*; http://guides.archaeologydataservice.ac.uk (acc. September 2024)

Armstrong, A. L. 1932 'Excavations in the Pin Hole Cave, Creswell Crags, Derbyshire', *Proceedings of the Prehistory Society of East Anglia*, 6 (for 1931), 330–4; https://doi.org/10.1017/S0958841800026156

Ascough, P. L., Bird, M. I., Brock, F., Higham, T. F. G., Meredith, W., Snape, C. E., and Vane, C. H. 2009 'Hydropyrolysis as a new tool for radiocarbon pre-treatment and the quantification of black carbon', *Quaternary Geochronology*, 4(2), 140–7; https://doi.org/10.1016/j.quageo.2008.11.001

Ashton, N., Lewis, S. G., Parfitt, S. A., Penkman, K. E. H., and Coope, G. R. 2008 'New evidence for complex climate change in MIS 11 from Hoxne, Suffolk, UK', *Quaternary Science Reviews*, 27, 652–68; https://doi.org/10.1016/j.quascirev.2008.01.003

Association of County Archaeological Officers 1993 *Model Briefs and Specifications for Archaeological Assessments and Field Evaluations* (Bedford); https://www.algao.org.uk/localgov/planning (acc. September 2024)

Atkinson, T., Briffa, K., and Coope, G. 1987 'Seasonal temperatures in Britain during the past 22,000 years, reconstructed using beetle remains', *Nature*, 325, 587–92; https://doi.org/10.1038/325587a0

Avery, R. S., Xuan, C., Kemp, A. E. S., Bull, J. M., Cotterill, C. J., Fielding, J. J., Pearce, R. B., and Croudace, I. W. 2017 ‘A new Holocene record of geomagnetic secular variation from Windermere, UK’, *Earth and Planetary Science Letters*, 477, 108–22; http://dx.doi.org/10.1016/j.epsl.2017.08.025

Ballantyne, C. K. 2010 ‘Extent and deglacial chronology of the last British-Irish Ice Sheet: implications of exposure dating using cosmogenic isotopes’, *Journal of Quaternary Science*, 25, 515–34; https://doi.org/10.1002/jqs.1310

Barton, R. N. E. 1992 *Hengistbury Head Dorset. Volume 2: the Late Upper Palaeolithic and Early Mesolithic sites*, Oxford University Committee for Archaeology Monograph Series 34 (Oxford)

Barton, N., Ford, S., Collcutt, S., Crowther, J., Macphail, R., Rhodes, E., and van Gijn, A. 2009 ‘A Final Upper Palaeolithic site at Nea Farm, Somerley, Hampshire (England) and some reflections on the occupation of Britain in the Late Glacial interstadial’, in Haidle, M. N., Müller, W., Street, M. and Weniger, G. C., eds, *International Yearbook for Ice Age and Stone Age Research* (Rahden), *Quartär*, 56, 7–35; https://hdl.handle.net/1887/14296

Bayliss, A., and Marshall, P. 2022 *Radiocarbon dating and chronological modelling: guidelines and best practice* (Swindon); https://historicengland.org.uk/images-books/publications/radiocarbon-dating-chronological-modelling (acc. September 2024)

Bayliss, A., Bronk Ramsey, C., van der Plicht, J., and Whittle, A. 2007 ‘Bradshaw and Bayes: towards a timetable for the Neolithic’, *Cambridge Archaeological Journal*, 17(S1), 1–28; https://doi.org/10.1017/S0959774307000145

Bevan, A., College, S., Fuller, D., Fyfe, R., Shennan, S., and Stevens, C. 2017 ‘Holocene fluctuations in human population demonstrate repeated links to food production and climate’, *Proceedings of the National Academy of Sciences*, 114, 49, e10524–31; https://www.pnas.org/doi/full/10.1073/pnas.1709190114

Bird, M. I., Ayliffe, L. K., Fifield, L. K., Turney, C. S. M., Cresswell, R. G., Barrows, T. T., and David, B. 1999 ‘Radiocarbon dating of ‘old’ charcoal using a wet oxidation, stepped-combustion procedure’, *Radiocarbon*, 41, 127–40; https://doi.org/10.1017/S0033822200019482

Bird, D., Lux, M., Vander Linden, M., Robinson, E., Borinsky, R. K., Nicholson, C., Capriles, J. M., Byrd Finley, J., Gayo, E. M., Gil, A., d’Alpoim Gueoles, J., Hoggarth, J. A., Kay, A., Loftus, E., Lombardo, U., Mackie, M., Palmisano, A., Solheim, S., Kelly, R. L., and Freeman, J. 2022 ‘p3k14c, a synthetic global database of archaeological radiocarbon dates’, *Scientific Data*, 9, 27; https://www.nature.com/articles/s41597-022-01118-7#Abs1

Blaauw, M. 2010 'Methods and code for 'classical' age-modelling of radiocarbon sequences', *Quaternary Geochronology*, 5(5), 512–18; https://doi.org/10.1016/j.quageo.2010.01.002

Blaauw, M, and Christen, J. A., 2005 'Radiocarbon peat chronologies and environmental change', *Journal of the Royal Statistical Society: Series C*, 54, 805–16; https://doi.org/10.1111/j.1467-9876.2005.00516.x

Blaauw, M., and Christen, J. A. 2011 'Flexible paleoclimate age-depth models using an autoregressive gamma process', *Bayesian Analysis*, 6, 457–74; https://doi.org/10.1214/11-BA618

Blaauw, M., Christen, J. A., Mauquoy, D., van der Plicht, J., and Bennett, K. D. 2007 'Testing the timing of radiocarbon-dated events between proxy archives', *The Holocene*, 17, 283–8; https://doi.org/10.1177/0959683607075857

Blockley, S. P. E., Lowe, J. J., Walker, M. J. C., Asioli, A., Trincardi, F., Coope, G. R., Donahue, R. E., and Pollard, A. M. 2004 'Bayesian analysis of radiocarbon chronologies: examples from the European Late-glacial', *Journal of Quaternary Science*, 19, 159–75; https://doi.org/10.1002/jqs.820

Blockley, S. P. E., Lane, C. S., Lotter, A. F., and Pollard, A. M. 2007 'Evidence for the presence of the Vedde Ash in Central Europe', *Quaternary Science Reviews*, 26(25–8), 3030–6; https://doi.org/10.1016/j.quascirev.2007.09.010

Blockley, S. P., Bourne, A. J., Brauer, A., Davies, S. M., Hardiman, M., Harding, P. R., Lane, C. S., MacLeod, A., Matthews, I. P., Pyne-O'Donnell, S. D., and Rasmussen, S. O. 2014 'Tephrochronology and the extended intimate (integration of ice-core, marine and terrestrial records) event stratigraphy 8–128 ka b2k', *Quaternary Science Reviews*, 106, 88–100; https://doi.org/10.1016/j.quascirev.2014.11.002

Boismier, W. A., Gamble, C., and Coward, F. 2012 *Neanderthals among Mammoths: Excavations at Lynford Quarry, Norfolk,* (Swindon); https://doi.org/10.5284/1039453

Bond, G., Broecker, W. D., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J., and Bonani, G. 1993 'Correlations between climate records from North Atlantic sediments and Greenland ice', *Nature*, 365, 143–7; http://dx.doi.org/10.1038/365143a0

Bowen, D. Q. 1999 *A Revised Correlation of Quaternary Deposits in the British Isles*, Geological Society Special Report 23 (London); https://doi.org/10.1144/SR23

Bowen, D. Q., and Sykes, G. A. 1999 'Amino acid geochronology', in Roberts, M., and Parfitt, S., eds, *Boxgrove. A Middle Pleistocene hominid site at Eartham Quarry, Boxgrove, West Sussex* (London), 295–7; https://doi.org/10.5284/1028203

Bowen, D. Q., Rose, J., McCabe, A. M., and Sutherland, D. G. 1986 ‘Correlation of Quaternary glaciations in England, Ireland, Scotland and Wales’, *Quaternary Science Reviews*, 5, 229–340; https://doi.org/10.1016/0277-3791(86)90194-0

Brauer, A., Hajdas, I., Blockley, S. P. E., Ramsey, C. B., Christl, M., Ivy-Ochs, S., Moseley, G. E., Nowaczyk, N. N., Rasmussen, S. O., Roberts, H. M., Spotl, C., Staff, R. A., and Svensson, A. 2014 ‘The importance of independent chronology in integrating records of past climate change for the 60–8 ka INTIMATE time interval’, *Quaternary Science Reviews*, 106, 47–66: http://dx.doi.org/10.1016/j.quascirev.2014.07.006

Bridgland, D. R. 1994 *Quaternary of the Thames*. Geological Conservation Review Series, 7 (London)

Bridgland, D. R. 1996 ‘Quaternary river terrace deposits as a framework for the Lower Palaeolithic record’, in Gamble, C. S., and Lawson, A. J., eds, *The English Palaeolithic Reviewed,* (Salisbury), 23–39

Bridgland, D. R. 2000 ‘River terrace systems in north-west Europe: an archive of environmental change, uplift and early human occupation’, *Quaternary Science Reviews*, 19, 1293–1303; https://doi.org/10.1016/S0277-3791(99)00095-5

Bridgland, D. R. 2006 ‘The Middle and Upper Pleistocene sequence in the Lower Thames; a record of Milankovitch climatic fluctuation and early human occupation of southern Britain’, *Proceedings of the Geologists’ Association*, 117, 281–305; https://doi.org/10.1016/s0016-7878%2806%2980036-2

Bridgland, D. R. 2010 ‘The record from British Quaternary river systems within the context of global fluvial archives’, *Journal of Quaternary Science*, 25, 433–46; https://doi.org/10.1002/jqs.1383

Bridgland, D. R., and Allen, P. 2014. ‘Quaternary palaeohydrology and river terraces’, in Catt, J., and Candy, I., eds, *The History of the Quaternary Research Association*, 249–99 (London)

Bridgland, D. R., and Gibbard, P. L. 1997 ‘Quaternary river diversions in the London Basin and the eastern English Channel’, *Géographie physique et Quaternaire*, 51, 337–46; http://dx.doi.org/10.7202/033132ar

Bridgland, D., and Long, A. 2011 ‘Late Quaternary Landscape History of the Swale - Ure Washlands’ (York); https://doi.org/10.5284/1000106

Bridgland, D. R., and White, M. J. 2015 ‘Chronological variations in handaxes: patterns detected from fluvial archives in NW Europe’, *Journal of Quaternary Science*, 30, 623–38; https://doi.org/10.1002/jqs.2805

Bridgland, D. R., Maddy, D., and Bates, M. 2004 'River terrace sequences: templates for Quaternary geochronology and marine–terrestrial correlation', *Journal of Quaternary Science*, 19, 203–18; https://doi.org/10.1002/jqs.819

Bridgland, D. R., Harding, P., Allen, P., Candy, I., Cherry, C., Horne, D., Keen, D. H., Penkman, K. E. H., Preece, R. C., Rhodes, E. J., Scaife, R., Schreve, D. C., Schwenninger, J-L., Slipper, I., Ward, G., White, M. J., White, T. S., and Whittaker, J. E. 2013 'An enhanced record of MIS 9 environments, geochronology and geoarchaeology: data from construction of the High Speed 1 (London – Channel Tunnel) rail-link and other recent investigations at Purfleet, Essex, UK', *Proceedings of the Geologists' Association*, 124, 417–76; https://doi.org/10.1016/j.pgeola.2012.03.006

Bridgland, D. R., Howard, A. J., White, M. J., and White, T. S. 2014 *The Quaternary of the Trent* (Oxford)

Bridgland, D. R., Howard, A. J., White, M. J., White, T. S., and Westaway, R. 2015 'New insight into the Quaternary evolution of the River Trent, UK', *Proceedings of the Geologists' Association*, 126, 466–79; https://doi.org/10.1016/j.pgeola.2015.06.004

Bronk Ramsey, C. 1995 'Radiocarbon calibration and analysis of stratigraphy the OxCal program', *Radiocarbon*, 37, 425–30; https://doi.org/10.1017/S0033822200030903

Bronk Ramsey, C. 1998 'Probability and dating', *Radiocarbon*, 40, 461–74; https://doi.org/10.1017/S0033822200018348

Bronk Ramsey, C. 2001 'Development of the radiocarbon calibration program', *Radiocarbon*, 43, 355–63; https://doi.org/10.1017/S0033822200038212

Bronk Ramsey, C. 2008 'Deposition models for chronological records', *Quaternary Science Reviews*, 27, 42–60; https://doi.org/10.1016/j.quascirev.2007.01.019

Bronk Ramsey, C. 2009a 'Bayesian analysis of radiocarbon dates', *Radiocarbon*, 51, 337–60; https://doi.org/10.1017/S0033822200033865

Bronk Ramsey, C. 2009b' Dealing with outliers and offsets in radiocarbon dating', *Radiocarbon*, 51, 1023–45; https://doi.org/10.1017/S0033822200034093

Bronk Ramsey, C. 2017 'Methods for summarizing radiocarbon datasets'. *Radiocarbon*, 59, 1809–33; https://doi.org/10.1017/RDC.2017.108

Bronk Ramsey, C., van der Plicht, J., and Weninger, B. 2001 '"Wiggle matching" radiocarbon dates', *Radiocarbon*, 43, 381–91; https://doi.org/10.1017/S0033822200038248

Bronk Ramsey, C., Dee, M., Lee, S., Nakagawa, T., and Staff, R. A. 2010 'Developments in the calibration and modelling of radiocarbon dates', *Radiocarbon*, 52, 953–61; https://doi.org/10.1017/S0033822200046063

Bronk Ramsey, C., and Lee, S. 2013 'Recent and planned developments of the program OxCal', *Radiocarbon*, 55, 720–30; https://doi.org/10.1017/S0033822200057878

Bronk Ramsey, C., Albert, P. G., Blockley, S. P., Hardiman, M., Housley, R. A., Lane, C. S., Lee, S., Matthews, I. P., Smith, V. C., and Lowe, J. J. 2015a 'Improved age estimates for key Late Quaternary European tephra horizons in the RESET lattice', *Quaternary Science Reviews*, 118, 18–32; https://doi.org/10.1016/j.quascirev.2014.11.007

Bronk Ramsey, C., Housley, R. A., Lane, C. S., Smith, V. C., and Pollard, A. M. 2015b 'The RESET database and associated analytical tools', *Quaternary Science Reviews*, 118, 33–47; http://dx.doi.org/10.1016/j.quascirev.2014.11.008

Brough, S., Barclay, J., Andrews, J., and Bescoby, D. 2010 'Micro-tephra in the West Runton Freshwater Bed: preliminary results', *Quaternary International*, 228, 21–4; https://doi.org/10.1016/j.quaint.2008.07.011

Brown, D. H. 2011 *Archaeological Archives. A Guide to Best Practice in Creation, Compilation, Transfer and Curation*, 2 edn (Reading); https://doi.org/10.5284/1000078

Brown, T. A., Nelson, D. E., Vogel, J. S., and Southon, J. R. 1988 'Improved collagen extraction by modified Longin method', *Radiocarbon*, 46, 155–63; https://doi.org/10.1017/S0033822200044118

Brunning, R., and Watson, J. 2010 *Waterlogged Wood: Guidelines on the Recording, Sampling, Conservation, and Curation of Waterlogged Wood*, (Swindon); https://historicengland.org.uk/images-books/publications/waterlogged-wood/ (acc. December 2024)

Buck, C. E., Christen, J. A., and James, G. N., 1999 'BCal: an online Bayesian radiocarbon calibration tool', *Internet Archaeology*, 7; https://doi.org/10.11141/ia.7.1

Busschers, F. S., Wesselingh, F., Kars, R., Versluijs-Helder, M., Wallinga, J., Bosch, J., Timmner, J., Nierop, K., Meijer, T., Bunnik, F., and Wolf, H. 2014 'Radiocarbon dating of Late Pleistocene marine shells from the Southern North Sea', *Radiocarbon*, 56, 1151–66; https://www.doi.org/10.2458/56.16505

Campbell, G., Moffett, L., and Straker, V. 2011 *Environmental Archaeology. A Guide to the Theory and Practice of Methods, from Sampling and Recovery to Post-excavation*, 2nd edn (Swindon); https://historicengland.org.uk/images-books/publications/environmental-archaeology-2nd/ (acc. September 2024)

Candy, I., Schreve, D. C., and White, T. S. 2015 'MIS 13–12 in Britain and the North Atlantic: understanding the palaeoclimatic context of the earliest Acheulean', *Journal of Quaternary Science*, 30, 593–609; https://doi.org/10.1002/jqs.2816

Canti, M., and Corcoran, J. 2015 *Geoarchaeology: Using earth sciences to understand the archaeological record* (Swindon); https://historicengland.org.uk/images-books/publications/geoarchaeology-earth-sciences-to-understand-archaeological-record/ (acc. September 2024)

Channell, J. E. T., Xuan, C., and Hodell, D. A. 2009 'Stacking paleointensity and oxygen isotope data for the last 1.5 Myr (PISO-1500)', *Earth and Planetary Science Letters*, 283, 14–23; https://doi.org/10.1016/j.epsl.2009.03.012

Channell, J. E. T., Hodell, D. A., Crowhurst, S. J., Skinner, L. C., and Muscheler, R. 2018 'Relative paleointensity (RPI) in the latest Pleistocene (10–45 ka) and implications for deglacial atmospheric radiocarbon' *Quaternary Science Reviews*, 191, 57–72; https://doi.org/10.1016/j.quascirev.2018.05.007

Channell, J. E. T., Singer, B. S., and Jicha, B. R. 2020 'Timing of Quaternary geomagnetic reversals and excursions in volcanic and sedimentary archives', *Quaternary Science Reviews*, 228, 106114; https://doi.org/10.1016/j.quascirev.2019.106114

Chartered Institute for Archaeologists 2020a *Standard and Guidance for Archaeological Desk-based Assessment* (Reading); https://www.archaeologists.net/codes/cifa (acc. September 2024)

Chartered Institute for Archaeologists 2020b *Standard and Guidance for Archaeological Investigation and Recording of Standing Buildings or Structures* (Reading); https://www.archaeologists.net/codes/cifa (acc. September 2024)

Chartered Institute for Archaeologists 2020c *Standard and Guidance for the Collection, Documentation, Conservation and Research of Archaeological Materials* (Reading); https://www.archaeologists.net/codes/cifa (acc. September 2024)

Chartered Institute for Archaeologists 2022 *Code of Conduct* (Reading); https://www.archaeologists.net/codes/cifa (acc. September 2024)

Chartered Institute for Archaeologists 2023a *Standard for Archaeological Field Evaluation* (Reading); https://www.archaeologists.net/codes/cifa (acc. September 2024)

Chartered Institute for Archaeologists 2023b *Universal Guidance for Archaeological Field Evaluation* (Reading); https://www.archaeologists.net/codes/cifa (acc. September 2024)

Chartered Institute for Archaeologists 2023c *Standard for an Archaeological Monitoring and Recording* (Reading); https://www.archaeologists.net/codes/cifa (acc. September 2024)

Chartered Institute for Archaeologists 2023d *Universal Guidance for an Archaeological Monitoring and Recording* (Reading); https://www.archaeologists.net/codes/cifa (acc. September 2024)

Chartered Institute for Archaeologists 2023e *Universal Guidance for Archaeological Excavation* (Reading); https://www.archaeologists.net/codes/cifa (acc. September 2024)

Chartered Institute for Archaeologists 2023f *Standard for Archaeological Excavation* (Reading); https://www.archaeologists.net/codes/cifa (acc. September 2024)

Clark, C. D., Hughes, A. L. C., Greenwood, S. L., and Jordon, C. 2012 'Pattern and timing of retreat of the last British–Irish Ice Sheet', *Quaternary Science Reviews*, 44, 112–46; https://doi.org/10.1016/j.quascirev.2010.07.019

Clark, C. D., Ely, J. C., Greenwood, S. L., Hughes, A. L. C., Meehan, R., Barr, I. D., Bateman, M. D., Bradwell, T., Doole, J., Evans, D. J. A., Jordan, C. J., Monteys, X., Pellicer, X. M., and Sheehy, M. 2017 'BRITICE Glacial Map, version 2: a map and GIS database of glacial landforms of the last British–Irish Ice Sheet', *Boreas*, 47(1), 11-e8; https://doi.org/10.1111/bor.12273

Crisp, M. 2013 'Cracking the egg timer', *Chemistry Review*, 23, 20–5

Christen, T. A., and Pérez, S. 2009 'A new robust statistical model for radiocarbon data', *Radiocarbon*, 51, 1047–59; https://doi.org/10.1017/S003382220003410X

Cohen, K. M., MacDonald, K., Joordens, J. C., Roebroeks, W., and Gibbard, P. L. 2012 'The earliest occupation of north-west Europe: a coastal perspective', *Quaternary International*, 271, 70–83; https://doi.org/10.1016/j.quaint.2011.11.003

Cohen, K. M., Gibbard, P. L., and Weerts, H. J. T. 2014 'North Sea palaeogeographical reconstructions for the last 1 Ma', *Netherlands Journal of Geosciences*, 93(1-2), 7-29; https://doi.org/10.1017/njg.2014.12

Cohen, K. M., Westley, K., Erkens, G., Hijma, M. P., and Weerts, H. J. T. 2017 'The North Sea', in Flemming, N. C., Harff, J., Moura, D., Burgess, A., and Bailey, G. N., eds, *Submerged Landscapes of the European Continental Shelf: Quaternary Paleoenvironments* (Chichester), 147-86; https://doi.org/10.1002/9781118927823

Currant, A., and Jacobi, R. 2001 'A formal mammalian biostratigraphy for the Late Pleistocene of Britain', *Quaternary Science Reviews*, 20, 1707–16; https://doi.org/10.1016/S0277-3791(01)00035-X

Dansgaard, W., Johnsen, S. J., Clausen, H. B., Dahl-Jensen, D., Gundestrup, N. S., Hammer, C. U., Hvidberg, C. S., Steffensen, J. P., Sveinbjörnsdottir, A. E., Jouzel, J., and Bond, G. 1993 'Evidence for general instability of past climate from a 250-kyr ice-core', *Nature*, 364, 218–20; https://doi.org/10.1038/364218a0

David, A., and Linford, P. 1999 'Palaeomagnetic measurements', in Roberts, M. and Parfitt, S., eds, *Boxgrove. A Middle Pleistocene hominid site at Eartham Quarry, Boxgrove, West Sussex* (London), 297–9; https://doi.org/10.5284/1028203

Davies, S. M., Branch, N. P., Lowe, J. J., and Turney, C. S. M. 2002 'Towards a European tephrochronological framework for Termination 1 and the Early Holocene', *Philosophical Transactions of the Royal Society: Series A*, 360, 767–802; http://doi.org/10.1098/rsta.2001.0964

Davies, S. M., Abbott, P. M., Meara, R. H., Pearce, N. J., Austin, W. E., Chapman, M. R., Svensson, A., Bigler, M., Rasmussen, T. L., Rasmussen, S. O., and Farmer, E. J. 2014 'A North Atlantic tephrostratigraphical framework for 130–60 ka b2k: new tephra discoveries, marine-based correlations, and future challenges', *Quaternary Science Reviews*, 106, 101–21; https://doi.org/10.1016/j.quascirev.2014.03.024

Deviese, T., Comeskey, D., McCullagh, J., Bronk Ramsey, C., and Higham, T. 2018 'New protocol for compound-specific radiocarbon analysis of archaeological bones', *Rapid Communications in Mass Spectrometry*, 32, 5, 373–9; https://doi.org/10.1002/rcm.8047

Dickinson, M., Lister, A. M., and Penkman, K. E. H. 2019 'A new method for enamel amino acid racemization dating: a closed system approach', *Quaternary Geochronology*, 50, 29–46; https://doi.org/10.1016/j.quageo.2018.11.005

Dickinson, M. R., Scott, K., Adams, N. F., Lister, A. M., and Penkman, K. E. H. 2024 'Amino acid dating of Pleistocene mammalian enamel from the River Thames terrace sequence: a multi-taxon approach', *Quaternary Geochronology*, 82, 101543; https://doi.org/10.1016/j.quageo.2024.101543

Douka, K., Hedges, R. E. M., and Higham, T. F. G. 2010 'Improved AMS 14C dating of shell carbonates using high-precision X-ray diffraction (XRD) and a novel density separation protocol (CarDS)', *Radiocarbon*, 52, 735–51; https://doi.org/10.1017/S0033822200045756

Duller, G. A. T. 2008 *Luminescence Dating: Guidelines on using luminescence dating in archaeology* (Swindon); https://doi.org/10.5284/1000049

Duller G. A. T., and Roberts H. M. 2018 'Seeing snails in a new light: luminescence dating using calcite', *Elements* 14, 39–43; https://doi.org/10.2138/gselements.14.1.39

Dunai, T. 2010 *Cosmogenic Nuclides: Principles, concepts and applications in the earth surface sciences* (Cambridge); https://doi.org/10.1017/CBO9780511804519

Durcan, J. A., King, G. E., and Duller G. A. T. 2015 'DRAC: Dose Rate and Age Calculator for trapped charge dating Quaternary Geochronology', *Quaternary Geochronology* 28, 54–61; https://doi.org/10.1016/j.quageo.2015.03.012

Duval, M. 2016 'Electron Spin Resonance dating in archaeological contexts', in Gilbert, A. S., ed, *Encyclopedia of Geoarchaeology* (Dordrecht), 224–32; https://doi.org/10.1007/978-1-4020-4409-0_42

Elias, S. A., and Matthews I. P. 2013 'A comparison of reconstructions based on aquatic and terrestrial beetle assemblages: Late glacial-Early Holocene temperature reconstructions from the British Isles', *Quaternary International*, 341, 69–79; https://doi.org/10.1016/j.quaint.2013.08.004

Fletcher, W. J., Sánchez Goñi, M. F., Allen, J. R. M., Cheddadi, R., Combourieu-Nebout, N., Huntley, B., Lawson, I., Londeix, L., Magri, D., Margari, V., Müller, U. C., Naughton, F., Novenko, E., Roucoux, K., and Tzedakis, P. C. 2010 'Millennial-scale variability during the last glacial in vegetation records from Europe', *Quaternary Science Reviews*, 29, 2839–64; https://doi.org/10.1594/pangaea.872780

Garton, D., Barton, N. E. and Bateman, M. D. 2020 'Farndon Fields, Newark, Nottinghamshire: Windermere Interstadial deposits with potential for Late Upper Palaeolithic human activity', *Mercian Geologist*, 20(1), 5–14; https://eprints.whiterose.ac.uk/209689/ (acc. September 2024)

Gee, J. S., Cande, S. C., Hildebrand, J. A., Donnelly, K., and Parker, R. L. 2000 'Geomagnetic intensity variations over the past 780 kyr obtained from near-seafloor magnetic anomalies', *Nature*, 408, 827–32; https://doi.org/10.1038/35048513

Green, H. S. 1984 *Pontnewydd Cave. A Lower Palaeolithic hominid site in Wales: the first report*, National Museum of Wales Quaternary Studies Monograph 1, (Cardiff)

Grün, R., and Schwarcz, H. P. 2000 'Revised open system U-series/ESR age calculations for teeth from Stratum C at the Hoxnian Interglacial type locality, England', *Quaternary Science Reviews*, 19, 1151–4; http://dx.doi.org/10.1016/S0277-3791(00)00085-8

Harding, P., Ellis, C., and Grant, M. J. 2014. 'Late Upper Palaeolithic Farndon Fields', in Cooke, N. and Mudd, A., eds, *A46 Nottinghamshire: the archaeology of the Newark to Widmerpool Improvement Scheme, 2009* (Salisbury), 12–70

Harkness, D. D., and Wilson, H. W. 1972 'Some applications in radiocarbon measurement at the Scottish Research Reactor Centre', in Rafter, T. A., and Grant-Taylor, T., eds, *Proceedings of the 8th International Radiocarbon Conference, Wellington, New Zealand, October 1972* (Wellington), B101–B115

Haslett, J., and Parnell, A. C. 2008 'A simple monotone process with application to radiocarbon-dated depth chronologies', *Journal of the Royal Statistical Society: Series C*, 57, 399–418; https://doi.org/10.1111/j.1467-9876.2008.00623.x

Heaton, T. J., Köhler, P., Butzin, M., Bard, E., Reimer, R. W., Austin, W. E. N., Bronk Ramsey, C., Grootes, P. M., Hughen, K. A., Kromer, B., Reimer, P. J., Adkins, J., Burke, A., Cook, M. S., Olsen, J., and Skinner, L. C. 2020 'Marine20—the marine radiocarbon age calibration curve (0–55,000 cal BP)', *Radiocarbon*, 62, 779–820; https://www.doi.org/10.1017/RDC.2020.68

Heinrich, W. D. 1982 'Zur Evolution und Biostratigraphie von Arvicola (Rodentia, Mammalia) im Pleistozán Europas', *Zeitschrift für Geologische Wissenschaften*, 10, 683–735

Hendy, E. J., Tomiak, P. J., Collins, M. J., Hellstrom, J., Tudhope, A. W., Lough, J. M., and Penkman, K. E. H. 2012 'Assessing amino acid racemization variability in coral intra-crystalline protein for geochronological applications', *Geochimica et Cosmochimica Acta*, 86, 338–53: https://doi.org/10.1016/j.gca.2012.02.020

Hijma, M. P., Cohen, K. M., Roebroeks, W., Westerhoff, W. E., and Busschers, F. S. 2012 'Pleistocene Rhine–Thames landscapes: geological background for hominin occupation of the southern North Sea region', *Journal of Quaternary Science*, 27, 17–39; https://doi.org/10.1002/jqs.1549

Hinton, M. A. C. 1926 *Monograph of the voles and lemmings (Microtinae) living and extinct* (London)

Historic England 2023 *Curating the Palaeolithic* (Swindon); https://historicengland.org.uk/images-books/publications/curating-the-palaeolithic/ (acc. September 2024)

Historic England 2020 *Deposit Modelling and Archaeology. Guidance for Mapping Buried Deposits* (Swindon); https://historicengland.org.uk/images-books/publications/deposit-modelling-and-archaeology/ (acc. September 2024)

Hoffmann, D. L., Pike, A. W., Wainer, K., and Zilhão, J. 2013 'New U-series results for the speleogenesis and the Palaeolithic archaeology of the Almonda karstic system (Torres Novas, Portugal)', *Quaternary International*, 294, 168–82; http://dx.doi.org/10.1016/j.quaint.2012.05.027

Hosfield, R. T., and Green, C. P. 2013 *Quaternary History and Palaeolithic Archaeology in the Axe Valley at Broom, South West England* (Oxford)

Hosfield, R., Chambers, J., and Toms, P. 2007 *The Archaeological Potential of Secondary Contexts* (Southampton); https://doi.org/10.5284/1000291

Hounslow, M. W., Xuan, C., and Nilsson, A. 2022 'Chapter 5: Palaeomagnetism: using the geomagnetic field for correlation and dating', in Coe, A. L., ed, *Deciphering Earth's History: the Practice of Stratigraphy* (London), 81–100; https://doi.org/10.6084/m9.figshare.c.6179431.v1

Housley, R. A., Gamble, C. S., and RESET Associates 2015 'Examination of Late Palaeolithic archaeological sites in northern Europe for the preservation of cryptotephra layers', *Quaternary Science Reviews*, 118, 142–50; http://dx.doi.org/10.1016/j.quascirev.2014.05.012

Imbrie, J., and Imbrie, K. 1979 *Ice Ages: Solving the Mystery* (London)

Imbrie, J., Berger, A., Boyle, E. A., Clemens, S. C., Duffy, A., Howard, W. R., Kukla, G., Kutzbach, J., Martinson, D. G., McIntyre, A., Mix, A. C., Molfino, B., Morley, J. J., Peterson, L. C., Pisias, N. G., Prell, W. L., Raymo, M. E., Shackleton, N. J., and Toggweiler, J. R. 1993 'On the structure and origin of major glacial cycles 2: the 100,000-year cycle', *Paleoceanography and Paleoclimatology*, 8, 699–736; https://doi.org/10.1029/93PA02751

Jacobi, R. M., Rowe, P. J., Gilmour, M. A., Grün, R., and Atkinson, T. C. 1998 'Radiometric dating of the Middle Palaeolithic tool industry and associated fauna of Pin Hole Cave, Creswell Crags, England', *Journal of Quaternary Science*, 13, 29–42; https://doi.org/10.1002/(SICI)1099-1417(199801/02)13:1%3C29::AID-JQS346%3E3.0.CO;2-6

Jacobi, R. M., Higham, T. F. G., and Bronk Ramsey, C. 2006 'AMS radiocarbon dating of Middle and Upper Palaeolithic bone in the British Isles: improved reliability using ultrafiltration', *Journal of Quaternary Science*, 21, 557–73; https://doi.org/10.1002/jqs.1037

Jacobi, R. M., and Higham, T. F. G. 2009 'The early Lateglacial re-colonization of Britain: new radiocarbon evidence from Gough's Cave, southwest England', *Quaternary Science Reviews*, 28, 1895–913; https://doi.org/10.1016/j.quascirev.2009.03.006

Jacobs, Z., Roberts, R. G., Galbraith, R. F., Deacon, H. J., Grun, R., Mackay, A. W., Mitchell, P., Vogelsang, R., and Wadley, L. 2008 'Ages for the Middle Stone Age of Southern Africa: Implications for human behavior and dispersal', *Science*, 322, 733–5; http://dx.doi.org/10.1126/science.1162219

Key, A., Lauer, T., Skinner, M.M., Pope, M., Bridgland, D. R., Noble, L., and Proffitt, T. 2022 'On the earliest Acheulean in Britain: first dates and in-situ artefacts from the MIS 15 site of Fordwich (Kent, UK)', *Royal Society Open Science*, 9(6), 211904; https://doi.org/10.1098/rsos.211904

Laj, C., and Channell, J. E. T. 2015 'Geomagnetic excursions', in Schubert, G. and Kono, M., eds, *Treatise in Geophysics*, 2nd Edition, Vol. 5: Geomagnetism (Amsterdam), 343–86

Lane, C. S., Cullen, V. L., White, D., Branham-Law, C. W. F., and Smith, V. C. 2014 'Cryptotephra as a dating and correlation tool in archaeology', *Journal of Archaeological Science*, 42, 42–50; http://dx.doi.org/10.17863/CAM.6466

Lanos, P., and Dufresne, P. 2024 'ChronoModel version 3.2: software for chronological modelling of archaeological sites using Bayesian statistics' https://chronomodel.com/ (acc. September 2024)

Lanos, P., and Philippe, A. 2017 'Hierarchical Bayesian modeling for combining dates in archaeological context', *Journal de la Société Française de Statistique*, 158(2), 72–88; http://www.numdam.org/item/JSFS_2017__158_2_72_0/ (acc. September 2024)

Lanos, P., and Philippe, A. 2018 'Event date model: a robust Bayesian tool for chronology building', *Communications for Statistical Applications and Methods*, 25, 131–57; https://doi.org/10.29220/CSAM.2018.25.2.131

Lee, J. R., Rose, J., Hamblin, R. J. O., Moorlock, B. S. P., Riding, J. B., Phillips, E., Barendregt, R. W., and Candy, I. 2011 'The glacial history of the British Isles during the Early and Middle Pleistocene: implications for the long-term development of the British Ice Sheet', in Ehlers, J., Gibbard, P. L., and Hughes, P. D., eds, *Quaternary glaciations: extent and chronology.* Developments in Quaternary Sciences 15 (Amsterdam), 59–74; https://doi.org/10.1016/B978-0-444-53447-7.00006-4

Limpenny, S. E., Barrio Froján, C., Cotterill, C., Foster-Smith, R. L., Pearce, B., Tizzard, L., Limpenny, D. L., Long, D., Walmsley, S., Kirby, S., Baker, K., Meadows, W. J., Rees, J., Hill, J., Wilson, C., Leivers, M., Churchley, S., Russell, J., Birchenough, A. C., Green, S. L., and Law, R. J. 2011 *The East Coast Regional Environmental Characterisation*. Cefas Open report 08/0

Linick, T. W., Jull, A. J. T., Toolin, L. J., and Donahue, D. J. 1986 'Operation of the NSF-Arizona Accelerator Facility for radioisotope analysis and results from selected collaborative research projects', *Radiocarbon*, 28, 522–33; https://doi.org/10.1017/S0033822200007670

Linscott, B., Spindler, L., Cameron, J., Chivall, D., and Wood, R. 2024 'Achieving low backgrounds during compound-specific hydroxyproline dating: HPLC column effects', *Radiocarbon, 66(5), 1215-25;* https://www.doi.org/10.1017/RDC.2023.86

Lisiecki, L. E., and Raymo, M. E. 2005 'A Pliocene–Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records', *Paleoceanography*, 20, PA1003; https://doi.org/10.1029/2004PA001071

Lister, A. M. 1992 'Mammalian fossils and Quaternary biostratigraphy', *Quaternary Science Reviews*, 11, 329–44; https://doi.org/10.1016/0277-3791(92)90004-R

Longworth, C., and Wood, B. 2000 *Standards in Action Book 3: Working with Archaeology* (Cambridge)

Lougheed, B. C., and Obrochta, S. P. 2016 'MatCal: Open Source Bayesian ^{14}C Age Calibration in MatLab', *Journal of Open Research Software*, 4, e42; http://dx.doi.org/10.5334/jors.130

Lowe, D. J. 2011 'Tephrochronology and its application: a review', *Quaternary Geochronology*, 6, 107–53; https://doi.org/10.1016/j.quageo.2010.08.003

Lowe, J. J., Coope, G. R., Sheldrick, C., Harkness, D. D., and Walker, M. J. 1995 'Direct comparison of UK temperatures and Greenland snow accumulation rates, 15000—12000 yr ago', *Journal of Quaternary Science*, 10, 175–80; https://doi.org/10.1002/jqs.3390100207

Lowe, J. J., and Walker, M. J. C. 2015 *Reconstructing Quaternary Environments*, 3rd edn (Abingdon)

McNabb, J. 2007 *The British Lower Palaeolithic: Stones in Contention* (London)

Ministry of Housing, Communities and Local Government 2024 National Planning Policy Framework (London); https://www.gov.uk/ government/publications/national-planningpolicy-framework--2 (acc. December 2024)

Mitchell, G. F., Penny, L. F., Shotton, F. W., and West, R. G. 1973 *A Correlation of Quaternary deposits in the British Isles*. Geological Society of London: Special Report, 4 (London)

Mook, W. G., and Waterbolk, H. T. 1985 *Radiocarbon dating*. European Science Foundation Handbook for Archaeologists, 3 (Strasbourg)

Murton, D. K. and Murton, J. B. 2012 'Middle and Late Pleistocene glacial lakes of lowland Britain and the southern North Sea Basin', *Quaternary International*, 260, 115–42; https://doi.org/10.1016/j.quaint.2011.07.034

Museum and Galleries Commission 1992 *Standards in the Museum Care of Archaeological Collections* (London); https://collectionstrust.org.uk/wp-content/uploads/2016/11/Standards-in-the-museum-care-of-archaeological-collections.pdf (acc. September 2024)

Newton, A. J., Dugmore, A. J., and Gittings, B. M. 2007 'Tephrabase: tephrochronology and the development of a centralised European database', *Journal of Quaternary Science*, 22, 737–43; https://doi.org/10.1002/jqs.1094

Odé, O., Amkreutz, L., Cohen, K., and Hijma, M. 2022 'Mapping a drowning land', in Amkreutz, L., and van der Vaart-Vershoof, S., eds, Doggerland. *Lost World under the North Sea* (Leiden) 37–41; https://www.sidestone.com/bookviewer/9789464261134 (acc. September 2024)

Ogg, J. G. 2020 'Geomagnetic polarity time scale', in Gradstein, F. M., Ogg, J. G., Schmitz, M. D., and Ogg, G. M., eds, *Geologic Time Scale* (Amsterdam), 159–92; https://doi.org/10.1016/B978-0-12-824360-2.00005-X

Opdyke, N. D., Glass, B., Hays, J. D., and Foster, J. 1966 'Paleomagnetic study of Antarctic deep-sea cores', *Science*, 154, 349–57; https://doi.org/10.1126/science.154.3747.349

Parfitt, S. A., Barendregt, R. W., Breda, M., Candy, I., Collins, M. J., Coope, G. R., Durbidge, P., Field, M. H., Lee, J. L., Lister, A. M., Mutch, R., Penkman, K. E. H., Preece, R. C., Rose, J., Stringer, C. B., Symmons, R., Whittaker, J. E., Wymer, J. J., and Stuart, A. J. 2005 'The earliest record of human activity in northern Europe', *Nature*, 438, 1008–11; https://doi.org/10.1038/nature04227

Parfitt, S. A., Ashton, N. M., Lewis, S. G., Abel, R. L., Coope, G. R., Field, M. H., Gale, R., Hoare, P. G., Larkin, N. R., Lewis, M. D., Karloukovski, V., Maher, B., Peglar, S., Preece, R. C., Whittaker, J. E., and Stringer, C. B. 2010 'Early Pleistocene human occupation at the edge of the boreal zone in Northwest Europe', *Nature*, 466, 229–33; https://doi.org/10.1038/nature09117

Parnell, A. C., and Gehrels, W. R. 2015 'Using chronological models in late Holocene sea-level reconstructions from saltmarsh sediments', in Shennan, I., Long, A. J., and Horton, B. P., eds, *Handbook of Sea-Level Research* (Chichester), 500–13; https://doi.org/10.1002/9781118452547.ch32

Parnell, A. C., Buck, C. E., and Doan, T. K. 2011 'A review of statistical chronology models for high-resolution, proxy-based Holocene palaeoenvironmental reconstruction', *Quaternary Science Reviews*, 30, 2948–60; http://dx.doi.org/10.1016/j.quascirev.2011.07.024

Penkman, K. E. H., Kaufman, D. S., Maddy, D., and Collins, M. J. 2008 'Closed-system behaviour of the intra-crystalline fraction of amino acids in mollusc shells', *Quaternary Geochronology*, 3, 2–25; https://doi.org/10.1016/j.quageo.2007.07.001

Penkman, K. E. H., Preece, R. C., Bridgland, D. R., Keen, D. H., Meijer, T., Parfitt, S. A., White, T. S., and Collins, M. J. 2011 'A chronological framework for the British Quaternary based on *Bithynia* opercula' *Nature*, 476, 446–9; https://doi.org/10.1038%2Fnature10305

Pike, A. W. G., Hoffmann, D. L., García-Diez, M., Pettitt, P. B., Alcolea, J., De Balbín, R., González-Sainz, C., de las Heras, C., Lasheras, J. A., Montes, R., and Zilhão, J. 2012 'U-series dating of Palaeolithic art in 11 caves in Spain', *Science*, 336, 1409–13; https://doi.org/10.1126/science.1219957

Preece, R. C. 1995 *Island Britain: a Quaternary Perspective*. Geological Society of London Special Publication No. 96 (London)

Preece, R. C., Parfitt, S. A., Bridgland, D. R., Lewis, S. G., Rowe, P. J., Atkinson, T. C., Candy, I., Debenham, N. C., Penkman, K. E. H., Rhodes, E. J., Schwenninger, J. L., Griffiths, H. I., Whittaker, J. E., and Gleed-Owen, C. 2007 'Terrestrial environments during MIS 11: evidence from the Palaeolithic site at West Stow, Suffolk, UK', *Quaternary Science Reviews*, 26, 1236–1300; https://doi.org/10.1016/j.quascirev.2006.11.016

Preece, R. C., and Parfitt, S. A. 2012 'The Early and early Middle Pleistocene context of human occupation and lowland glaciation in Britain and northern Europe', *Quaternary International*, 271, 6–28; https://doi.org/10.1016/j.quaint.2012.04.018

Proctor, C., Douka, K., Proctor, J. W., and Higham, T. 2017 'The Age and Context of the KC4 Maxilla, Kent's Cavern, UK', *European Journal of Archaeology*, 20(1), 74–97; https://doi.org/10.1017/eaa.2016.1

R Core Team 2021 *R: A language and environment for statistical computing* (Vienna); https://www.R-project.org/ (acc. September 2024)

Rasmussen, S. O., Bigler, M., Blockley, S. P., Blunier, T., Buchardt, S. L., Clausen, H. B., Cvijanovic, I., Dahl- Jensen, D., Johnsen, S. J., Fischer, H., Gkinis, V., Guillevic, M., Hoek, W. Z., Lowe, J. J., Pedro, J. B., Popp, T., Seierstad, I. K., Steffensen, J. P., Svensson, A. M., Vallelonga, P., Vinther, B. M., Walker, M. J. C., Wheatley, J. J., and Winstrup, M. 2014 'A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy', *Quaternary Science Reviews*, 106, 14–28; http://dx.doi.org/10.1016/j.quascirev.2014.09.007

Reimer, P. J., Austin, W. E. N., Bard, E., Bayliss, A., Blackwell, P. G., Bronk Ramsey, C., Butzin, M., Cheng, H., Edwards, R. L., 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. W., Richards, D. A., Scott, E. M., Southon, J. R., Turney, C. S. M., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S. M., Fogtmann-Schulz, A., Friedrich, R., Köhler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., and Talamo, S. 2020 'The IntCal20 northern hemisphere radiocarbon age calibration curve (0–55 cal kBP)', *Radiocarbon*, 64(2), 725–57; https://doi.org/10.1017/RDC.2020.41

Richards, D. A., and Dorale, J. A. 2003 'Uranium-series chronology and environmental applications of speleothems', *Reviews in Mineralogy and Geochemistry*, 52, 407–60; https://doi.org/10.2113/0520407

Richter, D. 2007 'Advantages and limitations of thermoluminescence dating of heated flint from paleolithic sites', *Geoarchaeology*, 22, 671–83; https://doi.org/10.1002/gea.20180

Rixhon, G., Briant, B., Cordier, S., Duval, M., Jones, A., and Scholz, D. 2017 'Revealing the pace of river landscape evolution during the Quaternary: recent developments in numerical dating methods', *Quaternary Science Reviews*, 166, 91–113; https://doi.org/10.1016/j.quascirev.2016.08.016

Roberts, A. P., Tauxe, L., and Heslop, D. 2013 'Magnetic paleointensity stratigraphy and high-resolution Quaternary geochronology: successes and future challenges', *Quaternary Science Reviews*, 61, 1–16; https://doi.org/10.1016/j.quascirev.2012.10.036#

Roberts, M. B. 1986 'Excavation of a Lower Palaeolithic site at Amey's Eartham Pit, Boxgrove, West Sussex: a preliminary report', *Proceedings of the Prehistoric Society*, 52, 215–45; https://doi.org/10.1017/S0079497X00006666

Roberts, M. B., and Parfitt, S. A. 1999 *Boxgrove: a Middle Pleistocene Hominid Site at Eartham Quarry, Boxgrove, West Sussex* (London); https://doi.org/10.5284/1028203

Roberts, M. B., and Pope, M. I. 2009 'The archaeological and sedimentary records from Boxgrove and Slindon', in Briant, R. M., Hosfield, R. T., and Wenban-Smith, F. F., eds, *The Quaternary of the Solent Basin and the Sussex Raised Beaches: Field Guide* (London), 96–122

Roberts, R. G., Jacobs, Z., Li, B., Jankowski, N. R., Cunningham, A. C., and Rosenfeld, A. B. 2015 'Optical dating in archaeology: thirty years in retrospect and grand challenges for the future', *Journal of Archaeological Science*, 56, 41–60; http://dx.doi.org/10.1016/j.jas.2015.02.028

Roe, H. M., Coope, G. R., Devoy, R. J. N., Harrison, C., Penkman, K. E. H., Preece, R. C., and Schreve, D. C. 2009 'Differentiation of MIS 9 and MIS 11 in the continental record: vegetational, faunal, aminostratigraphic and sea-level evidence from coastal sites in eastern Essex, UK', *Quaternary Science Reviews*, 28, 2342–73; https://doi.org/10.1016/j.quascirev.2009.04.017

Shackleton, N. J., and Opdyke, N. D. 1973 'Oxygen isotope and palaeomagnetic stratigraphy of Pacific core V28-238: oxygen isotope temperatures and ice volume on a 105 and 106 year scale', *Quaternary Research*, 3, 39–55; https://doi.org/10.1016/0033-5894(73)90052-5

Schreve, D. C. 2001 'Differentiation of the British late Middle Pleistocene interglacials: the evidence from mammalian biostratigraphy', *Quaternary Science Reviews*, 20, 1693–705; https://doi.org/10.1016/S0277-3791(01)00033-6

Seierstad, I. K., Abbott, P. M., Bigler, M., Blunier, T., Bourne, A. J., Brook, E., Buchardt, S. L., Buizert, C., Clausen, H. B., Cook, E., Dahl-Jensen, D., Davies, S. M., Guillevic, M., Johnsen, S. J., Pedersen, D. S., Popp, T. J., Rasmussen, S. O., Severinghaus, J. P., Svensson, A., and Vinther, B. M. 2014 'Consistently dated records from the Greenland GRIP, GISP2 and NGRIP ice cores for the past 104 ka reveal regional millennial-scale $\delta^{18}O$ gradients with possible Heinrich event imprint', *Quaternary Science Reviews*, 106, 29–46; https://doi.org/10.1016/j.quascirev.2014.10.032

Sheldrick, C., Lowe, J. J., and Reynier, M. P. 1997 'Palaeolithic barbed point from Gransmoor, East Yorkshire, England', *Proceedings of the Prehistoric Society*, 63, 359–70; https://doi.org/10.1017/S0079497X00002486

Shotton, F. W. 1973 'General principles governing the subdivision of the Quaternary system', in Mitchell, G. F., Penny, L. F., Shotton, F. W., and West, R. G., eds, *A Correlation of Quaternary Deposits in the British Isles*. Geological Society of London: Special Report, 4 (London), 1–7

Schwenninger, J-L., and Rhodes, E. 2005. *Optically Stimulated Luminescence (OSL) Dating of Sediments from a Middle Palaeolithic Site at Lynford Quarry, Norfolk*. Research Department Report Series 25-2005 (London); https://historicengland.org.uk/research/results/reports/25-2005 (acc. September 2024)

Simon, Q., Thouveny, N., Bourles, D. L., Valet, J. P., Bassinot, F., Menabreaz, L., Guillou, V., Choy, S., and Beaufort, L. 2016 'Authigenic $^{10}Be/^{9}Be$ ratio signatures of the cosmogenic nuclide production linked to geomagnetic dipole moment variation since the Brunhes/Matuyama boundary', *Journal of Geophysical Research: Solid Earth*, 121, 7716–41; https://doi.org/10.1002/2016JB013335

Slota Jr., P. J., Jull, A. J. T., Linick, T. W., and Toolin, L. J. 1987 ‘Preparation of small samples for ^{14}C accelerator targets by catalytic reduction of CO’, *Radiocarbon*, 29(2), 303–6; https://doi.org/10.1017/S0033822200056988

Stuiver, M., and Reimer, P. J. 1993 ‘Extended ^{14}C data base and revised CALIB 3.0 14C calibration program’, *Radiocarbon*, 35, 215–30; https://doi.org/10.1017/S0033822200013904

Sutcliffe, A. J., and Kowalski, K. 1976 *Pleistocene Rodents of the British Isles*. Bulletin of the British Museum (Natural History), Geology 27/2 (London)

Tauxe, L. 1993 'Sedimentary records of relative paleointensity of the geomagnetic field: Theory and practice', *Review of Geophysics*, 31, 319–54; https://doi.org/10.1029/93RG01771

Timms, R. G. O., Matthews, I. P., Lowe, J. J., Palmer, A. P. Weston, D. J., MacLeod, A., and Blockley, S. P. E. 2019 ‘Establishing tephrostratigraphic frameworks to aid the study of abrupt climatic and glacial transitions: a case study of the Last Glacial–Interglacial Transition in the British Isles (c. 16–8 ka BP)’, *Earth-Science Reviews*, 192, 34–64; https://doi.org/10.1016/j.earscirev.2019.01.003

Tizzard, L., Bicket, A. R., Benjamin, J., and De Locker, D. 2014 ‘A Middle Palaeolithic site in the southern North Sea: investigating the archaeology and palaeogeography of Area 240’, *Journal of Quaternary Science*, 29, 698–710; http://dx.doi.org/10.1002/jqs.2743

Tizzard, L., Bicket, A. R., and De Locker, D. 2015 *Seabed Prehistory: Investigating the Paleogeography and early Middle Palaeolithic Archaeology in the Southern North Sea* (Salisbury)

Toms, P. 2011 *Seabed Prehistory Area 240: Optical Dating of Submarine Cores*, English Heritage Research Department Report Series 81-2011 (London); https://historicengland.org.uk/research/results/reports/81-2011

Toms, P. 2013 ‘Optical Dating’, in Hosfield, R., and Green, C. P., eds, *Quaternary History and Palaeolithic Archaeology in the Axe Valley at Broom, South West England* (Oxford), 157–64

Toms, P., Hosfield, R. T., Chambers, J. C., Green, C. P., and Marshall, P. 2005 *Optical dating of the Broom Palaeolithic Sites, Devon and Dorset*, Historic England Research Report Series, 16/2005 (London); https://doi.org/10.5284/1037468

Towe, K. M. 1980 ‘Preserved organic ultrastructure: an unreliable indicator for Paleozoic amino acid biogeochemistry’, in Hare, P. E., Hoering, T. C., and King, K., eds, *Biogeochemistry of Amino Acids* (New York), 65–74

Turner, C., and West, R, G, 1969 'The subdivision and zonation of interglacial periods', *Eiszeitalter und Gegenwart*, 19, 93–101; https://egqsj.copernicus.org/articles/19/93/1968/egqsj-19-93-1968.pdf (acc. September 2024)

Valet, J, P., Meynadier, L., and Guyodo, Y. 2005 'Geomagnetic dipole strength and reversal rate over the past two million years', *Nature*, 435, 802–5; https://doi.org/10.1038/nature03674

Voinchet, P., Moreno, D., Bahain, J.–J., Tissoux, H., Tombret, O., Falguères, C., Moncel, M –H., Schreve, D., Candy, I., Antoine, P., Ashton, N., Beamish, M., Cliquet, D., Despriée, J., Lewis, S., Limondin-Lozouet, N., Locht, J.–J., Parfitt, S., and Pope, M. 2015 'New chronological data (ESR and ESR/U-series) for the earliest Acheulian sites of north-western Europe', *Journal of Quaternary Science*, 30, 610–22; https://doi.org/10.1002/jqs.2814

Walker, K. 1990 *Guidelines for the Preparation of Excavation Archives for Long-term Storage* (London)

Walker, M. 2005 *Quaternary Dating Methods* (Chichester)

Walker, M. J. C., Coope, G. R., and Lowe, J. J. 1993 'The Devensian (Weichselian) Lateglacial palaeoenvironmental record from Gransmoor, East Yorkshire, England', *Quaternary Science Reviews*, 12, 659–80; https://doi.org/10.1016/0277-3791(93)90006-8

Walker, M., Johnsen, S., Rasmussen, S. O., Popp, T., Steffensen, J., Gibbard, P., Hoek, W., Lowe, J., Andrews, J., Björck, S., Cwynar, L. C., Hughen, K., Kershaw, P., Kromer, B., Litt, T., Lowe, D. J., Nakagawa, T., Newnham, R., and Schwander, J. 2009 'Formal definition and dating of the GSSP (Global Stratotype Section and Point) for the base of the Holocene using the Greenland NGRIP ice core, and selected auxiliary records', *Journal of Quaternary Science*, 24, 3–17; https://doi.org/10.1002/jqs.1227

Ward, G. K. and Wilson, S. R. 1978 'Procedures for comparing and combining radiocarbon age determinations: a critique', *Archaeometry*, 20, 19–32; https://doi.org/10.1111/j.1475-4754.1978.tb00208.x

Wessex Archaeology 2008, *Seabed Prehistory: Gauging the Effects of Marine Aggregate Dredging Final Report, Volume IV Great Yarmouth* (Salisbury); https://doi.org/10.5284/1009323

Westaway, R. 2011 'A re-evaluation of the timing of the earliest reported human occupation of Britain: the age of the sediments at Happisburgh, eastern England', *Proceedings of the Geologists' Association*, 122, 383–96; https://doi.org/10.1016/j.pgeola.2011.03.002

Westaway, R., Bridgland, D., and White, M. 2006 'The Quaternary uplift history of central southern England: evidence from the terraces of the Solent River system and nearby raised beaches', *Quaternary Science Reviews*, 25, 2212–50; https://doi.org/10.1016/j.quascirev.2005.06.005

White, M. J., and Ashton, N. M. 2003 'Lower Palaeolithic core technology and the origins of the Levallois method in North-Western Europe', *Current Anthropology*, 44, 598–609; http://dx.doi.org/10.1086/377653

White, M., Scott, B., and Ashton, N. 2006 'The Early Middle Palaeolithic in Britain: archaeology, settlement history and human behaviour', *Journal of Quaternary Science*, 21, 525–41; https://doi.org/10.1002/jqs.1034

White, M., Ashton, N., and Scott, B. 2011 'The emergence, diversity and significance of Mode 3 (Prepared Core) technologies', in Ashton, N., Lewis, S. G. and Stringer, C., eds, *The Ancient Human Occupation of Britain* (Amsterdam), 53–65: http://dx.doi.org/10.1016/B978-0-444-53597-9.00005-4

White, M. J., Bridgland, D. R., Schreve, D. C., White, T. S., and Penkman, K. E. H. 2018 'Well-dated fluvial sequences as templates for patterns of handaxe distribution: Understanding the record of Acheulean activity in the Thames and its correlatives', *Quaternary International*, 480, 118–131: https://doi.org/10.1016/j.quaint.2017.03.049

White, M., Rawlinson, A., Foulds, F., Dale, L., Davis, R., Bridgland, D., Shipton, C., and Ashton, N. 2024 'Making a U-turn on the Purfleet Interchange: Stone Tool Technology in Marine Isotope Stage 9 Britain and the Emergence of the Middle Palaeolithic in Europe', *Journal of Paleolithic Archaeology*, 7, 13; https://doi.org/10.1007/s41982-024-00177-z

White, T. S., Bridgland, D., Westaway, R., and Straw, A. 2016 'Evidence for late Middle Pleistocene glaciation of the British margin of the southern North Sea', *Journal of Quaternary Science*, 32, 261–75; https://doi.org/10.1002/jqs.2826

Wohlfarth, B., Skog, G., Possnert, G., and Holmqvist, B. 1998 'Pitfalls in the AMS radiocarbon-dating of terrestrial macrofossils', *Journal of Quaternary Science*, 13, 137–45; https://doi.org/10.1002/(SICI)1099-1417(199803/04)13:2%3C137::AID-JQS352%3E3.0.CO;2-6

Wolff, E. W. 2005, 'Understanding the past - climate history from Antarctica', *Antarctic Science*, 17(4), 487–95; https://doi.org/10.1017/S0954102005002919

Wymer, J. 1999 *The Lower Palaeolithic Occupation of Britain* (Salisbury); https://doi.org/10.5284/1000063

Xuan, C., Channell, J. E. T., and Hodell, D. A. 2016 'Quaternary magnetic and oxygen isotope stratigraphy in diatom-rich sediments of the southern Gardar Drift (IODP Site U1304, North Atlantic)', *Quaternary Science Reviews* 142, 74–89; https://doi.org/10.1016/j.quascirev.2016.04.010

Yamazaki, T., and Oda, H. 2005 'A geomagnetic paleointensity stack between 0.8 and 3.0 Ma from equatorial Pacific sediment cores', *Geochemistry, Geophysics, Geosystems*, 6, Q11H20, https://doi.org/10.1029/2005GC001001

9. Glossary

Accelerator Mass Spectrometry (AMS) — counting atoms by accelerating ions in a sample to very high speeds and then separating the isotopes using powerful electric charges and magnets.

Accuracy — one component of uncertainty, expresses how close a measurement comes to the true value.

Acheulian biface — a technological complex of stone-tool manufacture characterised by distinctive oval and pear-shaped 'handaxes'.

Aeolian — deposits that are produced, carried, borne, deposited or eroded by the wind.

Aliquot — an amount taken from a larger quantity.

Alluvial — made up of or found in the materials deposited by running water, such as streams, rivers and flood waters.

Ambient Magnetic Field — a vector field that describes the magnetic influence on electric currents, moving electric charges and magnetic materials.

Amino acid — a simple organic compound containing both a carboxyl (-COOH) and an amino ($-NH_2$) group.

Aminostratigraphy — the measurement of the extent of amino acid racemisation in biological deposits, used to separate (and correlate) deposits into approximate time periods.

Anglian — a glacial stage (MIS 12; *c.* 450,000 years ago) associated with a major Middle Pleistocene glaciation, during which ice sheets extended as far south as Oxfordshire and north London.

Anteroconid Complex — a single dentine field with four large folds present within water vole teeth.

Archaeostratigraphy — identifies artefact types that are characteristic of certain technological stages, used to the separate (and to correlate) deposits into approximate time periods.

Astrochronology — the dating of sedimentary units by calibration with astronomically tuned timescales, such as Croll–Milankovic cycles.

Bayesian statistics — the branch of statistics in which evidence about the true state of the world is expressed in terms of degrees of belief.

Bayes' Theorem — an expression of the relationship between prior and current beliefs.

Bifacial scraper — a lithic (stone) tool that has had flakes removed from both sides of the artefact.

Biomineral — a mineral produced by the activity of living things.

Bioturbation — the disturbance of sedimentary deposits by living organisms.

Biostratigraphy — branch of stratigraphical analysis concerned with fossils and their use in dating sedimentary deposits.

Boreal Zone — an ecosystem in the northern hemisphere with a subarctic climate, located between latitudes of 50° and 70°N.

Breccia — a rock composed of large angular broken fragments of minerals or rocks cemented together by a fine-grained matrix.

Brunhes chron — the final normal polarity chron in the Quaternary Period, preceded by the Matuyama chron, dated from 0.78 Ma to the present.

Cenozoic — last era of the Phanerozoic Eon, beginning at the end of the Mesozoic Era at the end of Cretaceous Period, *c.* 65 Ma, and divided into three periods: Paleogene (*c.* 65–23 Ma), Neogene (*c.* 23–2.6 Ma) and Quaternary (*c.* 2.6 Ma to present).

Chron — an interval of geological time; in palaeomagnetism, this relates to the time interval between polarity reversals of Earth's magnetic field.

Chronology — the science of arranging events in their order of occurrence in time.

Chronostratigraphy — branch of geology concerned with establishing the absolute ages of strata.

Clactonian — a stone tool industry typified by core and flake technology, within the main sites in England dating to early MIS 11 to early MIS 9.

Clastic material — created when bedrock is weathered chemically or mechanically, and then transported away by erosion.

Climatic optimum — period of highest prevailing temperatures within an interglacial.

Climatostratigraphy — the division of Quaternary sedimentary sequences based on the recorded climatic signals within a deposit, such as the Marine Oxygen Isotope Stages.

Coleopteran — an insect of the order Coleoptera (a large family of insects including beetles and weevils).

Colluvial — sediments that accumulate at the base of a hillslope by rainwash, sheetwash, slow downslope creep, or a combination of these processes.

Core and flake technology — stone tool-making technology characteristic of the Lower Palaeolithic, although it occurs in all periods of prehistory; it is defined by an absence of core preparation and the production of irregular flakes.

Cosmic Dose Rate — the quantity of cosmic radiation received over a specific time.

Cosmic ray — a highly energetic atomic nucleus or other particle travelling through space at nearly light speed.

Cosmogenic isotopes (or nuclides) — produced by cosmic rays colliding with atoms in the atmosphere or on the surface of the Earth.

Coversand — windblown periglacial aeolian deposits, consisting of fine- to very fine-grained sands.

Coercivity — the resistance of a magnetic material to changes in magnetisation.

Cretaceous — last period of the Mesozoic Era, starting at the end of the Jurassic Period *c.* 145 Ma and ending at the beginning of the Paleogene Period 65 Ma.

Croll–Milankovitch cycle — describes orbital forcing through variations in the eccentricity, the axial tilt and the precession of the Earth's orbit and their effects on climatic patterns on Earth.

Cromerian Complex — an Early-to-Mid Pleistocene stage in the NW Europe Quaternary climatostratigraphic scheme associated with MIS 21-13 (*c.* 866–478 ka).

Cromer Forest-bed Formation (sometimes known as the Cromer Forest Bed) — a geological formation in Norfolk and the type locality for the Cromerian Complex in Britain.

Cryptotephra — volcanic ash layers invisible to the naked eye and usually consisting of shards less than 125µm in size.

Curie temperature (Curie point) — on heating a material, the temperature above which it loses its ferromagnetic properties; the blocking temperature of a particular mineral is related to its Curie temperature but may be lower owing to such considerations as chemical impurities, crystal size and shape.

Dansgaard–Oeschger cycles — describe rapid climate fluctuations that occurred during the last glacial (Devensian) period.

Declination — the angle in the horizontal plane between the geographic north and the projection of the magnetisation vector on the horizontal plane (i.e. the direction of magnetic north); directions to the east of geographic north are in positive values, and those to the west are in negative values.

(Post) Depositional Remanent Magnetisation (DRM) — a remanent magnetisation acquired during or shortly after sediment deposition; this is usually due to magnetic particles of sediment rotating to align their intrinsic magnetisations with the ambient field as they settle out of a relatively nonturbulent water solution. They then become locked into position by the weight of sediment settling above them.

Detritus — loose material, such as rock fragments or organic particles, that results directly from disintegration of the primary deposit.

Devensian — relating to or denoting the most recent Pleistocene glaciation in Britain, identified with the Weichselian of northern Europe.

Diamicton — a poorly sorted type of sediment or sedimentary rock containing a wide range of clast sizes.

Dip and strike — a measurement convention used to describe the plane orientation or attitude of a planar geologic feature. Strike refers to the line formed by the intersection of a horizontal plane and an inclined surface; dip is the angle between that horizontal plane and the tilted surface.

Dipolar Geomagnetic Signal — a geomagnetic signal that relates to the Earth's magnetism.

Dose Rate measurements — the quantity of radiation received by a sample: alpha particles (α), beta particles (β), gamma rays (γ) and cosmic rays; measured to determine the Dose Rate ($\dot{D}$).

Dosimeter — a device that measures exposure to radiation.

Electron Probe Microanalyser (EPMA) — a microbeam instrument used primarily for the in situ non-destructive chemical analysis of minute solid samples.

Enamel Differentiation Ratio (SDQ) — method based on differences in the thickness of enamel bordering distal and mesial faces of enamel prisms in the first lower molar (m1), observed in the fossil water vole (genus *Arvicola*).

Erratic boulder — a rock or boulder that differs from the surrounding rock and is believed to have been brought from a distance by glacial action.

Flowstone — sheetlike deposit of calcite or other carbonate minerals, which forms when water flows down the walls or along the floors of a cave.

Fluvial — of or found in a river.

Foraminifera — single-celled, predominantly marine organisms with shells made of calcium carbonate (calcareous) or from tiny grains of sand stuck together (agglutinate).

Gamma spectrometry — a technique that measures the gamma radiation emitted during radioactive decay.

Geological timescale — system of chronological dating that relates geological strata (stratigraphy) to time; the largest defined units of time are eons, which, in turn, are divided into eras, periods, epochs and ages/stages.

Geomagnetic field — the Earth's spontaneously generated magnetic field. Largely due to movements of electrically conductive material in the Earth's molten outer core but with a smaller magnitude contribution from ionic movements in the upper atmosphere.

Geomagnetic Polarity Time Scale (GPTS) — geomagnetic timescale constructed from an analysis of magnetic anomalies measured over the ocean basins and tying these anomalies to known and dated magnetic polarity reversals found on land.

GISP2 — the second Greenland Ice Sheet Project.

Glacial — interval of cold climate associated with larger glaciers and expansion of continental ice-sheets, coupled with lower global sea level.

Glacial Maximum — period within a glacial when global ice sheets reach their greatest extent.

Glaciation — the process or state of being covered by glaciers or ice sheets.

Glacial valley — a valley U-shaped in section, formed by the erosive forces of a moving glacier.

Glacially dammed lake — a body of water formed when a glacier blocks the flow of water.

GRIP — the Greenland Ice Core Project.

Half-life — the time required for half the atoms in a sample of radioactive material to decay.

Handaxe — a usually large, general-purpose bifacial Palaeolithic stone tool, often oval or pear-shaped in form and characteristic of certain Lower Palaeolithic stone tool industries.

Heinrich events — a natural phenomenon in which large armadas of icebergs break off from glaciers and traverse the North Atlantic.

Highest Posterior Density intervals — a range in which a certain proportion (usually 95% or 68%) of the true values of a distribution will lie.

Holocene — the second (and present) epoch within the Quaternary Period, starting *c.* 11.7 ka.

Hominin — the group consisting of modern humans (*Homo sapiens*), extinct human species and all our immediate ancestors.

Hoxnian — a warm interglacial period following the Anglian glaciation, equivalent to MIS 11 (*c.* 424–374 ka).

Ice sheet — a layer of ice covering an extensive tract of land for a long period of time.

Igneous rock — a rock formed through the cooling and solification of magma or lava.

Inclination — the angle between the magnetisation vector and the horizontal plane; magnetisations pointing downward have positive inclination values, and those pointing upward have negative values.

Interglacial — an interval of warmer global average temperature lasting thousands of years that separates consecutive glacial periods.

Interstadial — relating to a minor period of less cold climate during a glacial period.

Intra-crystalline fraction — a fraction of proteins that are not removed after prolonged strong oxidation.

Ipswichian — the last Pleistocene warm interglacial period, equivalent to MIS 5e (*c.* 124–119 ka).

Isochron — a line on a diagram or map connecting points relating to the same time or equal times.

Isotope — one of two or more forms of an element differing from each other in the number of neutrons present.

Kettle hole — a depression or hole formed by the melting of ice buried in an outwash plain formed by a retreating glacier.

Lacustrine — relating to or associated with lakes.

Laminated sands — a deposit made up of fine- to medium-grained sand with flat, parallel laminae that are a few grains thick.

Laser Ablation Inductively Coupled Plasma Mass Spectrometry — an analytical technique that performs highly sensitive elemental and isotopic analysis directly on solid samples.

Last Glacial Maximum — the most recent time during the Devensian glaciation when ice sheets reached their greatest extent in Britain, *c.* 26–20 ka.

Levallois technology — stone tool technology characteristic of the early Middle Palaeolithic in Britain, defined by the careful preparation of cores to enable the production of flakes with particular sizes and shapes.

Liquid Scintillation Spectrometry — a technique that counts the electrons emitted during radioactive decay.

Loess — an unstratified wind-deposited sedimentary deposit consisting of silt-size grains that are loosely cemented by calcium carbonate.

Marine Magnetic Anomaly Profiles — variation in the strength of the Earth's magnetic field recorded in rocks on the spreading ocean floor. Marine magnetic anomalies are formed when magma rises at spreading ridges and cools below the Curie point.

Marine Oxygen Isotope Stage — alternating warm and cool periods in the past climate of the Earth, deduced from oxygen isotope data from deep sea core samples.

Markov Chain Monte Carlo (MCMC) — a class of algorithms for sampling from a probability distribution.

Matuyama chron — the final reverse polarity chron in the Quaternary, following the Gauss chron and preceding the Brunhes chron, dated from to 2.58 to 0.78 Ma.

Morphostratigraphy — a body of sediment that is identified primarily from the surface form it displays.

Mousterian tradition— a technological complex of stone-tool manufacture primarily associated with Neanderthals in Europe; it largely defines the later part of the Middle Palaeolithic.

Mutual Climatic Range method — a method for determining the past climate at a site by examining the tolerances of a range of species found there.

Natural Remanent Magnetisations (NRM) — the remanence of a natural sample as first measured in the laboratory (before any partial demagnetisation). The term implies nothing about the origin of the remanence, which could be thermoremanence or depositional remanence etc.

NGRIP — the drilling site of the North Greenland Ice Core Project (NGRIP or NorthGRIP) near the centre of Greenland.

Nuclide — a distinct kind of atom or nucleus characterised by a specific number of protons and neutrons.

Operculum — an anatomical feature resembling a lid or a small door that opens and closes, controlling contact between the outside world and an internal part of an animal.

Orbital tuning — the process of adjusting the time scale of a geologic or climate record so that the observed fluctuations correspond to the Croll–Milankovitch cycles (q.v.) in the Earth's orbital motion.

Ostracods — small crustaceans found in various aquatic and terrestrial environments.

Ovate bifaces — a lithic (stone) tool characterised by rounded edges and weak definition in shape to both the bottom (proximal) and top (distal) ends.

Palaeolithic — the cultural period once referred to as the Old Stone Age. It is defined by the practice of hunting and gathering and the use of chipped flint tools. This period is usually divided up into:

> **Lower Palaeolithic (pre *c.* 300 ka):** the earliest subdivision of the Palaeolithic, or Old Stone Age, when hominins began to make and use the earliest flint tools found in the current archaeological record. These were *Homo antecessor*, *Homo heidelbergensis* and early Neanderthals;
>
> **Middle Palaeolithic (*c.* 300–43 ka):** the second subdivision of the Palaeolithic, or Old Stone Age, when Neanderthals began to manufacture and use stone tools using Levallois technology (q.v.) and the fine flake tools of the Mousterian tradition (q.v.);
>
> **Upper Palaeolithic (*c.* 43–11.5 ka):** the third and last subdivision of the Palaeolithic, or Old Stone Age, in which modern humans had evolved and arrived in Europe, and began to manufacture and use a variety of fine-blade flint tools from prepared cores and to make projectile points from bony materials.

Palaeointensity-Assisted Chronology (PAC) — the use of Relative Palaeointensity (RPI, q.v.) to constrain the chronology of a sedimentary sequence.

Palaeosecular Variation (PSV) — short-period secular variations in both direction and magnitude, capable of providing decadal to millennial age resolutions.

Palaeomagnetic polarity — the relative orientation of the Earth's magnetic poles in the past.

Palynology — the recovery and study of ancient pollen grains for the purposes of analysing ancient climate, vegetation and diet.

Pedostratigraphy — the study of the stratigraphical and spatial relationships of surface and buried soils.

Pedoturbation — the process by which a soil is physically mixed or disturbed.

Pleistocene — the first epoch within the Quaternary Period, between *c.* 2.58 Ma and 11.7 ka.

Pliocene — the last epoch of the Tertiary Period, between the Miocene and Pleistocene Epochs, between *c.* 5.3 and 2.6 Ma.

Polarity — the relative orientation of magnetic poles.

Post-glacial — relating to or occurring during the time following a glacial period, usually referring to the time after the Last Glacial Maximum (q.v.).

Posterior beliefs — our state of understanding a problem after considering new data.

Posterior density estimate — a function that describes the likelihood of a date occurring at a particular point in time.

Pretreatment — physical and chemical processing of a sample to purify it before combustion.

Prior beliefs — our state of understanding a problem before considering new data.

Precision — one component of uncertainty, indicating the degree to which measurements are repeatable and reproducible.

Quaternary Period — the most recent period of the Cenozoic Era, starting *c.* 2.6 Ma. It follows the Tertiary Period, and is subdivided into the Pleistocene and Holocene Epochs.

Racemisation — the transformation of one-half of the molecules of an optically active compound into molecules that possess exactly the opposite (mirror-image) configuration.

Radiocarbon calibration — the process of converting a radiocarbon measurement into a distribution, or range, of possible calendrical dates, expressed as cal BC or cal BP.

Radioactive decay — the spontaneous distintegration of atoms by emission of matter and energy.

Radioactivity — the emission of radiation from a radionuclide during radioactive decay.

Radionuclide — an atom that has excess nuclear energy, making it unstable and subject to radioactive decay.

Relative Palaeointensity (RPI) — the record of relative geomagnetic intensity variations measured from normalised natural remanent magnetisation of sedimentary samples. The normalisation is typically done by a laboratory-introduced magnetisation to compensate for the ability of the sample to acquire magnetisation.

Sand reactivation — the act or process of making a previously fixed sand deposit active, or becoming active, again.

Secondary Ion Mass Spectrometry (SIMS) — a technique for chemical analysis and imaging of solid materials.

Solifluction — slow, downslope movement of fine-grained surface material owing to repeated freezing and thawing cycles.

Speleothem — chemically-precipitated deposits that accumulate over time within cave environments.

Stable isotope — an isotope that does not undergo radioactive decay.

Stadial — a relatively cold period during a glacial period.

Stage — the lowest ranking unit of time for a geological time scale (q.v.) that can be recognised on a global scale.

Stratigraphy — study of the order and relative position of strata/archaeological deposits.

Stratotype — designated exposure of a named layered stratigraphic unit or of a stratigraphic boundary that serves as the standard of reference (type site).

Student's-t distribution — a statistical function that creates a probability distribution, similar to the normal distribution with its bell shape.

Superconducting Rock Magnetometer — a technique for measuring the magnetic properties of samples.

Taphonomy — the circumstances and processes of fossilisation.

Tephra — fragments of rock that are produced when magma or rock is explosively ejected by a volcano.

Tephrochronology — a method of age determination that uses discrete layers of tephra from a single eruption to create a chronological framework.

Tertiary — the first period of the Cenozoic Era, between the Cretaceous and Quaternary Periods, *c.* 65–2.6 Ma.

Thermal Remanent Magnetisation (TRM) — a remanent magnetisation acquired after a substance has been heated then cooled in an ambient magnetic field.

Total Hydrolysable Amino Acid Fraction — a measure of all amino acids in a sample after they have been hydrolysed.

Travertine — a sedimentary rock formed by the chemical precipitation of calcium carbonate minerals from fresh water, typically in springs rivers or lakes.

Tufa — a sedimentary rock formed by the chemical precipitation of calcium carbonate minerals from fresh water, characterised by their large microbiological component and high porosity.

Ultrafiltration — filtration using a medium fine screen mesh size, enough to retain colloidal particles, viruses or large molecules.

Uranium-series — the radioactive decay chain where unstable heavy atomic nuclei decay through a sequence of alpha and beta decays until a stable nucleus is achieved. This sequence begins with ^{238}U and ends with ^{206}Pb. It is used to quantify dose rate in luminescence dating and in Electron Spin Resonance (ESR). Uranium-Thorium dating is based on part of the Uranium-series radioactive decay chain.

Virtual Geomagnetic Pole (VGP) — a point on the Earth's surface at which a magnetic pole would be located if the observed direction of remanence at a particular location was due to a geocentric magnetic dipole field.

Vitreous — like glass in appearance or physical properties.

10. Abbreviations

^{14}C – Radiocarbon Dating
AAR – Amino Acid Racemisation
ACC – Anteroconid Complex
AF – Alternating Field
AHOB – Ancient Human Occupation of Britain
AMS – Accelerator Mass Spectrometry
B2k – years before AD 2000
BGS – British Geological Survey
D/L – Dextrorotatory/Levorotatory
DRM – Depositional Remanent Magnetisation
EPMA – Electron Probe Microanalyzer
ESR – Electron Spin Resonance
FAA – Free Amino Acid
HER – Historic Environment Record
IRMS – Isotope Ratio Mass Spectrometry
IRPL – Infrared Photoluminescence
IR-RF – Infrared Radiofluorescence
IRSL – Infrared-Stimulated Luminescence
GI – Greenland Interstadial
GISP – Greenland Ice Sheet Project
GPTS –- Geomagnetic Polarity Time Scale
GRIP – Greenland Ice Core Project
GS – Greenland Stadial
ka – kilo annum (1,000 years)
LA-ICPMS – Laser Ablation Inductively Coupled Plasma Mass Spectrometry
LAT – Lowest Astronomical Tide
Ma – Mega Annum (million years)
MCMC – Markov Chain Monte Carlo
MIS – Marine Isotope Stage
NGRIP – North Greenland Ice Core Project
NPPF – National Planning Policy Framework
NRM – Natural Remanent Magnetisation
OASIS – Online AccesS to the Index of archaeological InvestigationS
OD – Ordnance Datum
OSL – Optically Stimulated Luminescence
pIR-IRSL – Post Infrared-Infrared Stimulated Luminescence
PAC – Palaeointensity-Assisted Chronology

PSV – Palaeosecular Variation
RESET – Response of Humans to Abrupt Environmental Transitions
RPI – Relative Palaeointensity
SIMS – Secondary Ion Mass Spectrometry
SDQ – Schmelzband-Differenzierungs-Quotient = Enamel Differentiation Ratio/Quotient
TIMS – Thermal Ionisation Mass Spectrometry
TL – Thermoluminescence
THAA – Total Hydrolysable Amino Acid
TRM – Thermal Remanent Magnetisation
U-Th – Uranium-Thorium
VADM – Virtual Axial Dipole Moment
VGP – Virtual Geomagnetic Pole

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