Scientific Dating of Pleistocene Sites: Guidelines for Best Practice

Contents

Foreword

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These guidelines provide advice on best practice for the effective 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 (eg **Radiocarbon Dating**), although special considerations for their effective use may apply. Other methods (eg the **'Vole Clock'**) are only used in the Pleistocene. The selection of appropriate techniques, 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, is key. Different strands of evidence can be explicitly combined using Bayesian statistical 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, seek expert advice. 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 with you. It is by working together with a range of specialists that you will provide the best dating possible for your site.

PART 1 - OVERVIEW

1. Introduction

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The Pleistocene is the geological period during which multiple ice ages, or glacials, occurred, the last of which ended only *c* 11,700 years ago, at the beginning of the Holocene, or the post-glacial. The Pleistocene and Holocene together are termed the Quaternary. The Pleistocene began 2.58 million years ago, and we now know that there were numerous ice ages during this period, although 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 1973a; 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 yielding their climatic signal from fluctuation 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. Higher-resolution records of latest Pleistocene climate gleaned from palaeobotanical studies from the last glacial suggest that this cold stage was punctuated by several oscillations of warmer climate, albeit achieving less warmth than a full interglacial and so termed interstadials, with the term stadial 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, with a formal definition requiring deciduous woodland in NW Europe for an interglacial rather than an interstadial (Turner and West 1969).

The glacials and interglacials as recognised in marine oxygen isotope curves have been classified as numbered stages, counted downwards through the oceanic sedimentary sequence, so that the Holocene is Marine Oxygen Isotope Stage (MIS) 1 and the last glacial minimum is MIS 2 (Fig 2). The curve does not show a simple fluctuation between interglacial and glacial maxima and minima but rather there is considerable complexity, with substages recognized during the various interglacial stages. Thus MIS 5 is subdivided into MIS 5e, 5d, 5c, 5b and 5a, an interglacial (5e) and two interstadials (5c and a) separated by two cold episodes (5d and b).

The changes in climate through the Quaternary have been driven by the collective 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 rive the 100,000 years (100 ka) climate cycles that have dominated during this period (for example Imbrie *et al* 1993; Fig 2).

The Quaternary stratigraphical framework

Current understanding of the climato-stratigraphy, palaeogeography, and human occupation of Britain during the Quaternary is summarised in Figure 3.

This classification of Pleistocene strata is based on the recognition of temperate- and (less commonly) cold-climate proxies in certain deposits, taken together with other evidence for the deposition of some sediments under warm (temperate) conditions and others under intensely cold or even glacial conditions. In Britain, for many years, this division was primarily based on palynological distinction between different interglacials (summarised by Mitchell *et al* 1973). The glacial episodes were characterized by major continental ice sheets, two of which, during the Devensian (*c* 110,000–11,700 years ago; equivalent to MIS 5d–MIS 2) and the Anglian (*c* 450,000 years ago; equivalent to MIS 12 in Fig 1), were periods when land-based ice extended across large parts of Britain (Bowen *et al* 1986; Clark *et al* 2012), with the later Britain's most extensive. Together these two glaciations were responsible for almost all the surface cover in Britain of the glaci-genic diamicton deposits formerly called 'boulder clay'. Between the Devensian and Anglian there was perhaps more than a single glacial during which ice advanced southwards across England, although the evidence is preserved only where not destroyed by the later Devensian ice advances (Lee *et al* 2011). People are thought not to have lived in Britain during glaciations.

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

There is no convincing evidence for human presence during the Ipswichian, either from archaeological material or from butchery damage to any of the large vertebrate bone collections from that stage. This is probably because Britain was an island at this time.

The next-youngest ‘Aveley’ interglacial, equivalent to MIS 7, is recognized to be complex, with perhaps three temperate peaks, although none as warm as the Ipswichian or earlier MIS 9e. Human occupation of Britain during MIS 7 saw consolidation of Levallois knapping and something of a decline in handaxe use, although there are numerous handaxes of that age in a rare North Wales interglacial context: Pontnewydd Cave, Clwyd (Green 1984).

The MIS 9 ‘Purfleet’ interglacial is securely established in the British terrestrial record, thanks to its representation in the Corbets Tey Terrace, east of London. The Lower Thames sequence as a whole is of considerable importance, because it takes the form of a staircase of four terraces, within which all four of the post-Anglian interglacials are represented (Fig 4). Recent investigations at Purfleet, Essex (Bridgland *et al* 2013) have confirmed the correlation of the sediments there with the relatively short but strikingly warm MIS 9e interglacial optimum. This site is of considerable importance as it records three major divisions of the Palaeolithic in superposition: Clactonian, overlain by Acheulian, overlain by Levallois, the second of these changes representing the Lower–Middle Palaeolithic transition (Wymer 1999; White and Ashton 2003; White *et al* 2011).

The Hoxnian is well represented in lacustrine basins formed during the preceding MIS 12 Anglian glaciation. Thus the Hoxnian type locality, in Suffolk, is a kettle-hole lake overlain by fluvial deposits (Ashton *et al* 2008), while the para-stratotype, at Marks Tey in Essex, is a section of subglacially overdeepened valley, infilled with lake sediments. This interglacial is well represented in the Lower Thames at sites in North Kent, at Dartford Heath and, in particular, at Swanscombe (Fig 4), where a hominin skull fossil has been found, as well as copious numbers of artefacts and vertebrate and molluscan fossils. There are three separate Lower Palaeolithic industries in superposition here: a basal Clactonian, an assemblage with pointed handaxes, and an upper distinctive handaxe assemblage with examples having twisted edges, thought to represent MIS 11a (Bridgland and White 2015).

Mitchell *et al* (1973) also identified by palynology an interglacial immediately prior to the Anglian glaciation, the Cromerian. This is now also recognized to be an oversimplification, with the Cromerian now divided into at least four different interstadials, although data from vertebrates and non-marine Mollusca suggest at least five distinct warm episodes within what would once have been termed ‘Cromerian’, probably representing isotopic substages within the range MIS 21–13. The term ‘Cromerian Complex’ is generally used for this sequence of early Middle Pleistocene interglacials and the cold episodes that separate them. The oldest of these interglacials has a negative magnetic polarity, indicating that it pre-dates the Matuyama–Bruhnes 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 some, but not all, of these Cromerian Complex interglacials. Of particular importance in distinguishing between these Cromerian interglacials is the change, during MIS 15, in water-vole molar tooth morphology (**see Section 10: The ’Vole Clock’**).

MIS 22, immediately before 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 is probably older than this: Happisburgh 3, where artefacts occur in reversedmagnetised sediments that have been attributed to MIS 21 or 25, late in the (reversed polarity) Matuyama chron (Parfitt *et al.*, 2010). However Westaway (2011) has suggested that the reversed-magetised sediments could date from a magnetic excursion within the Bruhnes chron and date from part of MIS 15; attribution by Parfitt *et al.* (2010, supplement) of the Happisburgh 3 sediments to the Thames, based on their composition, renders this unlikely, as it is clear that by MIS 15 the River Bytham flowed across Suffolk from west to east and entered the North Sea at Lowestoft (Parfitt *et al.* 2005), so the Thames could not have reached Happisburgh.

The terrestrial record lacks the universally applicable and supposedly continuous framework provided by the oceanic oxygen isotope signal and the longer ice cores. River terrace and raised beach sequences, however, can provide terrestrial frameworks in uplifting areas (for example Bridgland 2000; 2006; Bridgland *et al* 2004), with both available in parts of Britain (for example Bridgland 2010; Bridgland and Allen 2014).

Palaeogeography

The landscape and environment that the early occupants of Britain inhabited was, for much of the time, very different to that of the present day. Notwithstanding that sea level was generally much lower during the predominantly colder Pleistocene (because global water was locked up in larger polar ice caps), it is clear that, prior to MIS 12, there would have been a 'British Peninsula' at the NW extremity of the European continent, rather than an Island Britain (Preece 1995; Fig 5a). The timing of and mechanism for the formation of the Strait of Dover is controversial, but it seems likely that the 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 5b). This drained into the English Channel and thus cut the earliest Dover Strait. At this time the route of the Thames moved further south, into its modern valley through London, again the result of glacial-lake overflow (Bridgland 1994) and the Bytham river was obliterated by the Anglian ice sheet, which engulfed its valley completely. Although parts of the former valley formed the route-ways for post-Anglian drainage, that huge river system was not restored, being replaced by a proto-Trent system that required a further two climate cycles and another glaciation before it reached anything like its modern configuration; indeed its drainage into the Humber did not come about until Devensian deglaciation (Bridgland *et al* 2014; 2015; Fig 6). The Solent river was unaffected by any glaciation, its eventual demise coming about through 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).

Fitting the archaeological record into this dynamic landscape

Recent work as part of the Ancient Human Occupation of Britain (AHOB) project has revealed, for the first time, human occupation in the Early Pleistocene (http://www.ahobproject.org), with sites at Pakefield, Suffolk and Happisburgh 3, Norfolk (see **Happisburgh 3)** producing Lower Palaeolithic artefacts dated to MIS 17, and MIS 21 or MIS 25, respectively. The British archaeological record also covers much of the Middle Pleistocene, with Lower Palaeolithic human occupation apparent from sites such as the MIS 13 Happisburgh 1 and the Boxgrove raised beach, West Sussex (see **Boxgrove**), beyond the reach of the ice sheets. During the MIS 6 glacial, the final stage of the Middle Pleistocene, humans disappeared from Britain and were absent during the last (Ipswichian) interglacial and, indeed, did not return until MIS 4 / MIS 3, when Late Pleistocene Neanderthal occupation and Middle Palaeolithic (Mousterian) artefacts are seen at a number of sites (such as

Lynford Quarry), with modern humans appearing 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 for most of the late Middle Pleistocene. These are Clactonian assemblages (Mode 1 characterised by hand axes) and Acheulian assemblages (Mode 2). The distinction of these two knapping technologies is far from straightforward, however, since the Acheulian or handaxe industries produce flakes and cores that are identical to those in Clactonian assemblages. This means that Clactonian assemblages cannot be recognized 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 climato-stratigraphy and dating of Quaternary deposits across Britain. Handaxe making dwindled in importance once the next development in lithic technology arose; the use of Levallois technique in the knapping of prepared cores (Mode 3). This heralded the transition into the Middle Palaeolithic. It has been shown that this occurred over a very wide area at the time of the MIS 9–8 transition.

The Upper Palaeolithic first appeared during MIS 3 (by *c* 33 ka) with the arrival of *Homo sapiens* (eg The Red 'Lady' of Paviland; Jacobi and Higham 2008). During MIS 2 there was probably complete depopulation of Britain, with people returning as the climate ameliorated at the beginning of the Late glacial and into the subsequent Holocene.

Shorter-timescale division of the Late Pleistocene

The Late Pleistocene begins with the warming transition that led to the MIS 5e (Ipswichian) interglacial (Fig 1). The preceding glacial produced the most extensive glaciation of the neighbouring part of the European mainland, so, 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. That can perhaps explain why there is no compelling evidence for human occupation of Britain during either MIS 6 or MIS 5e. Indeed, there is no good evidence that humans returned prior to MIS 3.

The level of resolution available for the various palaeoclimatic records of the Late Pleistocene is significantly greater than for the Early–Middle Pleistocene, with considerable enhancement in understanding during recent years thanks to evidence from ice cores, especially for fluctuations during the last climate cycle (**Text Box 2**; Fig 7). The MIS 3 interstadial (generally correlated with the mid-Devensian Upton Warren Interstadial), was relatively cold and rather unstable in comparison 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 the order of 500–2000 years duration (Fig 7). Known as 'Dansgaard–Oeschger' cycles, these saw abrupt warming by 5–8°C within 50 years, perhaps as little as a decade, followed by more protracted cooling. 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. The record is divided into a series of alternating Greenland Stadial (GS) and Greenland Interstadial (GI) stages, with GS-1 representing the pre-Holocene Younger Dryas (in Britain called the Loch Lomond) Stadial and GI-1 representing the Bølling–Allerød (in Britain called the Windermere) Interstadial (see Fig 8).

2. Scientific Dating methods for the Pleistocene

The relative sequence provided by stratigraphy can be placed on a calendar timescale using various methods of scientific dating and many of the most important advances came from understanding radioactivity. Detailed explanations of the major techniques are provided below, along with a series of case studies. Further information can be found in Walker (2005), Lowe and Walker (2015), and Rixhon *et al* (2017).

Generally the application of scientific dating methods in the Pleistocene is limited by the availability of suitable material for dating. Replicate determinations should be obtained and, wherever possible, ages should be obtained from more than one technique. This allows an assessment of the reliability of the individual dating technique and proposed chronology to be made. Stratigraphy also forms a key cross-check and results should accord with the relative dating provided by this method. **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 application:

- Applicability: is there something dateable within the deposit that is to be dated?
- 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 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 applications in the Pleistocene:

- The application of scientific dating techniques should, wherever possible, be underpinned by a thorough understanding of stratigraphy
- Some types of stratigraphy provide means of relative dating (eg biostratigraphy, pedostratigraphy, morphostratigraphy)
- Multiple age determinations from a single stratigraphic unit should be compatible
- Independent dating techniques from the same stratigraphic unit should give concordant ages
- Scientific dates should conform with the stratigraphy (ie 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.

Radiometric methods

These methods make use of radioactive isotopes, which decay at rates predicted by their half-lives, with different isotopes utilised for dating different time ranges (Fig 9). Thus radiocarbon dating is used in the very Late Pleistocene and through the Holocene, thanks to a half-life of 5730 years (**Radiocarbon Dating**). Isotopes with half-lives suited to dating longer-timescale Pleistocene sequences are, unfortunately of more restricted occurrence. Argon–Argon (^{40}Ar-^{39}Ar) and

Potassium–Argon (^{40}K-^{40}Ar) dating is of considerable precision but these elements are largely restricted to igneous rocks, which are not found in the English Quaternary record. Uranium-series (including Uranium–Thorium; U-Th) dating requires the appropriate elements to be present and for there to be a closed system. It has mainly been applied to calcareous deposits in caves (**Uranium-Thorium dating**). Cosmogenic nuclide dating is based on the reaction between cosmic rays and certain elements in minerals in rocks. The bombardment by cosmic rays, which is continuous and predictable (with certain provisos) leads to the formation and accumulation of 'cosmogenic isotopes' in rock surfaces (**Text Box 3**). Potentially this is a powerful tool, but there are significant issues with the approach that are currently under development. At present, its use for archaeological applications has been very limited and, given the substantial costs involved, it should only be employed in collaboration with expert practitioners.

Trapped Charge Methods

These techniques use signals arising from electrons trapped in a sampled crystalline structure to calculate the time since the 'traps' were emptied by a 'zeroing' event, such as exposure to sunlight or heating. Radioactive decay within the environment supplies a stream of electrons that will progressively fill these traps at a predictable rate, following the aforementioned 'zeroing' event. Once the majority of traps are occupied the mineral is in saturation, which constitutes a limitation of the dating timescale. For luminescence techniques, the trapped charge is measured by the amount of light emitted by electrons released from their traps. Electron Spin Resonance (ESR) does not evict its electrons and instead it is the strength of the signal emitted by these trapped electrons that is measured. This signal must be compared with the natural level of radioactivity in the sediment from which the dating sample was collected. Different techniques have different applications and timespans (the latter always dependant on the natural level of radioactivity on the site, with low levels of natural radioactivity-rates allowing dating over a longer-timescale):

(1) **Thermoluminescence** – in which heat is used to release the trapped electrons. This was the first luminescence dating technique to be used widely and is applicable as a measure of the time since the firing of pottery or the heating of burnt flint recovered from hearths. It has also been used to measure the exposure to daylight of wind-blown sand and silt (loess) (**Luminescence Dating**).

(2) **Optically Stimulated luminescence (OSL)** – in which light is used to release the trapped electrons in multiple (aliquots) or single grains of quartz sand. An important consideration will be whether the grains will have been fully zeroed by the light exposure, which is why the method works best for dating wind-blown sediments. (**Luminescence Dating**)

(3) **Infrared-stimulated luminescence (IRSL)** – in which the trapped electrons, often in feldspar crystals, are released by infra-red radiation. This methodology has the advantage that feldspar crystals can trap sufficient electrons to extend the dating interval to 1 Ma or more, depending on the natural radioactivity on the site. (**Luminescence Dating**)

(4) **Electron spin resonance (ESR)** - this technique measures mineral exposure to environmental radiation and is calculated based upon the signal emitted by these trapped electrons. The dating range is dependent on the nature and state of conservation of the sample and the surrounding environment but is between a few thousands and over a million years (**Text Box 4**).

OSL has been applied successfully to sediments in many areas of England, with something of an explosion in its application during the past two decades (**The Axe Valley and Broom; Seeing beneath the Sea; Neanderthals in Norfolk**). In some cases, however, incomplete bleaching of sediments and the unsuitability of the available quartz sand grains (for example Pennine quartz in northern England) prevents successful dating.

ESR has been much used in France in recent decades, but applications in Britain are rare and have produced mixed results (Grün and Schwarcz 2000; Voinchet *et al* 2015). Again, this technique should only be employed in collaboration with expert practitioners.

Other scientific dating methods

There are non-radiometric methods that have also proved to be valuable for dating Pleistocene contexts. One of these is Amino-Acid Racemization (AAR) dating, based on the predictable diagenesis of proteins within biological materials after organisms die, particularly the shells of molluscs. The method has been applied to the British Lower–Middle Palaeolithic archive, with emphasis on the fluvial localities that share the occurrence of artefacts and molluscan faunas (**Amino Acid Racemization (AAR)**).

Palaeomagnetism is valuable in providing isochrons (age-equivalent stratigraphical horizons). One of the most important is the Matuyama–Bruhnes magnetic reversal (when the north and south poles reversed), which is a Global Boundary Stratotype Section and Point (GSSP) marking the start of the Middle Pleistocene (780 ka; Fig 3). This marker can be an important element in dating river terrace sequences, although it has yet to be located in Britain (**Palaeomagnetism**).

Tephrochronology is a useful means for identifying isochrons across widespread areas, making use of volcanic ash layers (tephras), distributed by wind, which can be correlated with particular eruptions using geochemical analyses and radiometric/OSL dating. To date in Britain work has mainly focused on Late Pleistocene isochrons (**Tephrochronology**).

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 inserted. A key relative dating method is biostratigraphy. This ranges from the identification of particular episodes of time based on the assemblages of remains in particular kinds of deposit, to the higher-resolution of climatic zonation of biological remains. An important part of the method is correlation, using biostratigraphical characteristics to establish the relative position of sediments in different geographic localities. Biostratigraphy may be based on a single taxon, on assemblages of taxa, on relative abundances, and on specified morphological features, including changes of an evolutionary nature. The latter can be the most powerful biostratigraphical technique (**The 'Vole Clock'**). Mammalian faunas have proved to be the most effective for dating, since they show greater change during the Quaternary than other types of biological remains. This same 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 stratigraphical unit.

3. Bayesian Chronological Modelling

Alex Bayliss and Peter Marshall, Historic England

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 (Fig 10), 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 which incorporates both our existing knowledge and our new data (our "posterior beliefs"). This is not the end of the matter, however, since today's posterior belief becomes tomorrow's prior belief, informing the collection of new data and their interpretation as the cycle repeats.

At its simplest 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: this scatter matters.

Figure 11 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; 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 *14,990–14,670 cal BP (95% probability; OxA-18035*; Fig 11), probably to *14,870–14,740 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 *15,070–14,740 cal BP (95% probability; start Gough's Cave*; Fig 11), probably in *14,950–14,790 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.

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 (**Gransmoor**) or within the geomorphology of sets of related features, such as river terraces (**The Axe Valley at Broom**). Often an archaeological intervention will provide limited new evidence on a particular issue, but any new scientific dates or limiting information will need to be interpreted within an updated chronological model of the problem at hand.

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 to provide sufficient information to allow them to be criticised and reconstructed in the future. They should include:

1. 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.
2. Methodology: including a statement of the approach adopted and the statistical methods and software used.
3. 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.
4. Details of scientific dates: see the appropriate sections of these guidelines for the information required for different techniques.
5. Model definition and description: each model must be explicitly defined so that it can be recreated (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.
6. 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 Buck and Millard (2004).

PART 2 – SCIENTIFIC DATING METHODS

4. Radiocarbon Dating

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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, charred 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 million carbon atoms). This makes detecting a radiocarbon atom in a sample at the limit of detection (about 50 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 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 age. 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. 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 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. Precious 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. 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.

Over the past decade much research has focussed 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 routinely applied (Brown *et al* 1988; Jacobi *et al* 2006). Improved accuracy may be obtained by the implementation of an acid-base-wet oxidation (ABOX) pretreatment for charcoal samples (Bird *et al* 1999), 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 which produced the results and how samples were pre-treated, prepared for measurement, and dated;
- Details of the radiocarbon results and associated measurements and how these have been calculated; and
- 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 asymetrical error terms (for example, GrN-12876 from Lynford Quarry, which produced an age of 35,710±930/−830 BP), and some may produce minimum ages (for example OxA-11572 also from Lynford Quarry, which produced an age of >49,700 BP) (**Neanderthals in Norfolk**).

Radiocarbon calibration can now be undertaken using an internationally-agreed calibration curve for the northern hemisphere, IntCal13, back to 50,000 cal BP (Fig 12; Reimer *et al* 2013). All radiocarbon results within this range should be calibrated, and details of the calibration protocols used, including any reservoir corrections employed, published. Calibration in this period is, however, likely to be subject to significant refinement over the coming decades, so it is essential that laboratory numbers and uncalibrated radiocarbon ages are also published to allow them to be re-calibrated with new calibration curves in due course.

Nowadays, with the advent of Bayesian Chronological Modelling, calibration is often simply part of formal statistical modelling. Where further statistical analysis is undertaken, it may be more appropriate to provide posterior density estimates, rather than simple calibrated date ranges.

5. Uranium-Thorium dating

Alistair Pike, University of Southampton

Uranium-Thorium (U-Th) dating exploits the build-up of the isotope ^{230}Th (itself radioactive) from the radioactive decay of ^{238}U to ^{234}U to ^{230}Th. Over time, the activity ratio ^{238}U/^{230}Th 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 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 10,000. 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 ±40/−31 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) which bring with them ^{230}Th, which without correction would lead to older apparent dates. The level of detritus is monitored by measurement of the common isotope of thorium, ^{232}Th, usually expressed at 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 which is 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) which allows the construction of an 'isochron' to correct for detritus. Again, the errors will increase, sometimes drastically.

An additional, though apparently rare, problem is the leaching of U or Th 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). Thus, securely demonstrating the stratigraphic 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 open systems, and ensuring samples are suitable for the laboratory to take multiple sub-sample to construct an isochron and/or to check for 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 (Fig 13). These can be detached as a block, cut with a grinder, or cored with a coring drill. Photographic and other documentation of the position of the sample, and especially its relation to archaeological layers, is essential, as well as indicating on the sample the uppermost (youngest) layer. 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 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*; thisprovides fewer opportunities to control for open system behaviour, contamination from the sampling equipment and other complexities, so it is best to consult with a specialist and arrange for them to take the sample.

The minimum required data for reporting a U-Th date is: sample code; laboratory code; U concentration; $^{234}U/^{238}U$ ± error; $^{230}Th/^{238}U$ ± error; $^{230}Th/^{232}Th$ ± error; uncorrected U-Th age ± error; and corrected U-Th age ± error. There is no convention on reporting ages relative to a datum, though BP (before 1950 AD) has been used, as has B2k (before 2000 AD), 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, the half-lives (or published source) for the date calculations should be given, along with details of the method of correcting for detrital contamination and the ratios used. If isochron dating is used, the graphical plot of the isochron and associated statistics (as produced by software such as *Isoplot*) should be included either in the publication or as supplementary information.

6. Luminescence dating in the Pleistocene

Geoff Duller, Aberystwyth University

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 / Middle Stone Age 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 14).

There are a variety of luminescence techniques, based on different minerals and different signals. Quartz dating using optically stimulated luminescence (OSL) has been well established since 2000, whilst infrared stimulated luminescence (IRSL) from feldspars has been revolutionised by work published in 2008. Other luminescence signals are also available; each has its strengths and weaknesses. 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 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, but fluvial and some colluvial materials are also suitable. The key consideration is whether there is a high probability that the mineral grains were exposed to daylight at, or prior, to deposition.

Luminescene 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).

Samples for luminescence dating can be collected by non-specialists, but it is preferable for a luminescence practitioner to undertake this. The luminescence signals used for dating are sensitive to light, and thus samples have to 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 back to the laboratory, and to avoid moisture loss. If this is not possible then an alternative approach is to use a large sheet of black plastic to exclude daylight from the section and for a sample to be collected using a trowel and collected in an opaque bag that will exclude daylight. Red LEDs can be used during sampling to provide limited lighting.

A critical part of calculating a luminescence age is to measure the natural radioactivity at the site. Some measurements can be made in the laboratory, but *in situ* measurements are preferable using a gamma spectrometer (Fig 15). 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 the artefact should be shielded from as much light as possible, but complete exclusion of light is not necessary since the inside of the artefact is normally used for measurement. A representative sample of the sediment surrounding the artefact should be submitted 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 in excess of one hundred thousand years. 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, and the rate at which energy is delivered to the sample varies depending upon the dose rate. It is common to be able to date to 100 ka, not unusual to be able to reach 200 ka, and in unusual circumstances ages of 400 or 500 ka are feasible. 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.

Ages are normally given in kiloannum (ka) before the date of measurement. No agreed datum exists for luminescence ages but it is good practice to report the date (such as 2015 CE) when a luminescence age was measured (Brauer *et al* 2014). The term “BP” which is used for radiocarbon ages should never be used when reporting luminescence ages. Supporting information required for luminescence ages includes the mineral and analytical method used for luminescence measurement, details of any statistical analysis of the luminescence data, and the equivalent dose (D_e) for the sample. Details of measurement of the dose rate must also be included: what methods were used for dose rate determination, the water content used in calculation, the individual dose components (alpha, beta and gamma) and the cosmic dose rate.

7. Amino acid racemization (AAR)

Kirsty Penkman, University of York

Amino acid racemization dating relies upon 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 Period. 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 a number of sources (see 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 shells or coral. Most amino acids can exist in two forms which are non-superimposable mirror images of each other (Fig 16), designated left-handed (*laevo,* L-form) and right-handed (*dextro,* D-form). In living organisms, proteins are almost exclusively made from the L-form. However after death, a spontaneous reaction (called racemization) starts to occur. 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 17a). Different species break down at different rates, so analyses are undertaken on monospecific samples (usually individual mollusc shells, 1–5mg in size). The extent of amino acid racemization (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), 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). This technique has been particularly successful in dating carbonate and phosphate fossils (shells, tooth enamel, eggshells, foraminifera, ostracods, earthworm granules), and in long-lived biominerals (corals), it can be used to provide age information *within* an individual sample (Hendy *et al* 2012). The AAR labs 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 material for AAR dating are tooth enamel, *Bithynia* opercula 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 allows correlation of deposits with the Marine Oxygen Isotope Record stages (Fig 17b), 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 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/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 instance by sieving with warm water, or by drying in an oven). Suitable material for AAR dating in the residues can be identified to species-level by a faunal (eg vertebrate or mollusc) 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 labs tend to issue results via a report, with laboratory numbers 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) and provenance information on the dated material, together with the provenance of material contributing to the reference framework.

8. Palaeomagnetism

Chuang Xuan, University of Southampton

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 (eg lava, volcanic glass) and archaeological artefacts acquire NRM through thermal remanent magnetisation (TRM) when magnetic minerals such as magnetite in these archives cool from high temperatures to below Curie temperature. In contrast, sedimentary rocks formed in a marine or lake environment record palaeomagnetic field information through (post) depositional remanent magnetisation (DRM) acquisition, during which magnetic particles in the sediments align themselves to ambient magnetic field during or shortly after sediment deposition. Palaeomagnetic records reconstructed from geological and archaeological archives play a fundamental role in revealing the dynamics and causes of geomagnetic change and provide a valuable geophysical process based stratigraphic correlation and dating tool that is independent from those based on palaeoenvironmental variations (eg, oxygen isotope stratigraphy; **Introduction**).

Palaeomagnetism has been widely used for dating Pleistocene sedimentary sequences. The process typically involves the reconstruction of palaeomagnetic directions and/or intensity preserved within samples and subsequent comparison of the results to other well-dated palaeomagnetic reference records. Magnetostratigraphy based on geomagnetic polarity reversals (ie chron boundaries) has been the backbone for stratigraphic correlation and dating of worldwide sedimentary sequences for over 50 years (eg Opdyke *et al* 1966). Polarity (ie normal or reversed) chrons in a sedimentary sequence are recognised by NRM directions including declinations and inclinations, defined as the angle between geographic north and horizontal projection of the NRM vector and the angle between horizontal plane and the NRM vector, respectively (see Fig 18). For example, a stratigraphic interval from the northern hemisphere with positive (negative) inclinations and around 0° (180°) declinations would have been deposited during a normal (reversed) chron. The established chron pattern of a sedimentary sequence is then compared with a geomagnetic polarity time scale (GPTS) so that reversal ages in the GPTS could be assigned to depths in the sequence where the corresponding reversals occurred.

Confident geomagnetic polarity stratigraphy interpretation often requires guidance/verification from other independent dating methods (eg, biostratigraphy, oxygen isotope stratigraphy; **Happisburgh 3**), especially when the top of a sequence does not have a modern age, or when a sequence contains a hiatus. In addition, any significant geological rotation or tilting caused by tectonic events (usually negligible for Pleistocene-aged sequences) should be corrected for magnetostratigraphy construction. The resolution and accuracy of palaeomagnetism dating based on geomagnetic polarities are determined by the number of reversals available to correlate and uncertainties associated with the age of these reversals in the GPTS. The Pleistocene epoch is occupied by the Brunhes and the Matuyama Chrons, as well as the Jaramillo, Cobb Mountain, Olduvai and Reunion subchrons, with a total of ten reversals including the base of the Matuyama Chron that marks the beginning of the Pleistocene (Fig 19, top). GPTS ages for all Pleistocene reversals have been calibrated by astrochronology (see Ogg 2012) and should have uncertainties of less than 10–20 ka.

During the last few decades, palaeomagnetists have begun to document more frequent brief geomagnetic excursions and to accumulate records of changes in relative palaeointensity (RPI) and palaeosecular variation (PSV) of the field. These records provide detailed insights on geomagnetic field behaviour while offering opportunities for high resolution stratigraphic correlation and dating within polarity chrons. Geomagnetic excursion is often defined as brief (<10 kyrs) deviation of virtual geomagnetic poles (VGPs) from the geocentric axial dipole (eg with >45° changes in VGP latitudes). As higher fidelity records of excursions become available, it appears that the majority of the excursions are associated with 180° directional changes, followed by a return to pre-exciursion directions within a few hundred to thousand years (Laj and Channell 2015). At least seven excursions are well established during the Brunhes Chron, and eight excursions are well documented during the Matuyama Chron (Fig 19, top).

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 quality of the RPI records (eg Tauxe 1993). RPI records constructed from different worldwide sedimentary sequences appear to record a dominantly dipolar geomagnetic signal, and are generally coherent at least on a few tens of thousands-year scale. These

RPI records can also be correlated to palaeointensity changes estimated using other independent methods such as cosmogenic nuclides (eg Simon *et al* 2016; **Text Box 3**) and marine magnetic anomaly profiles (Gee *et al* 2000). 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 (eg, Valet *et al* 2005; Yamazaki and Oda 2005; Channell *et al* 2009) (see Fig 19, bottom). In addition, PSV (eg declination and inclination) records have also been widely used to provide millennial scale age constraints especially for late Pleistocene and Holocene sequences, usually by comparing the PSV records to a regional reference curve or geomagnetic field model predictions for a location (eg Avery *et al* 2017).

Samples used for palaeomagnetic analyses are typically oriented and can be taken in the form of discrete cubes/cylinders or continuous sections/u-channels (Fig 18b–c) marked with a reference orientation (eg dip/strike direction, true north, upward direction, etc.). 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 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 (see Fig 18d) capable of resolving weak magnetisations (ie 10-5 A/m level). 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. 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 time offsets to sedimentary palaeomagnetic records (see Roberts *et al* 2013), which might define the ultimate resolution of palaeomagnetism dating for Pleistocene sequences.

9. Tephrochronology

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When volcanoes erupt they disperse ash over thousands of kilometres in a matter of days–months and hence, when identified in Pleistocene deposits, they provide time-parallel marker horizons (isochrons). Tephrochronology is the use of these volcanic ash layers (tephras) to determine the age of associated sediments. The detection of tephra layers is achieved via the careful extraction of volcanic material (usually the glass fraction) from the host sediments and then the chemical classification of that material. Once a chemical dataset has been obtained, it is matched to a particular eruption (a correlative) by comparing this chemical signal with those from previously recorded eruptions within an international database (Fig 20 and for a full review see Lowe 2011).

Tephra research is primarily stratigraphic, but calendar dating for Pleistocene sequences may be acquired by two methods: direct dating of the tephra itself or dating of associated material. Direct dating of volcanic deposits, through Argon-Argon, Uranium-series or Fission Track methods (Walker 2005), requires large amounts of material, which is usually not available in areas distant from the source volcano. England receives ash from Iceland and Continental Europe but the ash is in too low concentrations and lacks the relevant mineral material to be directly dated. More commonly, tephras are dated by determining the age of the layer in which they are found. Either the layer may be directly dated using datable material within it, or a series of dates may be obtained for a stratigraphic sequence of deposits (for example, through age-depth Bayesian modelling of series of radiocarbon dates; **Gransmoor**). In some cases, it is possible to directly estimate the date of the layer by counting in annually-laminated lakes and 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. Tephra studies have focused on the Late Pleistocene, with a robust tephrochronology for Northern Europe comprising *c* 20 tephras between 15-11.5ka, while 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 (for example, it has recently been identified in the West Runton Bed (Brough *et al* 2010)), but this earlier period has not yet received the same level of research. To date, there has been only a limited number of studies applying tephrochronology to English archaeological sites, but distribution maps of ash fall suggest there is good potential to apply tephra studies to sites across the entire country (Fig 20a). 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 may be as good as 1–2% of the determined age (Bronk Ramsey *et al* 2015a). When reporting tephra data, it is convention to provide the tephra counts, the chemical data alongside chemical standards, the analytical conditions used, the proposed correlative and how the age estimate is derived.

Sampling for cryptotephra (ash layers invisible to the naked eye and usually comprising grains less than 125µm in size) on archaeological sites requires the collection of a continuous sediment record covering the entire studied sequence. Because tephra may be unevenly represented on a site it is advisable to sample two or more separate sections (Fig 21). In fine-grained sediments, sampling is achievable with overlapping monolith tins. Where coarse clastic material predominates, collection in clean small bags from an exposed face is necessary which involves taking contiguous 10–20mm intervals working from the section base upwards. Exceptionally clastic-rich sediments may not be fully sampled, or a lower resolution (such as 50–100mm) must be accepted. The relationship of samples to geological layers and archaeology must be recorded. In England, it is likely that any tephras encountered will be not be visible in the field due to their small grain sizes.

Cryptotephra processing (Lane *et al* 2014) involves the laboratory 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 (Fig 21). A third stage separates sufficient vitreous tephra shards for major (using EPMA (Electron Probe Microanalyzer)) and trace element (using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) or SIMS (Secondary Ion Mass Spectrometry)) chemical analysis (Fig 20b). Databases of chemical signatures may identify correlation to known tephra horizons (Tephrabase: Newton *et al* 2007; RESET: Bronk Ramsey *et al* 2015b).

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 in Britain, but recent work has demonstrated that 22% of open-air ‘dry’ sites and 34% of rock shelters and caves produced tephras in Continental Europe (Housley *et al* 2015). Success rates in wetlands sites are likely to be higher as they are generally undisturbed.

10. The ’Vole Clock’

Danielle Schreve, Royal Holloway, University of London

Often overlooked as a source of evidence in the past, the recovery of small vertebrate remains is now a recommended routine procedure when investigating sites of Quaternary age. Any calcareous fine-grained deposits (generally sands, silts and clays, or seams of these within coarser gravel bodies) may be suitable for sampling. The process of hand excavation with a trowel will often damage fragile specimens, so the best way to proceed is for bulk samples of sediment to be extracted, either as a column (in order to investigate any change up through a sequence) or as spot 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 and any bones and teeth extracted using foil tweezers. If the sample is clay-rich, air-drying the sediment or soaking with a dispersant such as 1% sodium hexametaphosphate before wet-sieving may help to weaken the hydrophilic bond of the clay particles, allowing the samples to be processed more easily.

The remains of small vertebrates can offer highly detailed insights into many aspects of past environments and climates, food webs and evolutionary trends. In particular, the cycle of long-term glacial to interglacial climate change and the succession of abrupt (decadal to centennial) climatic changes observed in the Late Pleistocene have had a profound effect on the composition of the vertebrate fauna in Britain (Schreve 2001). This has influenced changes in vertebrate species’ biogeographical range, as well driving extinction events and evolutionary trends (Lister 1992). Taken together, these changes can be used for establishing the relative age of fossil assemblages (biostratigraphy), something that is particularly useful for many Quaternary sites that lie beyond the range of radiocarbon dating.

One notable example of a biostratigraphically-significant evolutionary trend is that seen in the water vole lineage, sometimes referred to as the ’Vole Clock’. Although highly endangered in Britain today, remains of fossil water voles are common in Quaternary deposits, thereby providing a large sample of teeth through which quantifiable changes may be observed. This is important because morphological change is often small over Quaternary timescales and tooth morphology may be highly variable, meaning that large samples are necessary in order to capture variation within a population accurately.

The genus *Mimomys* appeared in Europe around 4 million years ago and evolved through a number of species, surviving until around 600 ka, when the final representative, *Mimomys savini*, was replaced by representatives of the modern genus *Arvicola*. The key features of interest are present in the first lower molar (m1), which is composed of a ‘cloche hat-shaped’ anterior loop (the anteroconid complex, ACC, see Fig 22), followed by a series of three closed interlocking triangles and a posterior loop. At the point of transition from *Mimomys* to *Arvicola* during the early Middle Pleistocene (late Cromerian Complex), an important change occurs in the switch from rooted teeth to permanently-growing molars (Fig 23). This apparently rapid event forms a highly significant biostratigraphic marker over western Eurasia. In Britain, the transition allows a clear separation of an 'old' group of early Middle Pleistocene sites such as West Runton, Norfolk and Pakefield, Suffolk that are characterised by *Mimomys*, and a 'young' group of early Middle Pleistocene sites with *Arvicola*, such as 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 consequently their breeding opportunities, thus perpetuating the mutation.

Within the genus *Arvicola*, there are further trends noted over the last half million years. Two subspecies are noted in the British fossil record, *Arvicola terrestris cantiana* (also known as *Arvicola mosbachensis*) and the modern *Arvicola terrestris terrestris* (also known as *Arvicola amphibius*). As well as a lengthening of the m1 and an increase in the ratio of the ACC to overall tooth length, the *Mimomys* fold, an archaic feature in the ACC, also become progressively uncommon in younger samples until finally disappearing (Fig 22). However, the key trend relates to the 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, the situation 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 22) (Hinton 1926). A method known as the *Schmelzband-Differenzierungs-Quotient* (enamel differentiation ratio) or SDQ was proposed by Heinrich (1982) in order 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 resulting figure (the SDQ) can then be used to compare different populations of *Arvicola* in order to establish their relative age. This technique has been widely applied in Britain in order to provide an independent chronology for many Quaternary localities (for example Schreve 2001; Roe *et al* 2009).

PART 3 – CASE STUDIES

11. Happisburgh Site 3, Norfolk

Zoe Outram and Peter Marshall, Historic England

The Cromer Forest-bed formation, that formed between 2 and 0.5 million years ago along the coast of Norfolk and Suffolk, is famous for its rich flora and fauna such as mammoth, rhinoceros and hippopotamus that 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 (Fig 24), 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, as well as the stone tools, floral, and faunal remains that allowed a detailed study of not only the hominin activities being carried out in this area, but also of the environment that they occupied. Although stratigraphic evidence indicated 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 of the site was essential in order to understand their significance and place them into a broader context.

Samples for palaeomagnetic dating 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 into the Matuyama chronozone (2.52–0.78 Ma). Biostratigraphic evidence including the presence of key plant taxa (identified from the pollen spectra), such as *Tsuga* (hemlock) and *Ostrya*-type (hop-hornbeam type) which are unknown in Northern Europe after the Early Pleistocene, together with extinct mammals (mammoths, equids and voles) suggested the age of the site was towards the end of the Early Pleistocene. Taken together the biostratigraphic and palaeomagnetic data indicated that the hominin occupation at Happisburgh occurred towards the end of the Mutayama chronozone, placing the deposits between 990 and 780 ka (Parfitt *et al* 2010).

Further evidence of when in this period hominin occupation took place is provided by the palaoebotanical record that indicates it would have been during a phase of climatic cooling in the second half of an interglacial cycle (Fig 25). Together with the other evidence, Parfitt *et a*l (2010) suggested that the site was occupied at the end of either MIS 21 (866–814 ka) or MIS 25 (970–936 ka). More recently Westaway (2011) has proposed an alternative, younger, dating for the site (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. Although Parfitt *et al.* (2010, supplement) assign the sediments, based on their composition, to the Thames, Westaway's (2011) hypothesis is unlikely, as it is clear that by MIS 15 the River Bytham flowed across Suffolk from west to east and entered the North Sea at Lowestoft (Parfitt *et al*. 2005), and thus the Thames could not have reached Happisburgh.

The evidence from Happisburgh Site 3 has redefined our understanding of the earliest known occupation of Britain. If the later suggested dating is correct (Westaway 2011), Happisburgh Site 3 is very 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 the earlier dating of Parfitt *et al* (2010) is accepted, then Happisburgh Site 3 has yielded the oldest hominin occupation north of Iberia and the first occupation within the northern boreal zone, with important implications for our understanding of populations, in terms of their movements/migrations, their behaviour, and their ability to adapt and survive different environments, such as the cooler climates recorded towards the end of an interglacial.

The resolution of this controversy, which clearly fundamentally depends on the production of an accurate chronology for the site, highlights the importance of Pleistocene dating techniques.

12. Boxgrove

Danielle Schreve, Royal Holloway, University of London

The site of Boxgrove is located in West Sussex, 12km north of the English Channel coast. Its modern position is significant, since 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 26). 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 and 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, including several hundred ovate bifaces (handaxes) made on flint sourced from the Chalk cliff nearby, its rich and diverse fossil vertebrate assemblage, and the presence of hominin remains (two incisors and a tibia) attributed to *Homo heidelbergensis*. Over 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, as witnessed by evidence for a soil (palaeosol). 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. The fine-grained nature of the sediments is such that individual episodes of handaxe knapping can be identified (Fig 27) 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 appears to have acted as a focal point for human activity. 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).

The site has also yielded extensive proof for large mammal butchery, including evidence for the dismemberment of wild horse, red deer, giant deer, bison and three extinct Hundsheim rhinoceroses. The carcasses of these animals are littered with cutmarks from stone tools, indicating a complete process from skinning through to the removal of the major muscle blocks and tendons. Where present, carnivore gnawmarks overlie anthropogenic cutmarks, 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, the evidence from the site 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) also has 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 an absolute chronology has been problematic, particularly in the absence of suitable materials for particular geochronological techniques, 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 analysis of the Slindon Sands in the 1990s confirmed that the sediments were normalised and were therefore younger than 780 ka old but could not provide any further resolution (David and Linford 1999).

The age of the Boxgrove deposits has been controversial with different authors advancing both pre- and post-Anglian (MIS 12) ages. The evidence for a post-Anglian age can now be questioned, however, on the basis of scientific advances since the original studies were undertaken. For example, the 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 (**Amino acid racemization (AAR) geochronology**). The mammalian biostratigraphy from the site, in particular the presence of a large number of taxa (for example the shrews *Sorex runtonensis* and *Sorex savini*, the vole *Pliomys episcopalis*, the cave bear *Ursus deningeri*, the rhinoceros *Stephanorhinus hundsheimensis* (Fig 28) and the giant deer *Megaloceros dawkinsi* and *Megaloceros* cf. *verticornis*) that became extinct in Britain during the Anglian glaciation, strongly imply that the Boxgrove temperate climate sediments must pre-date, rather than post-date, MIS 12.

Further resolution in the likely chronological position of the Boxgrove deposits is provided by the **’Vole Clock‘**. The Cromerian Complex interglacials may 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 (ie advanced) form of narrow-skulled vole, *Microtus gregalis*, suggests a more recent age for Boxgrove within the *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 allows the timing of the earliest Acheulean in Britain to be more firmly established, since 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 beyond the range of radiocarbon dating.

13. The Axe Valley at Broom – OSL dating Middle Pleistocene fluvial sediments

Peter Marshall, Historic England

The sand and gravel exposures at Broom, located 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 southwest England (Fig 29). The deposits exposed in three working pits have yielded at least 2,301 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 further by the river during the Middle Pleistocene. The archaeology is of both regional importance for the understanding of the Lower Palaeolithic occupation of southwest 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 had emphasized a tripartite sequence comprising 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), resonating with Bridgland's (1996) model of the typical aggradational terrace. This framework associated major fluvial aggradations and incisions with the cyclical shifts from interglacial to glacial recorded in the Marine Isotope Record (**Text Box 1**). However, the age of the sediments remained unknown.

A project funded by the Aggregates Levy Sustainability Fund (ALSF), The Archaeological Potential of Secondary Contexts, was undertaken by Reading and Gloucestershire Universities. It sought to assess the interpretative potential of the secondary context archaeological resource for the Lower and Middle Palaeolithic in England, included excavations at Broom that built on a long history of research to contextualise the artefact collections and date the fluvial sediments. In order to provide an absolute chronology for the Middle Pleistocene terrace succession and the artefacts at Broom, and assess whether the River Axe's fluvial record mapped onto the classic Bridgland model, 18 OSL samples were dated (Table 4; Toms 2013). The optical age estimates from the Wadbrook Member and the Fortfield Farm Gravel Member were combined with relative dating information provided by the stratigraphic relationships among the samples to create a Bayesian chronological model (Fig 30). 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. The model provides an estimate for the transition from the Wadbrook Member and the Fortfield Farm Gravel Member of *312–274 ka* (*95% probability*; *Wadbrook/Fortfield EarmMember*; Fig 30) and probably *301 ka–283 ka* (*68% probability*). These results indicate that the Wadbrook Member formed between mid-MIS 9 (interglacial) and early MIS 8 (glacial), and the Fortfield Farm Gravel Member between MIS 8 (glacial) and MIS 7 (interglacial). Combined with the stratigraphic and sedimentary evidence at Broom these dates indicate that the Axe valley's terrace stratigraphy, as evident at Broom, does not fit exactly into existing models of terrace formation, 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

and are particularly notable since they clearly indicate that this Acheulean dominated assemblage at Broom formed when the Palaeolithic record in south-east England contains evidence of the beginnings of the shift towards prepared core (Levallois) dominated technologies (eg at Purfleet).

14. Seeing beneath the sea – Palaeolithic finds from Aggregate Area 240

Peter Marshall, Historic England

Between December 2007 and February 2008 gravel extraction 11km off the coast of East Anglia in Aggregate License Area 240 (Fig 31) produced an important collection of Middle Palaeolithic artefacts (Fig 32): 88 worked flints, including 33 handaxes plus faunal remains including woolly mammoth and rhinoceros, bison, reindeer and horse (Tizzard *et al* 2014; 2015). The unweathered nature of many of the hand axes 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 from the North Sea through fishing and dredging since the 1930s, the material from Area 240 came from a known areas (dredging lanes) within Area 240. Thus unlike the majority of chance finds, the Area 240 material offered the opportunity to establish the geological and geomorphological context of the material and provide an estimate of the age of the deposits.

Area 240 is situated 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. Work funded by the ALSF between 2008 and 2011 included a re-examination of geophysical and geotechnical data, new geophysical survey of the area from which the artefacts and faunal remains came, together with coring of the deposits to obtain material for dating and for reconstructing past environmental conditions (Tizzard *et al* 2015; Fig 31). This information was combined with stratigraphic information provided by the sequences from the individual cores into a Bayesian chronological model (Fig 33**Error! Reference source not found.**). The model suggest that Unit 3b, from which the majority of the artefactual and faunal material is thought to derive, dates to MIS 7 or possibly the beginning of MIS 6 – with the beginning of deposition starting in *248–206 ka* (*68% probability*; *start_unit_3B*; Fig 34) and finishing in *210–178 ka* (*68% probability*; *end_unit_3B*; Fig 34).

The material from Area 240 can now be considered within 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 prior to the hiatus of *c* 120 ka years between MIS 6–3 when hominins are completely absent.

Bayesian chronological modelling of the OSL dates from Area 240 (Table 5) has allowed the key depositional unit that is thought to have contained the flint artefacts to be correlated 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 undertaken in Area 240 (Tizzard *et al* 2014; 2015) the results confirmed that submerged landscapes have the potential to preserve *in situ* Middle Palaeolithic artefacts.

15. Uranium-series dating – constraining the age of the Middle Palaeolithic tools and fauna from Pin Hole, Creswell, Derbyshire

Alistair Pike, University of Southampton

While in ideal circumstances Uranium-series (U-series) samples would be removed in the course of a controlled excavation, caves containing intact Pleistocene deposits are rare in England. Many archaeologically important caves were excavated in the 19th or early 20th century using now-outdated methods of excavation and recording. Age constraints for the museum collections resulting from these excavations, however, can be obtained if flowstones were left *in situ* in the cave and can now be sampled and related to the excavated material, or where flowstones were collected as part of the archaeological assemblage. The latter was the case for excavations in 1925 at Pin Hole, Creswell Crags, Nottinghamshire (Fig 35) where the excavator, Leslie Armstrong, 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 by Armstrong, allowing a reconstruction of the stratigraphy (Fig 36) into 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 as well as datable speleothems (Jacobi *et al* 1998). The U-series ages (Table 6) are scattered, 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 was important because the maximum age of 64 ka supported the idea that humans 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 U-series dates and additional ESR and radiocarbon dates, was critical in defining a stage in the formal mammalian biostratigraphy for the Late Pleistocene of Britain (Currant and Jacobi 2001).

16. Neanderthals in Norfolk: Lynford Quarry

Peter Marshall and Zoe Outram, Historic England

In 2002 an archaeological watching brief at Lynford Quarry, Mundford, Norfolk revealed a palaeochannel with a dark organic fill containing *in situ* mammoth remains and associated Mousterian stone tools and debitage buried under 2–3m of bedded sands and gravels (Fig 37). Well-preserved *in situ* Middle Palaeolithic open-air sites are very unusual in Europe and exceedingly rare in England, and thus the site was recognized as of international importance and was subsequently investigated by the Norfolk Archaeological Unit (Boismier *et al* 2012).

The palaeochannel and associated deposits containing archaeological remains were excavated and recorded at a detailed level to provide a range of spatial, palaeoenvironmental, and taphonomic information concerning deposit formation and the nature of human behaviour. The lithic assemblage was dominated by Mousterian tools (handaxes and bifacial scrapers) that are characteristic of the Late Middle Palaeolithic, *c* 59–38 ka. The handaxes were of a form frequently associated with Neanderthals and as such obtaining dating evidence for the human activity was vital to investigate fully questions of diet, land use, and habitat. 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*).

The 17 OSL (Table 7; Schwenniger and Rhodes 2005) and eight radiocarbon dates (Table 8) obtained as part of geochronological investigations of the Lynford Quarry deposits (AAR analysis failed because of poor preservation of shells), have been incorporated into a Bayesian chronological model (Fig 38). Prior information about the relationship between samples is derived from direct stratigraphic relationships and 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 38) 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 38) and probably *62–54 ka* (*68% probability*) when beds of laminated sands began to accumulate.

Radiocarbon measurements from two mammoth bones recovered from the organic sediments of the Association B channel were close to the reliable limits of the technique (see **Radiocarbon Dating**) and suggest that the true age of the faunal material was probably in excess of 50 ka years – the model suggests that this is the case - and highlight one of the challenges faced when investigating Middle Palaeolithic sites; the earlier part of the period lies beyond the range of radiocarbon dating. The hominin activity recorded at Lynford can therefore be placed as occurring during late MIS 4 and/or MIS 3 with Neanderthals re-occupying England after a long hiatus during the cold stage of MIS 4.

17. Gransmoor, East Yorkshire – a precise chronology for environmental records

Peter Marshall, Historic England

The fill of a kettle-hole in a sand and gravel quarry at Gransmoor, East Yorkshire, revealed a 2.35m sequence of minerogenic and organic-rich sediments that had accumulated following ice-sheet wastage (Fig 39). Preserved pollen and beetle remains enabled a detailed reconstruction of environmental and climatic change during this period when the sediments formed (Walker *et al* 1993). The stratigraphic record for the shift from cold ('glacial') to warm ('interglacial') conditions is of great importance as it provides a unique archive of how earth and atmospheric processes interact during a period when rapid climate change occurs. The record also provides a context for better understanding the relationship between climatic, environmental, and vegetation changes at the end of the Devensian glaciation.

There are 25 radiocarbon measurements from Gransmoor, 19 AMS and six conventional measurements (Table 9), obtained on terrestrial macrofossils (15), wood (1), bulked aquatic plant macrofossils (4) and bulk sediment (5). The two results from 1.70m are statistically inconsistent (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) as providing the best estimate for the age of this horizon as the macrofossil date shows better agreement with the sequence (Blockley *et al* 2004). The four basal samples have elevated $\delta^{13}C$ values consistent with a hard-water reservoir effect which would make their dates anomalously old. These measurements have therefore been excluded from the age-depth model produced using Bchron (Haslett and Parnell 2008) shown in Figure 40.

Bchron is like other Bayesian age-depth modelling software - rBacon (Blaauw and Christen 2011) and OxCal (Bronk Ramsey 2008, Bronk Ramsey and Lee 2013) used to produce age estimates for all depths in a sequence by combining radiocarbon, or other scientific dates with prior information about their vertical relationships. Bchron differs from both rBacon and OxCal, however, in that variability in accumulation rates cannot be controlled by the user. Its approach is based on the assumption that the accumulation rate changes, even though it may be by a very small degree, at each depth where a radiocarbon date exists.

Unlike previous attempts to produce age-depth models for Gransmoor using OxCal (Blockley *et al* 2004; Elias and Matthews 2013) no radiocarbon dates, apart from those with a hard water offset, have been excluded from the initial Bchron model. Bchron has sophisticated methods of handling misfits - dates that lie well beyond the standard age-depth relationship – and outliers – those that require only a small shift to come into line (Parnell *et al* 2011). Outlier probabilities are given in Table 10 and reflect the weight each measurement is given in the model.

Producing an age-depth model is often the first step towards estimating the age of ‘events’ identified in proxy records that have not been directly dated at specific depths in a sediment sequence. For example, a feature of the pollen record from Gransmoor is the decline and subsequent recovery of *Betula* sp. (birch) values that follow an initial abrupt rise for the genus. The decline from 50% to below 20% Total Land Pollen in less than 100mm can be estimated from the age-depth model to have taken place between *13,340–13,250 cal BP (95% probability*; Fig 41, left) and *13,250–13,130 cal BP (95% probability;* Fig 41, right). The age-depth model can also be used to provide a chronology for the Late Glacial temperature changes derived from the beetle remains (Fig 42).

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

PART 4 – PRACTICALITIES

18. Project Organisation and Planning

Peter Marshall, Historic England

Government guidance set out in the National Planning Policy Framework (NPPF) (Department for Communities and Local Government 2012) 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 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 (eg desk based assessment or field evaluation where appropriate).

18.1 Specifications/briefs

These guidelines are applicable to all archaeological projects, but are aimed primarily at those undertaken as part of the planning process. Providing an accurate price for dating as part of projects with a Pleistocene component that do not adhere strictly to management principles, such as those outlined in MoRPHE (Lee 2015; Table 11), is inherently problematic and therefore the identification of ‘contingency funds’ in overall budgets should be encouraged.

For Pleistocene sites scientific dating can be expected to form an important part of any project and consequently specification of a fixed percentage of the overall tender for ‘scientific contingency’ (Brunning and Watson 2010) that could be spent on dating, for example, would be prudent. The use of the contingency would only take place following approval by the curator of costs resulting from the assessment. If following assessment the requirements for scientific dating are not as extensive as envisaged, then funds from the contingency budget would not be required. A practice such as this would encourage contractors to submit realistic tenders and thus avoid the tendency for very low post-excavation costs in project budgets.

Strategies for dating Pleistocene sites should be included in Project Designs and 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 the CIfA’s Standard and Guidance series (2014a–d; 2017a–b).

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 Appendix 1). 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 2014e).

Specifications and briefs should ask for scientific dating on Pleistocene sites to be carried out in accordance with these guidelines and as such written assurances to such an effect can be expected in Project Designs and Written Schemes of Investigation. Named specialists should be included in such documents and curators should, if necessary, ask for details of relevant experience (published papers, reports, etc) given there is no formal means of accreditation.

Full use should be made of all available sources of information on scientific dating potential when planning archaeological projects. Chronology is the framework for understanding all archaeological sites, particularly those from the Pleistocene and therefore the 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.

18.2 Desk-top assessment

The purpose, definition, and standards for desk-based assessment are given in CIfA (2014c). Specialists can contribute to desk-top assessments with information and evaluation of existing scientific dating evidence from previous investigations should they exist and the potential for scientific dating to contribute to the aims and objectives of the project. Such information can be used in order to help determine the location of interventions, and appropriate sampling strategies.

18.3 Watching briefs

The purpose, definition, and standard for watching briefs is given in CIfA (20017a). Scientific dating undertaken on samples obtained during watching briefs would only be expected in exceptional circumstances (eg completely unexpected archaeological finds).

18.4 Evaluation

The purpose, definition, and standard for evaluations are given in CIfA (2014d). In order to understand the nature of the archaeological resource evaluations are undertaken to inform decisions on planning and mitigation strategies. In some situations an evaluation might be the only intervention undertaken. Scientific dating as part of evaluations may therefore form an important contribution to an understanding of 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:

- What is the age of unexpected discoveries;
- What is the age of deposits; and
- What is the date of archaeological remains?

18.5 Excavation

Full excavation not only presents better opportunities for the recovery of samples (eg Campbell *et al* 2011) for scientific dating but more importantly for better understanding their context. Samples should ideally be retrieved by the appropriate specialist and if this is not feasible specific advice should be sort with regard to sampling methods and storage of samples.

18.6 Assessment

Scientific dating is not a technique that falls within the typical procedures for the assessment of archaeological potential (eg environmental remains). As a minimum the following information is required by the specialist to carry out an assessment:

- Brief account of the nature and history of the site;
- Aims and objectives of the project;
- Summary of the archaeological results;
- Context types and stratigraphic relationships;
- Sample locations;
- Assessment reports from other relevant specialists; and
- An idea of the project timetable and budget

The primary aim of the assessment will be to ascertain the potential of the samples to address the aims and objectives of the project.

The assessment report should contain:

- Aims and objectives of the project to which scientific dating can contribute;
- Specialist chronological aims and objectives;
- Summary of potential samples;
- Summary of potential samples to be assessed for samples suitable for dating;
- Statement of potential – how scientific dating can contribute to site, specialist, and wider research questions;
- Recommendations for further work, including for full analysis if applicable; and
- Tasks, time, and outline costings for future work (analysis and publication)

Given the potential expense of scientific dating programmes a staged-approach may be appropriate.

18.7 Post-excavation Analysis

Scientific dating should have been planned and, as a minimum, outline costs provided while preparing the updated project design. Scientific dating specialists will need to work closely with other specialists at all stages of the analysis stage.

A full report should be provided in accordance with specific guidance where it exists, eg for luminescence (Duller 2008, §9).

18.8 Dissemination and archiving

Historic Environment Record (HER)
In accordance with current best practice reports on any archaeological intervention, even if only an evaluation, should be deposited with the local HER as quickly as possible following completion. Chronological information may form a component of these reports and results from scientific dating methods should be recorded on Historic Environment Records.

Publication
Where possible the final reports on scientific dating should be included in the main body of the publication of a project (including in electronic supplementary information where this facility is available). As it may not always be feasible to integrate individual scientific reports with the full site publication, it might be appropriate for alternative publications in, for example, archaeological science or other specialist journals.

Archiving
All scientific dating reports should be included in the material deposited with the archival body, in accordance with their standards. For published overall guidelines on archive deposition see Brown (2007), Longworth and Wood (2000), Museums and Galleries Commission (1992), Walker (1990), and Archaeological Data Service (2015) and Archaeological Data Service and Digital Antiquity (2011).

Samples suitable for further dating are usually contained with the rest of the physical archive (eg bones, shells, etc) and do not require specialist archiving. They should be packaged and stored in accordance with current best practice. The general lack of long-term storage for soil and sediment samples means that in some circumstances sub-sampling for cold storage may need to be considered, although this has potential complications for radiocarbon dating of waterlogged plant macrofossils (Wohlfarf *et al* 1998).

19. Laboratories

Michael Grant, University of Southampton

An essential part of the successful application of any dating strategy is early discussion between the field project director and the specialist undertaking the analysis. Contact details of laboratories in the United Kingdom that are equipped to undertake the types of dating discussed within this guidance are given below. Note that not all laboratories undertake all forms of analysis nor do they all provide commercial services. Under each technique, the laboratories are listed in alphabetical order based upon their location or commercial name. Details were correct at the time of writing.

Radiocarbon Dating

TO BE ADDED FOLLOWING CONSULTATION

Uranium-Thorium Dating

U-Th dating facilities are fairly common in universities with large geochemistry, oceanography or geology departments. SUERC also provide a commercial service:

Radiogenic Laboratory, Scottish Universities Environmental Research Centre Rankine Avenue, Scottish Enterprise Technology Park, East Kilbride G75 0QF telephone: 01355 2233320 e-mail: director@suerc.gla.ac.uk
website: https://www.gla.ac.uk/research/az/suerc/researchthemes/isotopegeoscience/radiogenic/

The Natural Environmental Research Council (NERC) offer U-Th dates as grants-in-kind to individuals who are eligible for NERC training or research grants:

BGS Geochronology and tracers facility, British Geological Survey, Environmental Science Centre, Nicker Hill, Keyworth, Nottingham, NG12 5GG telephone: 0115 936 3425 e-mail: bbullock@bgs.ac.uk
website: https://www.bgs.ac.uk/sciencefacilities/laboratories/geochemistry/gtf/home.html

Luminescence Dating

Aberystwyth

Aberystwyth Luminescence Research Laboratory, Department of Geography and Earth Sciences Aberystwyth University Ceredigion SY23 3DB telephone: 01970 622611 e-mail: ggd@aber.ac.uk
website: https://www.aber.ac.uk/en/dges/research/quaternary/luminescence-research-laboratory/

Cheltenham

Luminescence Dating Laboratory, School of Natural & Social Sciences, University of Gloucestershire Swindon Road, Cheltenham GL50 4AZ telephone: 01242 714708 e-mail: ptoms@glos.ac.uk
website: www.glos.ac.uk/luminescence

Durham

Luminescence Dating Laboratory, Department of Archaeology, Durham University, South Road, Durham, DH1 3LE telephone: 0191 3341100 e-mail: ian.bailiff@durham.ac.uk
website: https://www.dur.ac.uk/archaeology/facilities_services/laboratories/136/

Liverpool

Liverpool Luminescence Laboratory, Department of Geography, Roxby Building, University of Liverpool, Liverpool L69 7ZT telephone: 0151 7942850 e-mail: rachel.smedley@liverpool.ac.uk website: https://www.liverpool.ac.uk/geography-and-planning/research/environmental-change/facilities/osl/

Oxford

Oxford Authentication Ltd Doreen Stoneham Oxford Authentication Ltd Boston House, Grove Technology Park Wantage Oxfordshire, OX12 9FF telephone: 01235 770998 e-mail: info@oxfordauthentication.com website: www.oxfordauthentication.com

Oxford Luminescence Dating Laboratory, OUCE / Dyson Perrins Building, University of Oxford, South Parks Road, Oxford, OX1 3QY telephone: 01865 285085 e-mail: richard.bailey@ouce.ox.ac.uk website: www.ouce.ox.ac.uk/research/aridenvironments/old

Royal Holloway

Optically Stimulated Luminescence Laboratory, Department of Geography Royal Holloway Egham, Surrey TW20 0EX telephone: 01784 276124 e-mail: simon.armitage@rhul.ac.uk website: https://www.royalholloway.ac.uk/research-and-teaching/departments-and-schools/geography/about-us/research-and-teaching-facilities/

Sheffield

Sheffield Luminescence Dating Laboratory, Department of Geography, The University of Sheffield Sheffield, S10 2TN telephone: 0114 222 7929 e-mail: M.D.Bateman@Sheffield.ac.uk website: https://www.sheffield.ac.uk/geography/facilities/luminescence-dating

SUERC

Luminescence Research Laboratory, Scottish Universities Environmental Research Centre, Rankine Avenue, Scottish Enterprise Technology Park, East Kilbride, G75 0QF. telephone: 01355 270110 e-mail: D.Sanderson@suerc.gla.ac.uk website: https://www.gla.ac.uk/research/az/suerc/researchthemes/radiometricsenvironmentalchemistry/luminescence/

St Andrews

School of Geography & Geosciences, Irvine Building, University of St Andrews, North Street, St Andrews, Fife, KY16 9AL telephone: 01334 46 3940 e-mail: earthsci@st-andrews.ac.uk website: https://www.st-andrews.ac.uk/earth-sciences/research/facilities/

Amino acid racemization (AAR)

NEaar: North East Amino Acid Racemization, Department of Chemistry, University of York, Heslington, York, YO10 5DD telephone: 01904 322574 e-mail: kirsty.penkman@york.ac.uk website: https://www.york.ac.uk/palaeo/services/ne-aar/

Tephrochronology

Chemical analysis of tephra shards is undertaken using an Electron Probe Microanalyzer (EPMA) for major elements and either Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) or Secondary Ion Mass Spectrometry (SIMS) for trace elements.

Aberystwyth (LA-ICPMS)

Department of Geography and Earth Sciences Aberystwyth University Ceredigion SY23 3DB telephone: 01970 622611 e-mail: ggd@aber.ac.uk website: https://www.aber.ac.uk/en/dges/research/quaternary/tephro/

Cambridge (EPMA)

Cambridge tephra laboratory, Department of Geography, University of Cambridge, Downing Place, Cambridge CB2 3EN telephone: 01223 330242 e-mail: christine.lane@geog.cam.ac.uk website: https://www.geog.cam.ac.uk/facilities/laboratories/facilities/cambridgetephralab.html

Edinburgh (SIMS, EPMA and LA-ICPMS)

Tephra Analysis Unit (TAU), School of GeoSciences, Grant Institute, James Hutton Road, University of Edinburgh, Kings Buildings, West Mains Road, Edinburgh. EH9 3FE telephone: 0131 650 5827 e-mail: Chris.Hayward@ed.ac.uk website: https://www.ed.ac.uk/geosciences/facilities/tephra

London (EPMA)

The Natural History Museum, Cromwell Road, London SW7 5BD telephone 020 7942 5000 e-mail: j.spratt@nhm.ac.uk website: https://www.nhm.ac.uk/our-science/departments-and-staff/core-research-labs/imaging-and-analysis/microanalysis.html

Royal Holloway (LA-ICPMS)

Earth Sciences, Royal Holloway, University of London, Egham, Surrey, TW20 0EX telephone: 01784 443835 e-mail: C.J.Manning@rhul.ac.uk website: https://www.royalholloway.ac.uk/research-and-teaching/departments-and-schools/earth-sciences/research/research-laboratories/laser-ablation-icpms-laboratory/

Oxford (EPMA)

Research Laboratory for Archaeology and the History of Art, School of Archaeology, 1 South Parks Road, Oxford OX1 3TG telephone: 01865 285202 e-mail: victoria.smith@arch.ox.ac.uk website: https://archit.web.ox.ac.uk/tephrochronology-and-electron-microprobe-commercial-services

Palaeomagnetism

Edinburgh

Rock and Palaeomagnetic Research Group, School of Geosciences, University of Edinburgh, Grant Institute, The King's Buildings, West Mains Road, Edinburgh EH9 3FE telephone: 0131-650-8510 e-mail: info@geos.ed.ac.uk
website: https://www.geos.ed.ac.uk/research/subsurface/palaeomagnetism/pmag.html

Lancaster

Lancaster University, Centre for Environmental Magnetism and Palaeomagnetism (CEMP), Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YQ telephone: 01524 510268 e-mail: b.maher@lancaster.ac.uk

Liverpool

Quaternary Environmental Change Laboratories, Department of Geography & Planning, University of Liverpool, Roxby Building, Liverpool, L69 7ZT telephone: 0151 794 3461 e-mail: Elliot.Hurst@liverpool.ac.uk website: https://www.liverpool.ac.uk/geography-and-planning/research/environmental-change/facilities/environmental-material-characterisation/

Geomagnetism Laboratory, Department of Earth, Ocean and Ecological Sciences, University of Liverpool, Jane Herdman Building, 4 Brownlow Street, Liverpool, L69 3GP telephone: 0151 794 3460 e-mail: maglab@liv.ac.uk website: https://www.liverpool.ac.uk/earth-ocean-and-ecological-sciences/research/earth-sciences/geomagnetism/

London

Palaeomagnetism Laboratory, Department of Earth Science and Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ telephone: 020 7594 6442 e-mail: adrian.muxworthy@imperial.ac.uk website: http://www.imperial.ac.uk/earth-science/research/research-groups/natural-magnetism-group/

Oxford

Palaeomagnetism and Rock Magnetism Group, Department of Earth Sciences, South Parks Road, Oxford OX1 3AN telephone: 01865 272000 e-mail: enquiries@earth.ox.ac.uk website: https://www.earth.ox.ac.uk/research-groups/palaeomagnetism-and-rock-magnetism/

Southampton

Palaeomagnetism and Environmental Magnetism Laboratory, Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, European Way, Southampton, SO14 3ZH telephone: 0 23 8059 6401 e-mail: C.Xuan@soton.ac.uk website: https://www.southampton.ac.uk/oes/research/facilities.page

20. Advice and Information

A: Historic England

The first point of contact for general archaeological science enquiries, including those relating to scientific dating and Bayesian chronological modelling, within Historic England should be the Historic England science advisors, who can provide independent, non-commercial advice. They are based in the Historic England 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 Scientific Dating Team (Alex Bayliss, Shahina Farid, Peter Marshall, and Cathy Tyers).

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

Email: alex.bayliss@historicengland.org.uk
Mobile: 07584 522 333

Email: shahina.farid@historicengland.org.uk
Mobile: 07754 776 230

Email: peter.marshall@historicengland.org.uk
Mobile: 07584 522 816

Email: cathy.tyers@historicengland.org.uk
Mobile: 07825 023 620

B. Scientific Dating Laboratories

All laboratories will be happy to advise on the technical aspects of applying their technique to Pleistocene deposits, including 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 thus welcome the opportunity to provide guidance on sample selection to ensure that together you provide the best dating possible for your samples.

C. On-line Resources

Radiocarbon Datelists

An Index to Radiocarbon Dates from Great Britain and Ireland can be found at https://archaeologydataservice.ac.uk/archives/view/c14_cba/. It contains basic information on more than 15,000 radiocarbon measurements. It was originally compiled by Cherry Lavell for the Council for British Archaeology and it comprehensive until 1982, with some later additions in 1991 and 2001. Between 2007 and 2012 the index was updated with details of the measurements included in the Gathering Time project (Whittle *et al* 2011), and with measurements funded by English Heritage before 1993.

More comprehensive details of measurements funded by English Heritage can be found in the series of volumes of Radiocarbon Dates that are freely downloadable from http://www.historicengland.org.uk/publications (available as print-on-demand hard copy).

Details of many of the 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).

Palaeomagnetism

GEOMAGIA50 - database providing access to published archeomagnetic/volcanic and sediment paleomagnetic and chronological data for the past 50 ka, available on-line at http://geomagia.gfz-potsdam.de/

PINT – the Absolute Palaeointensity (PINT) Database is a catalogue all absolute palaeointensity data with ages > 50 ka which have been published in the peer-reviewed literature. It is available at http://earth.liv.ac.uk/pint/

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

Tephrochronology

Resources containing geochemical data associated with tephra are available online. No single resource is completely 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 includes both information from the RESET project itself and from the published literature. In addition to this data, it also contains a series of tools for the analysis of this 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)

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 (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 from the past 10,000 years (https://volcano.si.edu/)

Radiocarbon Calibration Databases

The calibration curves that are currently internationally agreed are available from (http://www.radiocarbon.org/); and the data included in them is available from (http://intcal.qub.ac.uk/intcal13/about.html)

A database of marine reservoir values is provided by the ^{14}CHRONO Centre, Queen's University, Belfast (http://calib.qub.ac.uk/marine/).

Relevant Software

A variety of freely-downloadable software is available for radiocarbon calibration and Bayesian chronological modelling of radiocarbon and other scientific dates. Some packages allow a wide range of models to be constructed, others are more specialised.

(a) Calibration

Calib – on-line and downloadable versions available from http://calib.qub.ac.uk/calib/; described in Stuiver and Reimer (1993).

(b) Flexible Bayesian Chronological Modelling

BCal – on-line program available at http://bcal.shef.ac.uk/; described in Buck *et al* (1996; 1999).

OxCal – on-line and downloadable versions available from https://c14.arch.ox.ac.uk/OxCal; described in Bronk Ramsey (1995, 1998, 2001, 2008, 2009a–b), Bronk Ramsey *et al* (2001; 2010), and Bronk Ramsey and Lee (2013).

ChronoModel – downloadable versions available from https://chronomodel.com/download-chronomodel-software-mac-windows; described in Lanos and Phillipe (2015, 2017, 2018).

(c) Specialist Bayesian Chronological Modelling

rbacon – downloadable software for flexible Bayesian age-depth modelling, which runs in the R software environment (http://www.r-project.org/), available from http://cran.r-project.org/web/packages/rbacon/index.html; described in Blaauw and Christen (2011).

Bchron – downloadable program 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 from http://cran.r-project.org/web/packages/Bchron/index.html; described in Haslett and Parnell (2008) and Parnell and Gehrels (2015).

(d) Geochronology

IsoplotR– includes functions for U-Pb, Pb-Pb, ^{40}Ar/39Ar, Rb-Sr, Sm-Nd, Lu-Hf, Re-Os, U-Th-He, fission track and U-series disequilibrium dating. IsoplotR is programmed in R and can be run (1) online, via a Graphical User Interface (GUI) that runs in a web browser on any internet-connected device; (2) offline, natively running the GUI on any computer that has R installed on it; and (3) from the command line, which allows IsoplotR to be extended and incorporated into automation scripts, available from https://www.ucl.ac.uk/~ucfbpve/isoplotr/; described in Vermeesch (2018)

(e) Luminescence dating

DRAC – an online Dose Rate and Age Calculator (DRAC) designed to calculate environmental dose rates ($\dot{D}$) and ages for trapped charge dating applications. The calculations are applicable to both optically stimulated luminescence (OSL) and thermoluminescence (TL) dating and may also be useful in some electron spin resonance (ESR) applications. DRAC provides a standardised $\dot{D}$ calculator with transparent calculation using published input variables. It is an effective means of removing the potential for miscalculation, allowing improved assessment of $\dot{D}$ calculations and simpler inter-laboratory $\dot{D}$ comparisons. It is available from https://www.aber.ac.uk/en/dges/research/quaternary/luminescence-research-laboratory/dose-rate-calculator/; described in Durcan *et al* (2015)

Analyst - a Windows based program designed to view, edit and analyse luminescence data collected using a Risø automated TL/OSL reader, though other instruments may also generate datafiles that are compatible. It is available from http://users.aber.ac.uk/ggd/; described in Duller (2007; 2015)

(g) Palaeomagnetism

Palaeomag-Tools – downloadable software for the analysis and presentation of directional data applicable to palaeomagnetism, geomagnetism and archaeomagnetism. It is available from https://www.lancaster.ac.uk/staff/hounslow/resources/software/pmagtool.htm

Matlab Tool for Archaeomagnetic dating – permits archaeomagnetic direction (declination and/or inclination) and the archaeointensity obtained from the archaeological artefact to be compared with a master palaeosecular variation curves (PSVC). The master PSVCs included with the Matlab tool are the different European Bayesian curves and those generated using both regional and global geomagnetic field models. It is available from http://pc213fis.fis.ucm.es/archaeo_dating/index.html and described in Pavón-Carrasco *et al* (2011)

CPLSlot – downloadable software for the correlation between ordered successions of continuous or semi-continuous data, such as geochemical data (eg isotopes), fossil abundance data (eg pollen), and directional data (eg palaeomagnetic data). It is available from https://www.lancaster.ac.uk/staff/hounslow/resources/software/cplslot.htm

(f) Tephrochronology

GCDkit –the GeoChemical Data ToolKIT is a system for handling and recalculation of whole-rock analyses from igneous rocks, suitable for tephra-derived geochemical data, which runs in the R software environment (http://www.r-project.org/)/ It is available from http://www.gcdkit.org/; described in Janoušek *et al* (2006).

TAS Diagram Plotter v2.0 – an Excel spreadsheet that allows fast plotting onto a TAS (total alkali silica) diagram for use differentiating tephra by chemical composition. It is available from http://www.kaylaiacovino.com/tools-for-petrologists/

21. 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

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

Amino Acid a simple organic compound containing both a carboxyl (—COOH) and an amino (—NH2) group

Archaeostratigraphy branch of stratigraphy concerned with artefacts types that are characteristic of a certain part of the typological sequence, allowing the separation (and correlation) of stratigraphic layers into approximate time periods

Acheulian biface a techno complex of stone-tool manufacture characterised by distinctive oval and pear-shaped ‘hand axes’.

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

Bayes’ Theorem express the relationship between prior and current beliefs

Biomineral A mineral produced by the activity of living things

Biostratigraphy branch of stratigraphy concerned with fossils and their use in dating sedimentary deposits

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

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 an industry of European flint tool manufacture from bifacially working a flint core that dates from the early part of the Hoxnian.

Climatic optimum period of highest prevailing temperatures within an interglacial

Cosmic ray a highly energetic atomic nucleus or other particle travelling through space at a speed approaching that of light

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 eccentricity, axial tilt, and precession of the Earth's orbit upon the climatic patterns on Earth

Cryptotephra volcanic ash layers invisible to the naked eye and usually comprising grains less than 125µm in size

Curie temperature (Curie point) on heating, the temperature above which a material 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. Named after Pierre Curie (1859–1906)

Dansgaard–Oeschger cycles describes 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

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

Dosimeter a device that measures exposure to radiation

Fluvial of or found in a river

Glacial an interval of time (thousands of years) marked by colder temperatures and glacier advances

Glacial Maximum period within a glacial when global ice sheets reach their greatest extension; the Devensian Glacial Maximum was *c* 24.5 ka

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

Geological timescale: system of chronological dating that relates geological strata (stratigraphy) to time. The largest defined unit of time are Eons, which, in turn, are divided into Eras, Periods, Epochs and Ages

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

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 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 second (and present) epoch within the Quaternary period, starting *c* 11.7 ka

Hominin early human or pre-human beings: a member of the sub-family Homininae usually identified by bipedal adaptations

Human members of the genus *Homo*, including *Homo habilis*, *Homo rudolfensis*, *Homo erectus*, *Homo antecessor*, *Homo heidelbergensis*, *Homo floresiensis*, *Homo neanderthalensis, Homo naledi* and *Homo sapiens* (modern humans)

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

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 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

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

Lacustrine relating to or associated with lakes.

Levallios prepared core (**Levallios)** a distinctive style of flint knapping, the earliest of the core preparation technologies, that initially involves preparation of a pebble into a rough shape. Subsequent stages involve, removal of cortex, platform preparation and finally removal of flakes.

Loess an unstratified wind-deposited sedimentary deposit composed largely of silt-size grains that are loosely cemented by calcium carbonate

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

Mousterian a techno-complex of lithic tools primarily associated with Neanderthals in Europe that largely defines the later part of the Middle Palaeolithic.

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 characterized by a specific number of protons and neutrons

Orbital tuning process of adjusting the time scale of a geologic or climate record so that the observed fluctuations correspond to the Croll-Milankovitch cycles in the Earth's orbital motion

Palaeolithic the 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* 250 ka): earliest subdivision of the Palaeolithic, or Old Stone Age; when the earliest use of flint tools appears in the current archaeological record. A hunter gatherer society is a defining characteristic
- Middle Palaeolithic (*c* 250–40 ka): second subdivision of the Palaeolithic or Old Stone Age. Characterized by the fine flake tools of the Mousterian tradition and economically by a hunter gatherer society
- Upper Palaeolithic (*c* 40-11.5 ka): third and last subdivision of the Palaeolithic or Old Stone Age; characterized by the development of projectile points made from bony materials and the development of fine blade flint tools

Palaeointensity-Assisted Chronology (PAC) the use of Relative Palaeointensity (RPI) 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

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

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

Pleistocene: first epoch within the Quaternary period, between *c* 2.58 Ma and 11.7 ka

Pliocene last epoch of the Tertiary period, between the Miocene and Pleistocene epochs, between *c* 5.3 and 2.6 Ma

Post-glacial relating to or occurring during the time following a glacial period

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 and indicates the degree to which measurements are repeatable and reproducible

Racemization 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 AD, 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

Radioactive decay spontaneous transformation of a radionuclide towards a more stable state with a lower atomic number, resulting in the release of radiation in the form of alpha particles, beta particles or gamma rays

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 magnetization of sedimentary samples. The normalisation is typically done by a laboratory-introduced magnetisation to compensate for the ability of the sample to acquire magnetisation

Stable isotope an isotope that does not undergo radioactive decay.

Stadial relatively cold period during glacials

Stratigraphy study of the order and relative position of strata / archaeological material

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

Taphonomy the circumstances and processes of fossilisation.

Tephra fragments of rock that are produced when magma or rock is explosively ejected y a volcano

Tertiary 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.

Ultrafiltration filtration using a medium fine enough to retain colloidal particles, viruses, or large molecules

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

Quaternary 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

Vitreous like glass in appearance or physical properties

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24. Text Boxes

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. Palaeo-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 run parallel with the isotopic composition of seawater, 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) in comparison with the sea water from which it originates, so when larger amounts of global water are locked up in enlarged icesheets, as occurs during glacials, the world's oceans become relatively enriched in the heavy isotope (^{18}O). Thus the oxygen-isotope 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, plotted against time, as a curve (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.

Text Box 2: Oxygen isotopes in Ice Cores

Ice cores drilled from the Arctic and Antarctic shelves provide a high-resolution record of $\delta^{18}O$, which varies according to the temperature of the ocean. Ice is deposited in these archives as a series of annual layers, which can be counted 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 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 characterized by high-frequency, high-amplitude climate oscillations (Alley 2000; Bond *et al* 1993; Dansgaard *et al* 1993; Seierstad *et al* 2014; Rasmussen *et al* 2014; Fig 7). These 'Dansgaard–Oeschger' cycles saw abrupt warming by 5–8°C within 50 years, perhaps within as little as a decade, followed by more protracted cooling. Each cycle lasted in 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 that particular terrestrial proxy 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. The record is divided into a series of alternating Greenland Stadial (GS) and Greenland Interstadial (GI) stages (Fig 8).

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 when rock surfaces became exposed to cosmic radiation. It has been used to date past glaciation, for instance by dating ice-moulded bedrock and erratic boulders (eg Ballantyne 2010). ^{36}Cl, ^{10}Be and ^{26}Al isotopes, between them cover timescales from a few ka to 4 Ma. The amount of these isotopes built up, 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, which 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, both being 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. This must then have been rapidly buried at sufficient depth to prevent further cosmogenic nuclide production. As they decay at differing rates, and the surface concentration ratio is well understood, the ratio of the buried sample can be measured and dated.

Text Box 4: Electron Spin Resonance (ESR)

Electron spin resonance (ESR) is a technique related to the luminescence group, in that it measures mineral exposure to environmental radiation (Duval 2016; Rixhon *et al* 2017). The materials that can be dated include phosphates, carbonates and silicates, with fossil (including teeth) and optically bleached quartz grains being the most common applications to Pleistocene deposits in Britain. The main difference from luminescence dating is that the equivalent dose (electrons stored in traps in the crystal lattice) is obtained using ESR spectroscopy, which requires the aging of the samples artificially at increasing doses in order to describe the behaviour of the studied signal. A wide range of different analytical techniques can be used and correction is typically applied for the density of the material, its geometry and water content. Quoted errors are typically 15% of the estimated age

25. Tables

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 Number	Material and context	Radiocarbon Age (BP)	δ^{13}C (‰)	δ^{15}N (‰)	%C	CN ratio	Gelatin yield (mg)
OxA-18065	M.49797, *Equus ferus*, cut left 1^{st} 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 2^{nd} 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 2^{nd} 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*, righ 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
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	12,590±50	−19.3±0.2	7.7±0.3	50.4	3.1	51.4

Laboratory Number	Material and context	Radiocarbon Age (BP)	δ^{13}C (‰)	δ^{15}N (‰)	%C	CN ratio	Gelatin yield (mg)
	Natural History Museum excavation (1987–9).						
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

Table 2: The affect of contamination by modern carbon on samples of varying radiocarbon age

Actual ^{14}C Age (BP)	**Measured ^{14}C Age (BP) of sample contaminated by modern carbon**		
	1%	**5%**	**10%**
5,000	4,950	4,650	4,350
10,000	9,800	9,050	8,200
15,000	14,860	13,250	11,600
20,000	19,850	16,950	14,450
25,000	23,350	19,100	15,750
30,000	27,200	21,000	17,000
35,000	30,500	22,300	17,600
40,000	32,700	23,100	18,000
45,000	34,700	23,500	18,250
50,000	35,650	23,800	18,360

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 B, maximum age for A
Flowstone floor underlying layer B	Maximum age for Layer B and by implication B
Detached stalactites in later 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

Table 4: Broom Optical Stimulated Luminescence dates (Toms 2013)

Laboratory Code	**Depth (m)**	**Mean Age (ka) BP**	**Minimum Age (ka) BP**	***Highest Posterior Density Interval – ka (95% probability)***
GL02082	5.1	293±24	-	*301–237*
GL02083	15.6	287±22	-	*319–2839*
GL02084	16.5	279±20	-	*341–290*
GL02085	2.78	279±24	-	*290–254*
GL03001	1.65	460±38	215±13	*233–182*
GL03002	2.12	739±89	275±21	*254–206*
GL03003	2.68	870±76	326±53	*252–131*
GL03004	2.66	268±22	107±8.1	*273–227*
GL03005	2.95	226±16	-	*263–220*
GL03006	2.81	277±25	-	*284–241*
GL03007	2.96	271±22	-	*298–253*
GL03008	0.95	244±18	-	*269–205*
GL03009	1.09	270±19	-	*294–238*
GL03010	15.0	237±25	-	*281–187*
GL03011	16.2	297±29	-	*329–283*
GL03057	10.43	24±2	-	-
GL03058	10.65	20±2	-	-
GL03059	10.81	34±2	-	-

Table 5: Optical Stimulated Luminescence dates from in and around Area; Toms (2011) and Wessex Archaeology (2008)

Laboratory Code	Field Code	Age (ka)
GL 10037	VC7b 1.32–1.42m	109±11
GL10038	VC2b 0.85–0.95m	243±33
GL 10039	VC2b 3.1–3.2m	418±78
GL 10041	VC7b 0.45–0.55m	96±11
GL 10042	C7b 2.5–2.65m	207±24
GL 10043	C9b 4.51–4.61m	283±56
GL 10044	C9b 1.45–1.55m	36±3
GL 10045	C9b 0.7–0.8m	36±5
	VC1a: 1.14	17±2
	VC1a: 1.92	167±11
	VC1a: 3.3	176±23
	VC1a: 3.7	577±65
	VC29_1	207±30
	VC29_2	222±29
	VC29_3	188±19
	VC29_4	57±6

Table 6: Uranium-series TIMS data. Numbers in parentheses are the errors (1 SD) in the last one or two decimal places. 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 (2)	0.683 (1)	0.592 (5)	94.8±1.3
36/12'	0.120	26.6±0.2	1.212 (1)	0.605 (5)	0.499 (2)	73.4±0.4
51/8'	0.105	2625±7	1.219 (1)	0.715 (3)	0.587 (2)	92.8±0.4
59/11' upp	0.063	98±3	1.075 (1)	0.619 (22)	0.576 (20)	92.1±5.0
63/8' upp	0.121	523±2	1.195 (1)	0.539 (3)	0.451 (3)	63.9±0.3
64/10P	0.087	25.0±0.1	1.183 (1)	0.625 (4)	0.528 (2)	79.7±0.5
64/12P mid	0.098	98±1	1.191 (1)	0.619 (9)	0.519 (5)	77.8±1.0
64/12P upp	0.051	11.9±0.9	1.135 (3)	0.553 (34)	0.487 (36)	71.5±7.7
69/7'	0.116	2340±13	1.227 (1)	0.699 (7)	0.569 (3)	88.5±0.7
70/8'	0.094	95±3	1.190 (2)	0.534 (3)	0.449 (2)	63.7±0.4
12/Pii	0.060	87±2	1.140 (2)	0.544 (2)	0.477 (2)	69.4±0.4

Table 7: Lynford Quarry OSL measurements

Age estimate code	Field code	Lab. code	Facies unit	Height (m ODN)	Context (*contained lithic artefacts)	Palaeodose (Gy)	Total dose rate (mGy/a)	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	0.61 ± 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 measurements

Laboratory Code	**Sample number**	**Material & context**	**Radiocarbon Age (BP)**	**δ^{13}C (‰)**	***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	$35,710\pm^{930}_{830}$	−28.0	*41,800–38,900*
GrN-28396	30377	Peat, humin - as GrN-28395	$35,800\pm^{1200}_{1050}$	−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	$30,690\pm^{620}_{570}$	−27.8	
OxA-11571	50137	Tooth, *Mammuthus primigenius*, anterior fragment of molar DM$_3$ or M$_1$	53,700±3100	−21.2	-
OxA-11572	50000	Animal bone, *Mammuthus primigenius*, part of mandible attached to molar DM$_3$	<49,700	−21.1	-

Table 9: Gransmoor Quarry radiocarbon dates (Lowe *et al* 1995; Walker *et al* 1993)

Laboratory number	**Material & depth**	**$\delta^{13}C$ (‰)**	**Radiocarbon Age (BP)**	***Highest Posterior Density interval cal BP (95% probability)***
AA-13299	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 0.40m	−28.6	10,150±80	*11,615–11,985*
AA-13298	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 0.50m	−29.5	10,215±90	*11,735–12,050*
AA-13297	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 0.60m	−29	10,355±75	*11,825–12,130*
AA-13296	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 0.70m	−27.5	10,835±80	*11,875–12,170*
AA-13295	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 0.85m	−29.2	10,340±85	*11,980–12,260*
AA-13294	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 0.95m	−28.9	9745±85	*12,040–12,315*
AA-13293	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 1.01m	−28.8	10,565±75	*12,125–12,385*
AA-13292	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 1.15m	−29.7	10,385±75	*12,180–12,435*
SRR-3873	Bulk sediment, humic fraction from 1.20m	−27.8	11,715±45	*12,225–12,485*
AA-13291	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 1.35m	−29.2	10,275±90	*12,305–12,550*
SRR-3874	Bulk sediment, humic fraction from 1.38m	−28.0	11,530±50	*12,375–12,615*
AA-13290	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 1.42m	−29.5	10,575±80	*12,450–12,685*
AA-12005	Terrestrial plant macrofossils, mainly *Carex* and Cyperaceae, from 1.60m	−25.6	11,335±80	*12,610–13,135*
SRR-4920	Wood, from 1.69m	−27.2	11,475±50	*12,730 13,215*
AA-12004	*Carex* fruits, from 1.70m	−25.5	11,195±80	*12,795–13,250*
SRR-3875	Bulk sediment, humic fraction from 1.70m	−29.2	11,820±45	-
SRR-3876	Bulk sediment, humic fraction from 1.74m	−28.9	12,340±45	*12,850–13,295*
AA-12003	*Carex* fruits, from 1.78m	−26.2	10,905±75	*12,910–13,345*
AA-12002	*Carex* fruits, from 1.88m	−25.8	11,300±80	*13,045–13,410*
SRR-3877	Bulk sediment, humic fraction from 1.95m	−30.1	12,790±45	*13,125–13,525*
AA-12001	*Carex* fruits, from 2.05m	−24.8	11,565±85	*13,210–13,590*
AA-12000	Aquatic macrophytes from 2.14m	−12.5	15,060±100	-
AA-11999	Aquatic macrophytes from 2.17m	−11.5	13,375±90	-
AA-11998	Aquatic macrophytes from 2.24m	−9.9	13,160±90	-

Laboratory number	Material & depth	$\delta^{13}C$ (‰)	Radiocarbon Age (BP)	***Highest Posterior Density interval cal BP (95% probability)***
AA-11997	Aquatic macrophytes and sedge remains from 2.26m	−10.2	12,445±90	-

Table 10: Gransmoor Quarry outlier probabilities

Date	Outlier Probability
AA-13299	0.011
AA-13298	0.009
AA-13297	0.013
AA-13296	1
AA-13295	0.008
AA-13294	0.999
AA-13293	0.013
AA-13292	0.009
SRR-3873	1
AA-13291	0.016
SRR-3874	1
AA-13290	0.004
AA-12005	0.804
SRR-4920	0.906
AA-12004	0.005
SRR-3876	1
AA-12003	0.2
AA-12002	0.017
SRR-3877	0.798
AA-12001	0.007

Table 11: Summary of stages of project planning for Pleistocene scientific dating under MoRPHE (Lee 2015) with examples of activities at each stage

Start-up	Consider the main purpose and drivers for the project
	How will scientific dating contribute to the project aims and objectives?
	What types of samples for scientific dating are likely to survive?
	What types of samples for scientific dating might need to be recovered?
	Consult specialists for advice
Initiation	Design specifics of scientific dating strategy, if appropriate
	Clearly define how specific scientific dating if required will meets aims and objectives of the project
	Clearly state what products will result (eg reports, tables, illustrations)
Execution	Update Project design. Undertake analysis.
	Produce report(s) and any other dissemination products.
	Deposit scientific reports with site archive.
	NB There may be several iterations of this stage in more complex projects
Closure	Produce publication
	Review achievements and lessons learnt

26. Figures

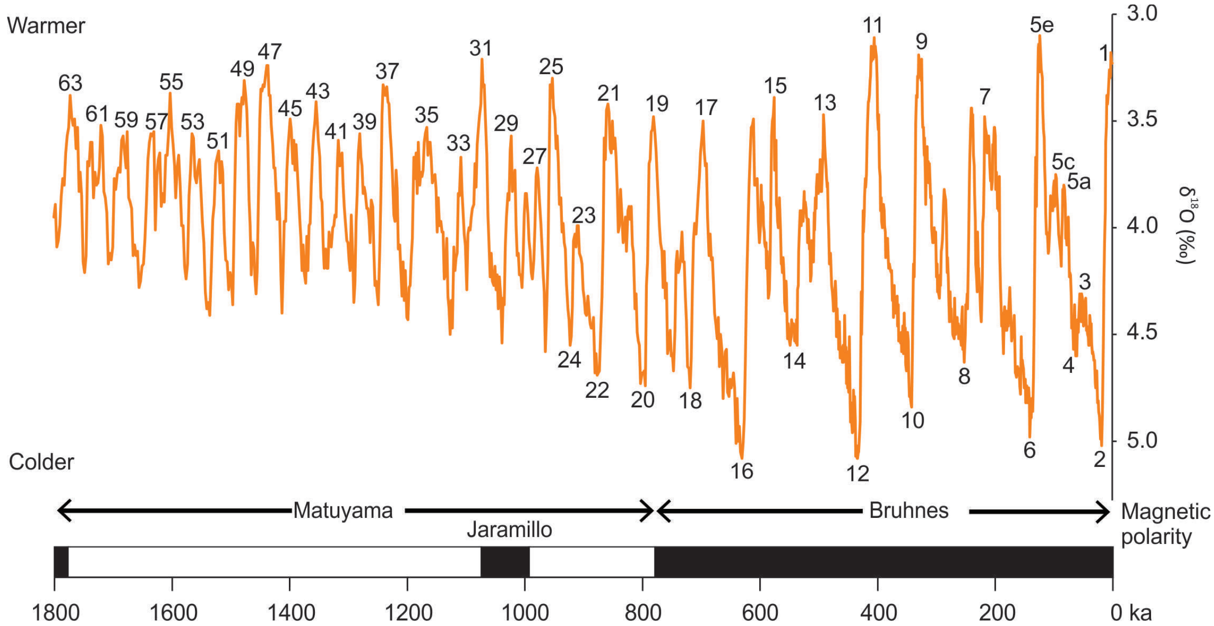


Fig 1 The Marine Oxygen Isotope Record from deep marine sediments, for the last 1.8 Ma, based on the LR04 benthic $\delta^{18}O$ stack constructed by Lisiecki and Raymo (2005) by the graphic correlation of 57 globally distributed benthic records. The record of palaeomagnetic polarity is shown below the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

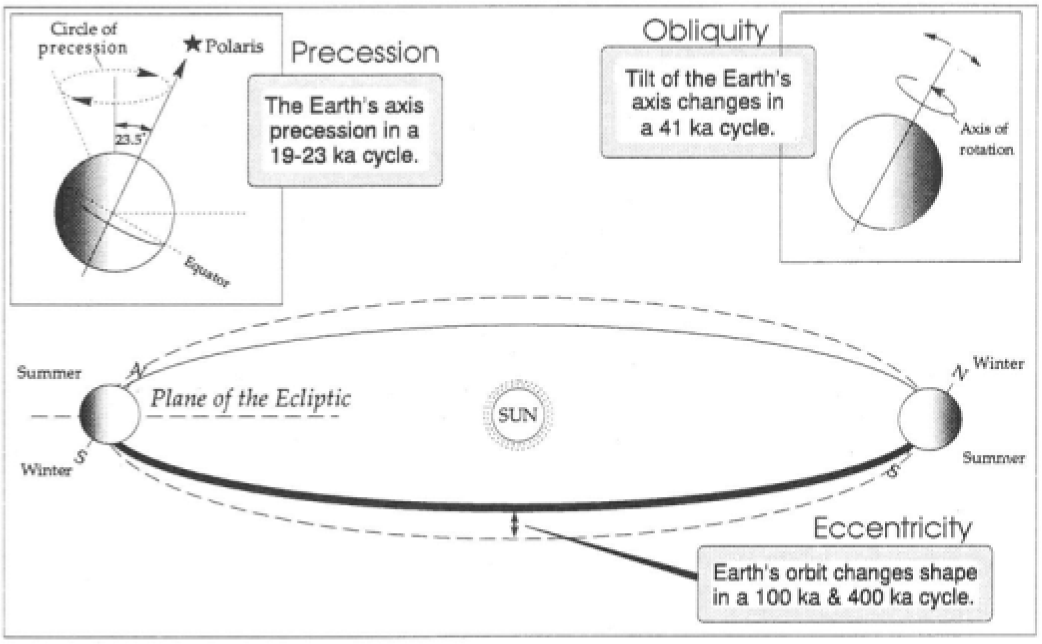


Fig 2 Summary of astronomical cycles (orbital eccentricity, obliquity, and precession) involved in solar input and climate variation

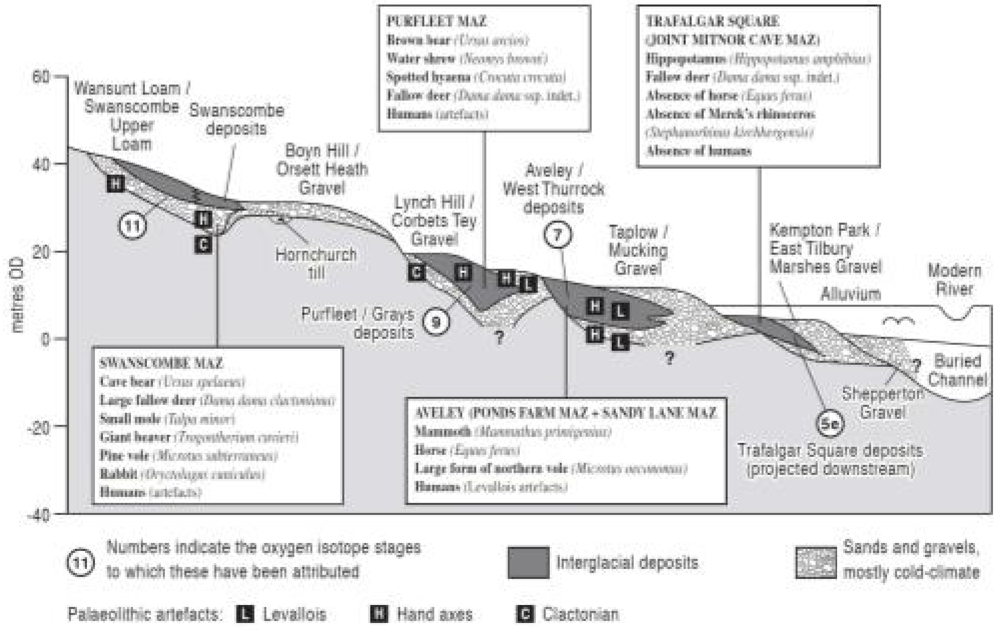
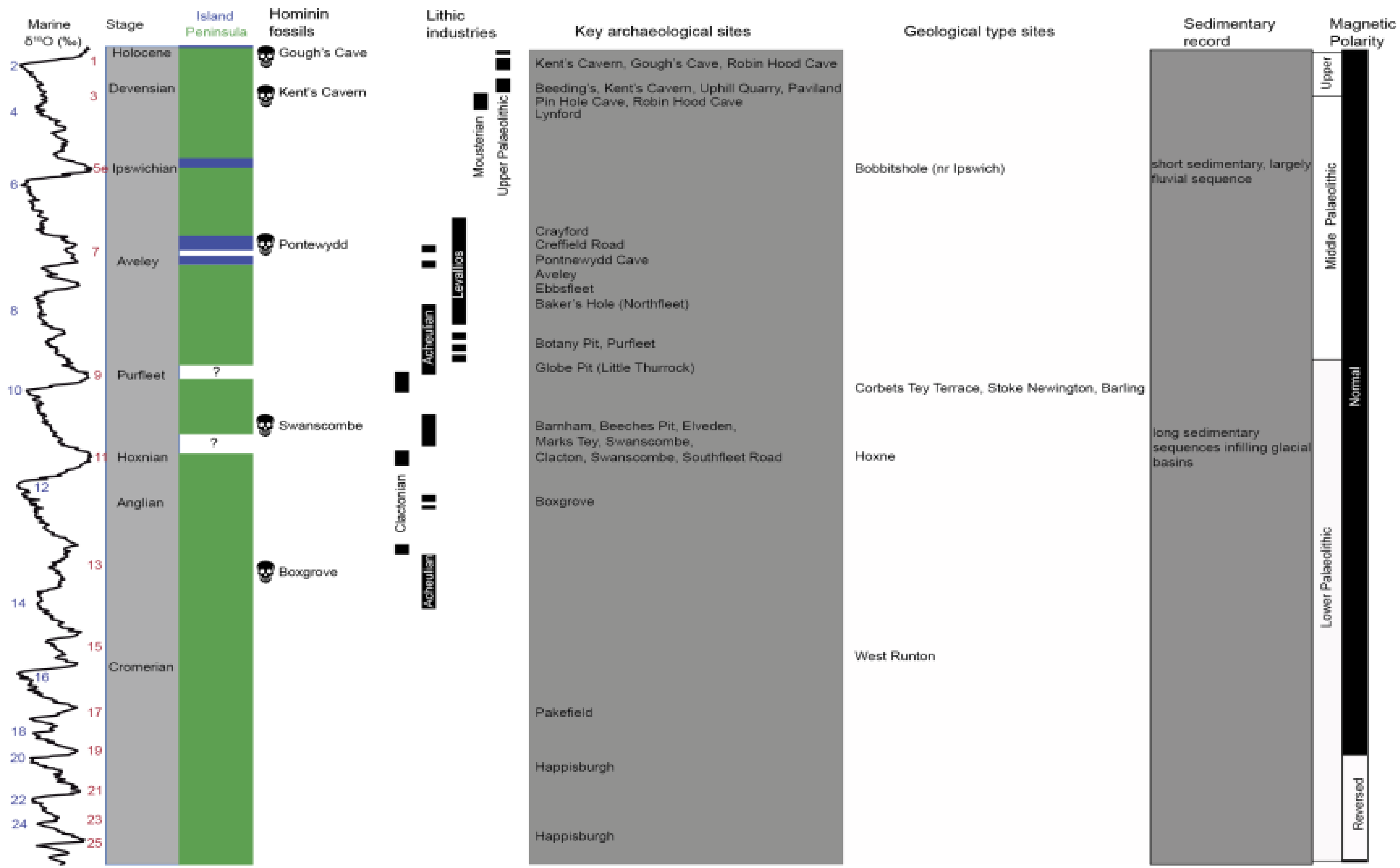


Fig 3 Idealised transverse profile of the Lower Thames terrace staircase, showing the mammalian assemblage zones (MAZ) and the distribution of main Palaeolithic artefact types (after Bridgland *et al* 2014). Marine Oxygen Isotope stage attributions of the interglacial components of this sequence are indicated



2363 **Fig 4** Climato-stratigraphy, paleogeography and human occupation of Britain during the Quaternary (modified from ahobproject.org/Downloads/Chart.PDF)

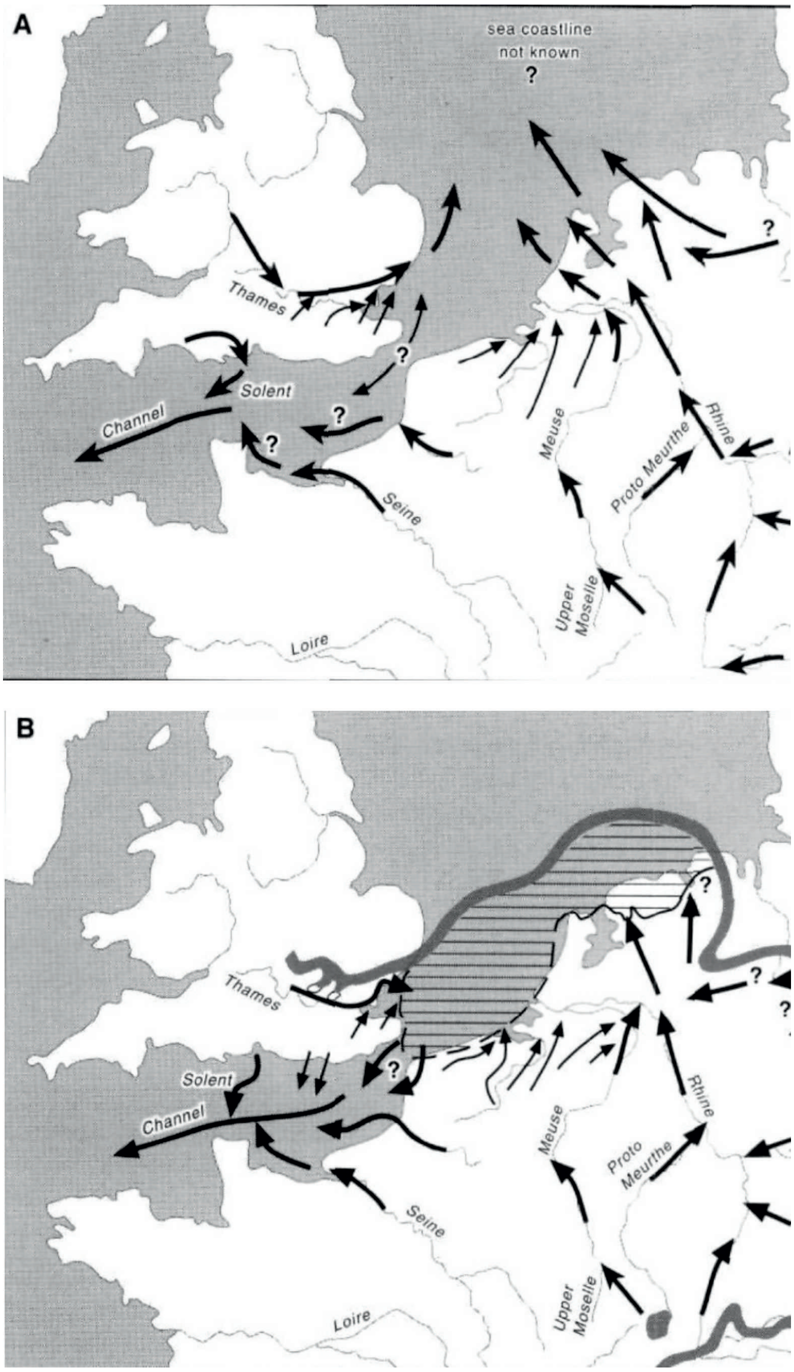


Fig 5 Evolution of the southern North Sea – English Channel and the glacial diversion of the Rhine–Thames during MIS 12. (A) Drainage of the southern North Sea region in the Cromerian Complex. (B) The same area during the MIS 12 glacial maximum, showing a large ice-dammed lake in the southern North Sea basin and the initiation of Rhine-Thames drainage through the English Channel, the result of overspill from this lake, which formed the valley through the Chalk ridge (continuation of the North Downs) that is now the Strait of Dover (from Bridgland and Gibbard 1997)

Fig 6 Key elements of British Quaternary drainage evolution: (a) Drainage systems that existed immediately prior to the Anglian (MIS 12) glaciation. (b) Drainage systems in the late Middle Pleistocene, with emphasis on data from MIS 11, although extensions that would have existed during low sea-level episodes are also shown. (c) Drainage pattern in the Last Glacial Maximum (MIS 2), as represented by floodplain and buried channel gravels (invariably present beneath modern rivers). Note that the equivalent gravel in the Trent extends both along its Pleistocene route to the Fen Basin and by way of the modern course to the Humber (occupied by proglacial Lake Humber during the MIS 2 glaciation, as shown) which dates only from latest MIS 2 deglaciation. After Bridgland and Allen (2014)

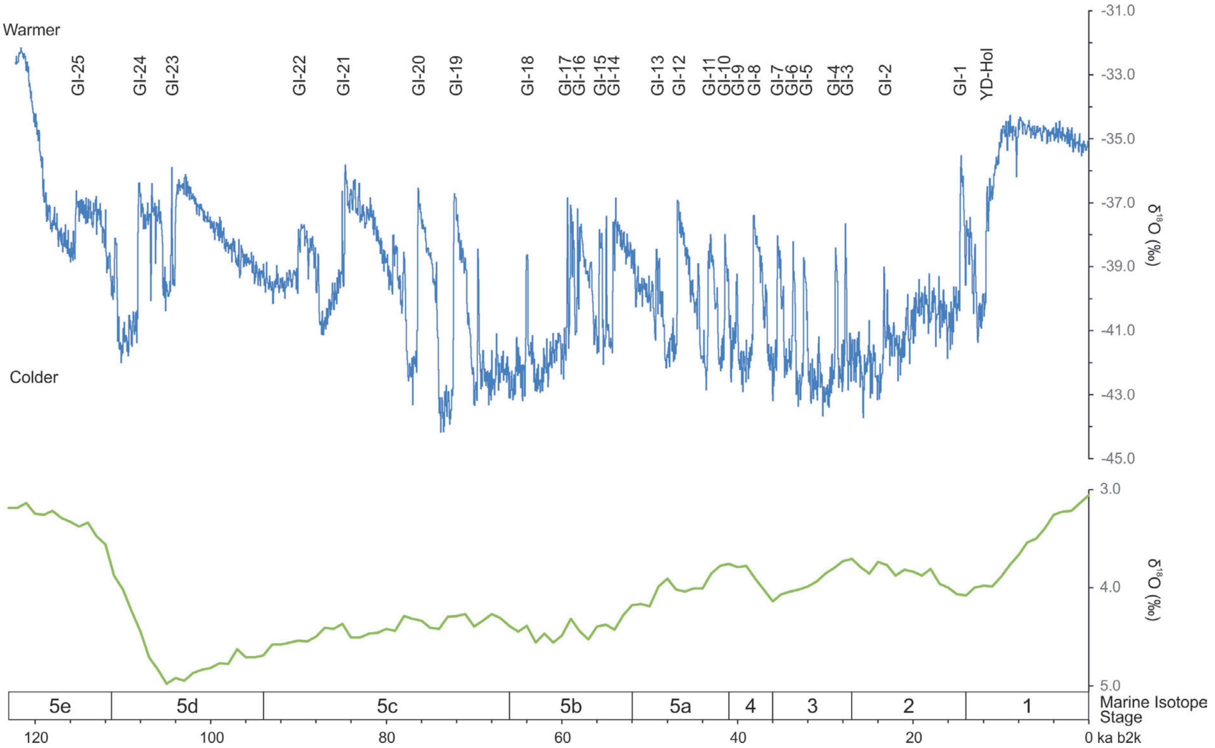


Fig 7 Ice Core Chronology for the Late Pleistocene-Holocene. NGRIP, GRIP and GISP2 ice core δ^{18}O record against the GICC05 timecale (Seierstad *et al* 2014) and Greenland event stratigraphy (onset of Greenland Interstadials (GI); Rasmussen *et al* 2014). "YD-Hol" marks the Younger Dryas-Holocene transition (see Walker *et al* 2009). Below this, the Marine Oxygen Isotope Record (Lisiecki and Raymo 2005), with ages for the start of each MIS derived from Lisiecki and Raymo (2005) except MIS 1 which is derived from the Holocene GSSP (Walker *et al* 2009)

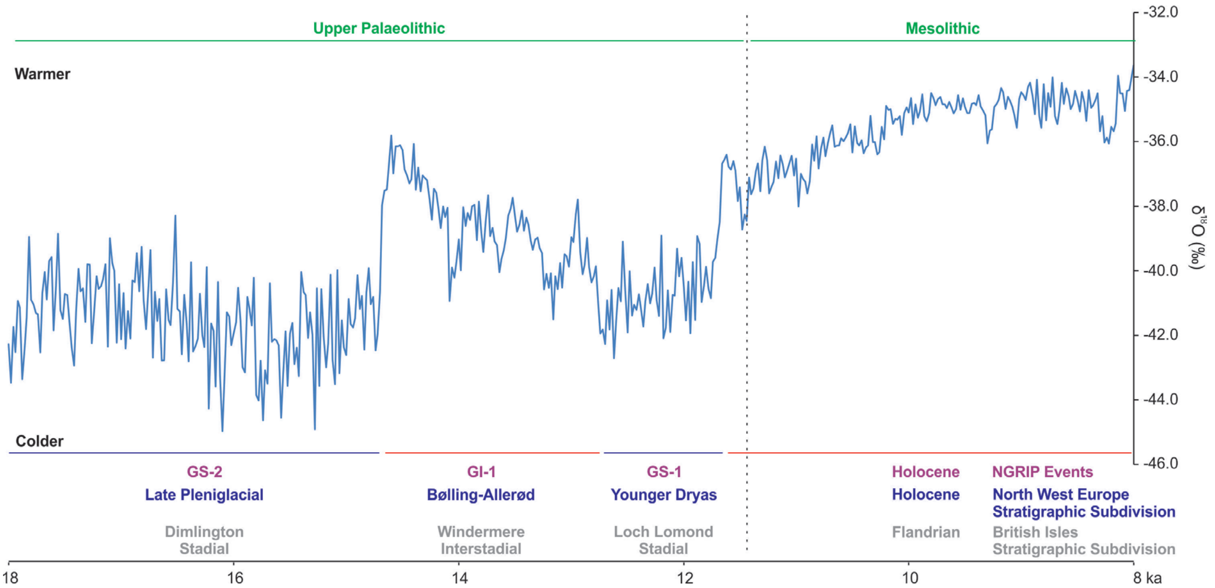


Fig 8 Late Glacial event stratigraphy derived from the NGRIP, GRIP and GISP2 ice core δ^{18}O record against the GICC05 timecale (Seierstad *et al* 2014), with stratigraphic subdivisions of the Late Glacial in north-west Europe and the British Isles, archaeological periods in the British Isles, based upon Walker (2005, fig 1.5). GI = Greenland Interstadial; GS = Greenland Stadial

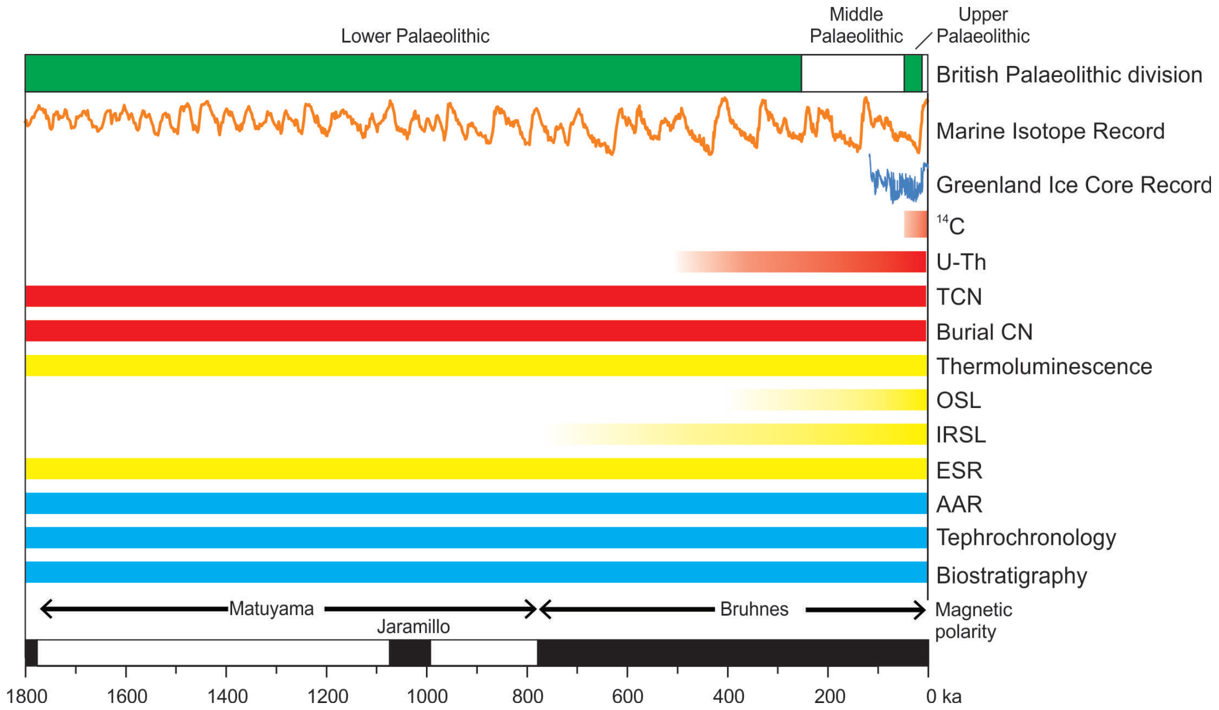


Fig 9 Timespans at which dating methods mentioned in this guidance are applicable. Maximum age limits are determined by material being dated, local environmental conditions and presence of suitable reference material (for example known dated tephra's or equivalent chrono-biostratigraphic information). Marine Oxygen Isotope Record from Lisiecki and Raymo (2005) and Greenland Ice Core Record from Seierstad *et al* (2014)

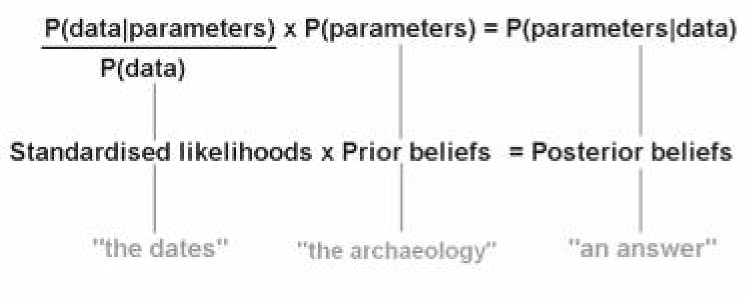


Fig 10 Bayes' theorem

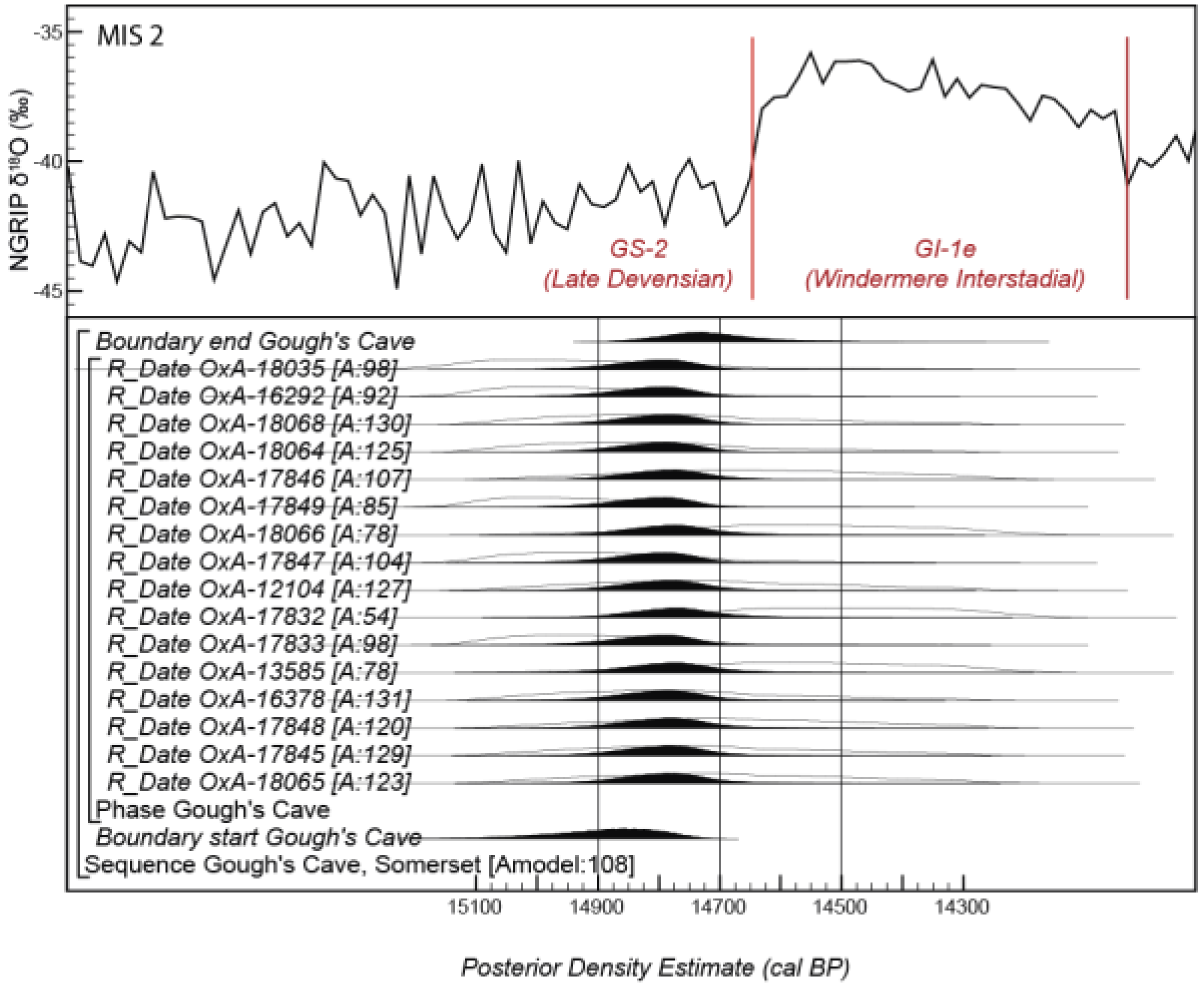


Fig 11 Probability distributions of dates from Gough's Cave, Somerset. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the result of simple radiocarbon calibration, and a solid one, based on the chronological model used. Other distributions correspond to aspects of the model. For example, the distribution '*start Gough's Cave*' 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 (http://c14.arch.ox.ac.uk/). The upper panel shows the correlated NGRIP, GRIP and GISP2 ice core $\delta^{18}O$ record against the GICC05 timecale (Seierstad *et al* 2014)

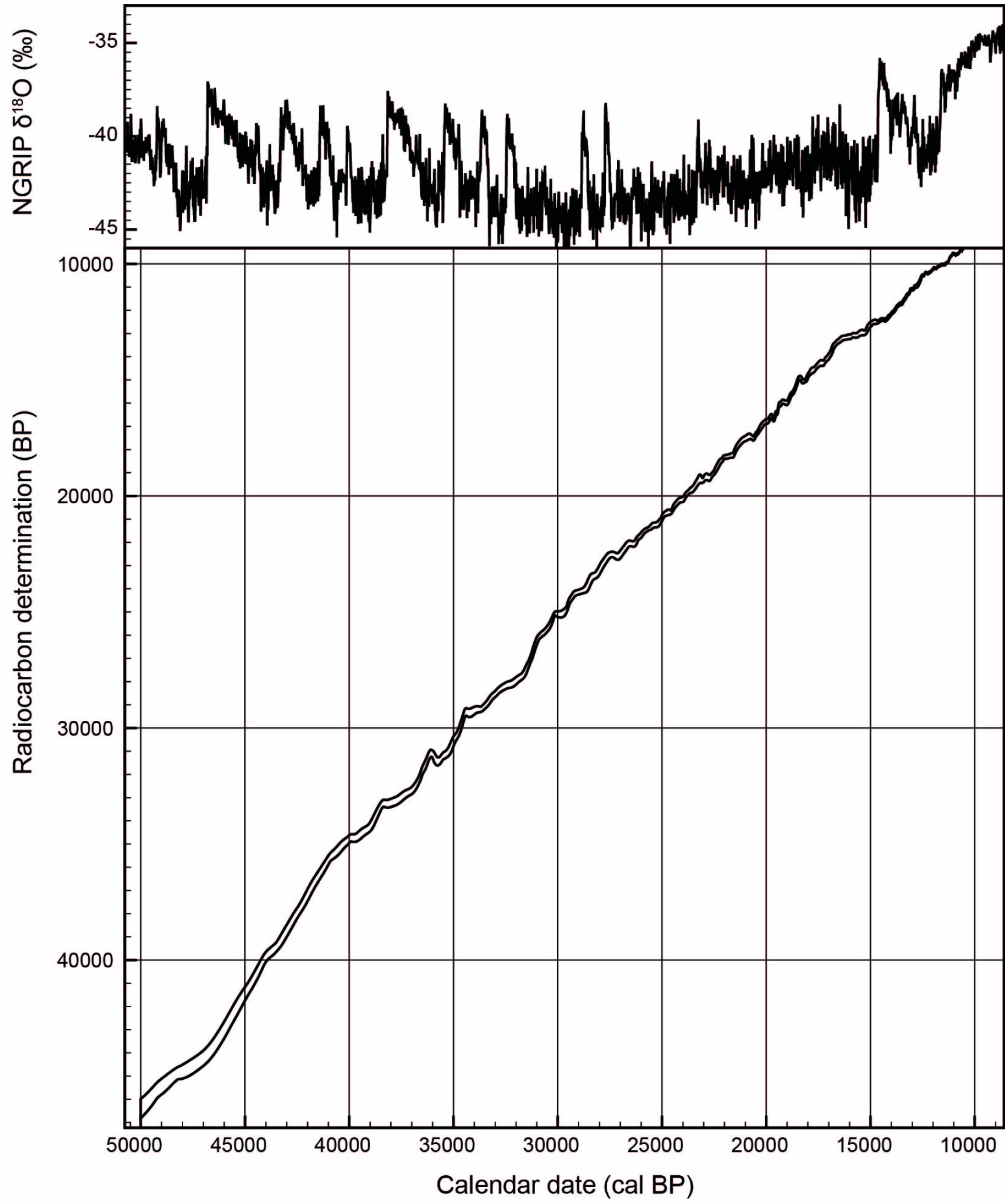


Fig 12 Radiocarbon calibration curve for atmospheric samples from the northern hemisphere, IntCal13 (Reimer *et al* 2013), plotted against the correlated NGRIP, GRIP and GISP2 ice core $\delta^{18}O$ record (Seierstad *et al* 2014)

Fig 13 Block of flowstone removed from a cave for U-Th dating

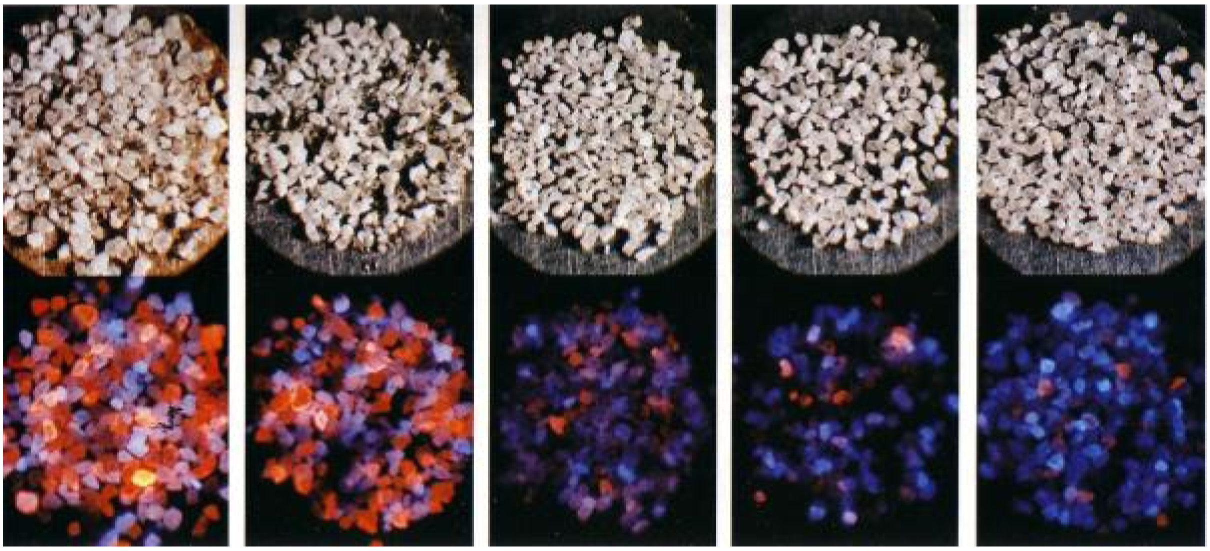


Fig 14 The upper row of photographs are sand sized grains of quartz (~0.2mm in diameter). The lower row of photographs shows the luminescence signal emitted from these grains after they were exposed to radioactivity

Fig 15 Three samples for luminescence dating have been collected from this Palaeolithic site at Broom using plastic tubes. A portable gamma spectrometer is being used to measure the radioactivity on the right hand side of the image. See Brown *et al* (2015) for further information

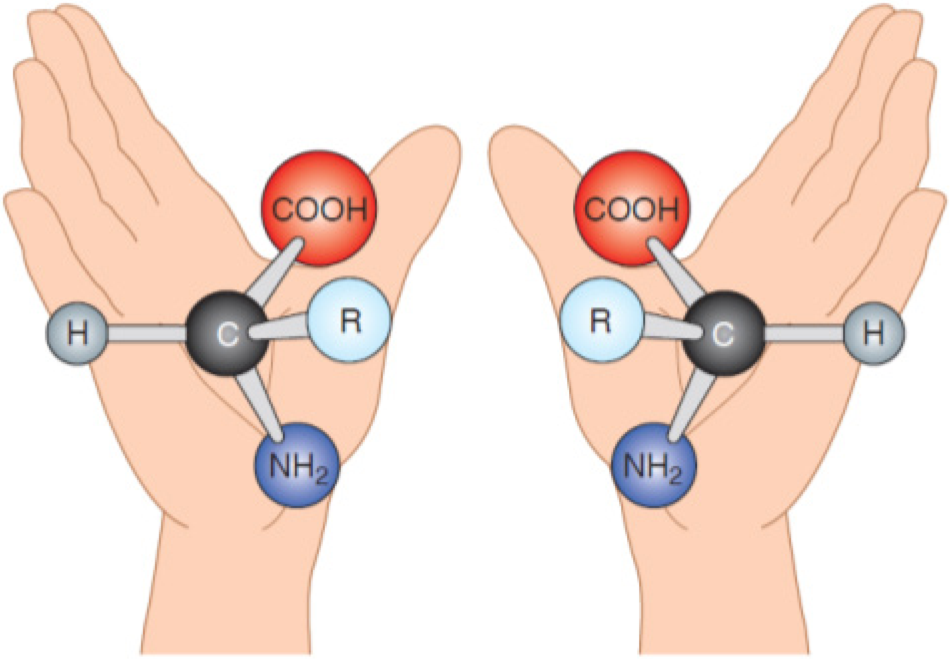


Fig 16 Most amino acids have no plane of symmetry, just like hands, so their mirror images are non-superimposable and therefore distinct from each other. The breakdown of left-handed molecules to the right-handed form over time provides a mechanism for estimating age of fossil material (modified from Crisp 2013)

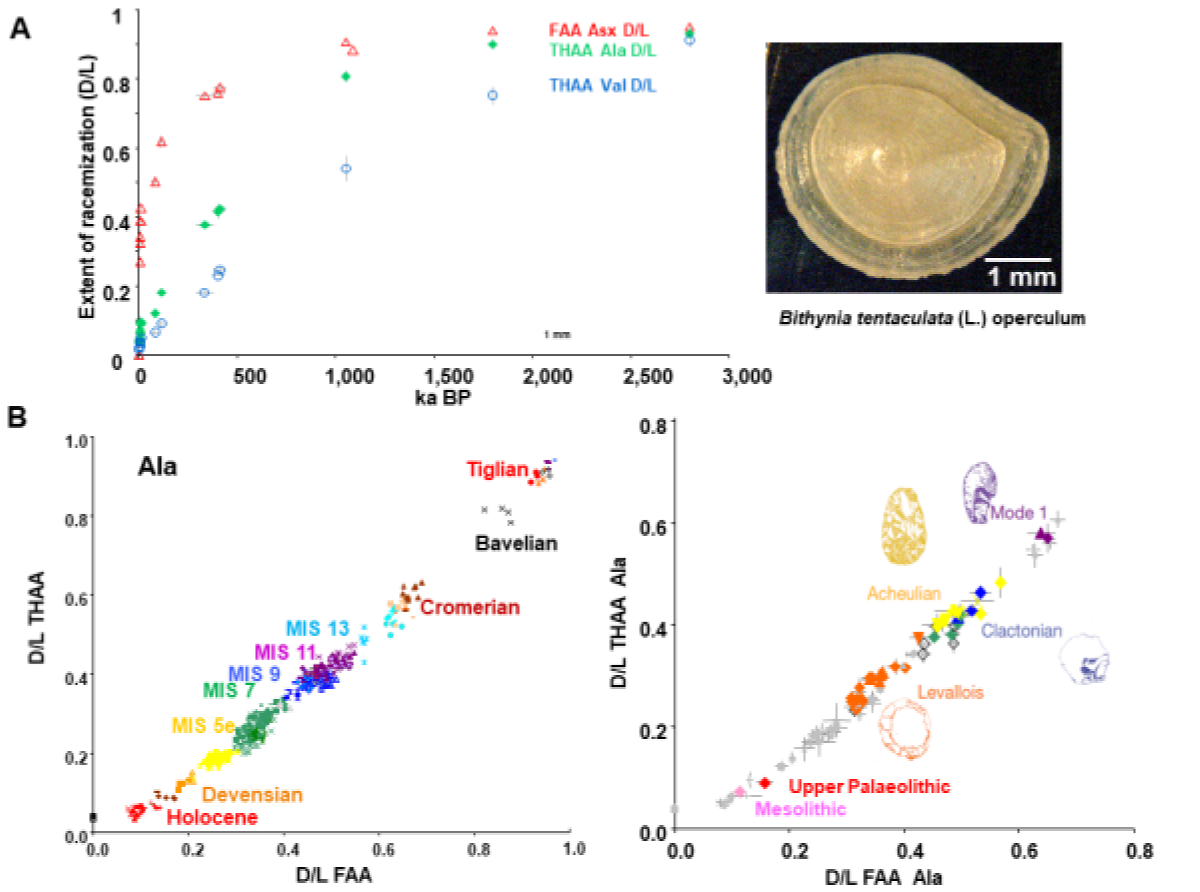


Fig 17 A) The increase in racemization in *Bithynia* opercula with age for the free amino acid (FAA) aspartic acid (Asx) and the total hydrolysable amino acids (THAA) valine (Val) and alanine (Ala). Asx racemises rapidly and is therefore most valuable for separating sites younger than MIS 7. Val, in contrast, racemizes more slowly and is able to differentiate between sites back to the Pliocene, but provides poorer resolution for young sites. Utilizing multiple amino acids with different rates of degradation therefore enables greater time depth and age resolution. 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 (left). These two measures of breakdown should be highly correlated in a closed-system, and so this plot forms an aminostratigraphic framework, where young samples fall towards the bottom left and old samples lie towards the top right of the graph. These frameworks allow temporal exploration of the archaeological record (right): data from British archaeological sites, coloured by occurrence of technology (green signifies occurrence of both Clactonian and Acheulian at a site). Modified from Penkman *et al* (2011)

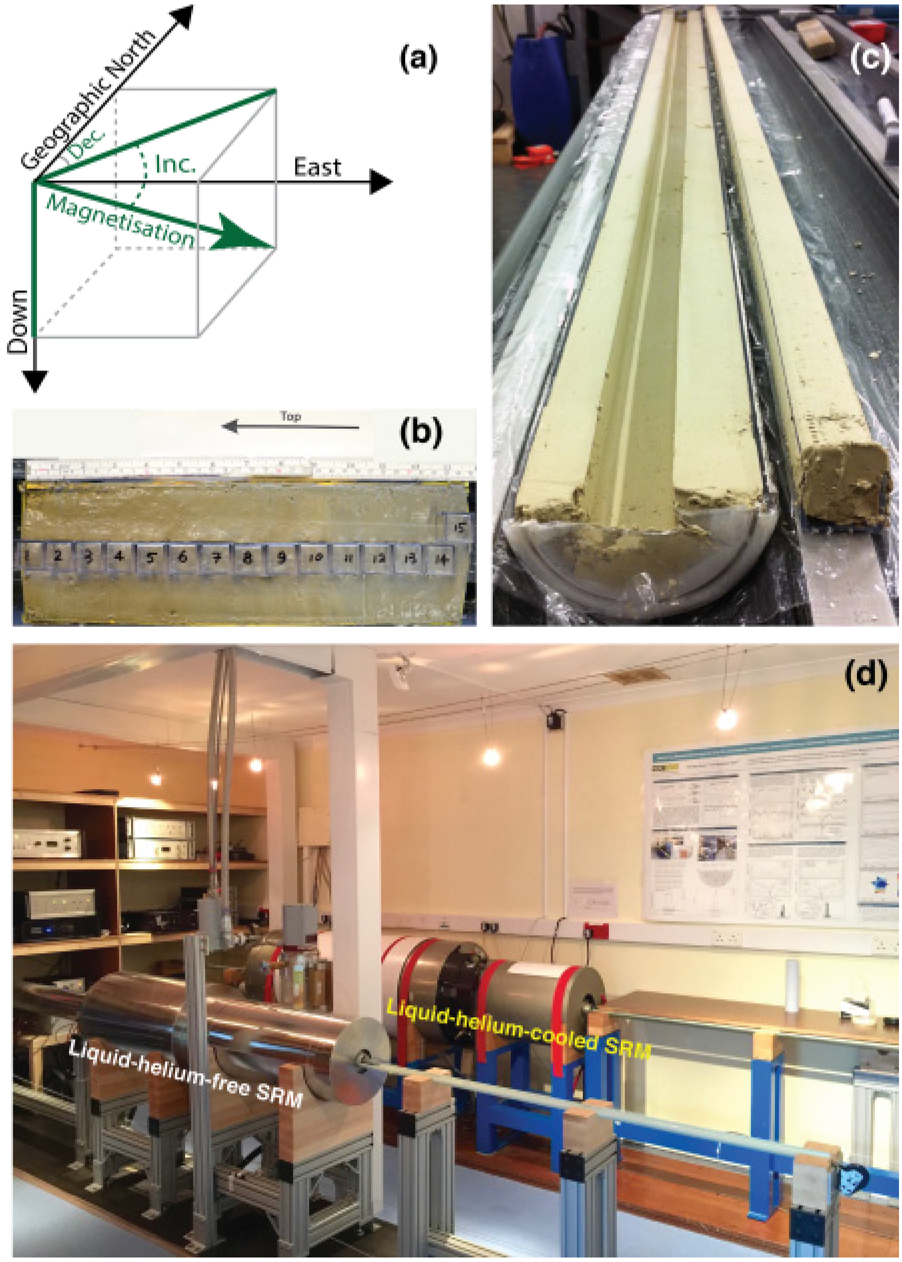


Fig 18 (a) Definition of declination (Dec.) and inclination (Inc.) of a remanent magnetisation signal (green arrow). Examples of (b) discrete and (c) continuous sampling of sedimentary sequences for palaeomagnetic analyses. Samples are typically taken from the centre part of cores that are usually less disturbed. (d) Photo of liquid-helium cooled and liquid-helium free superconducting rock magnetometers (SRM) at the University of Southampton, capable of measuring remanent magnetisations carried by a range of different materials including sediments, igneous rocks, and archaeological **artefacts**

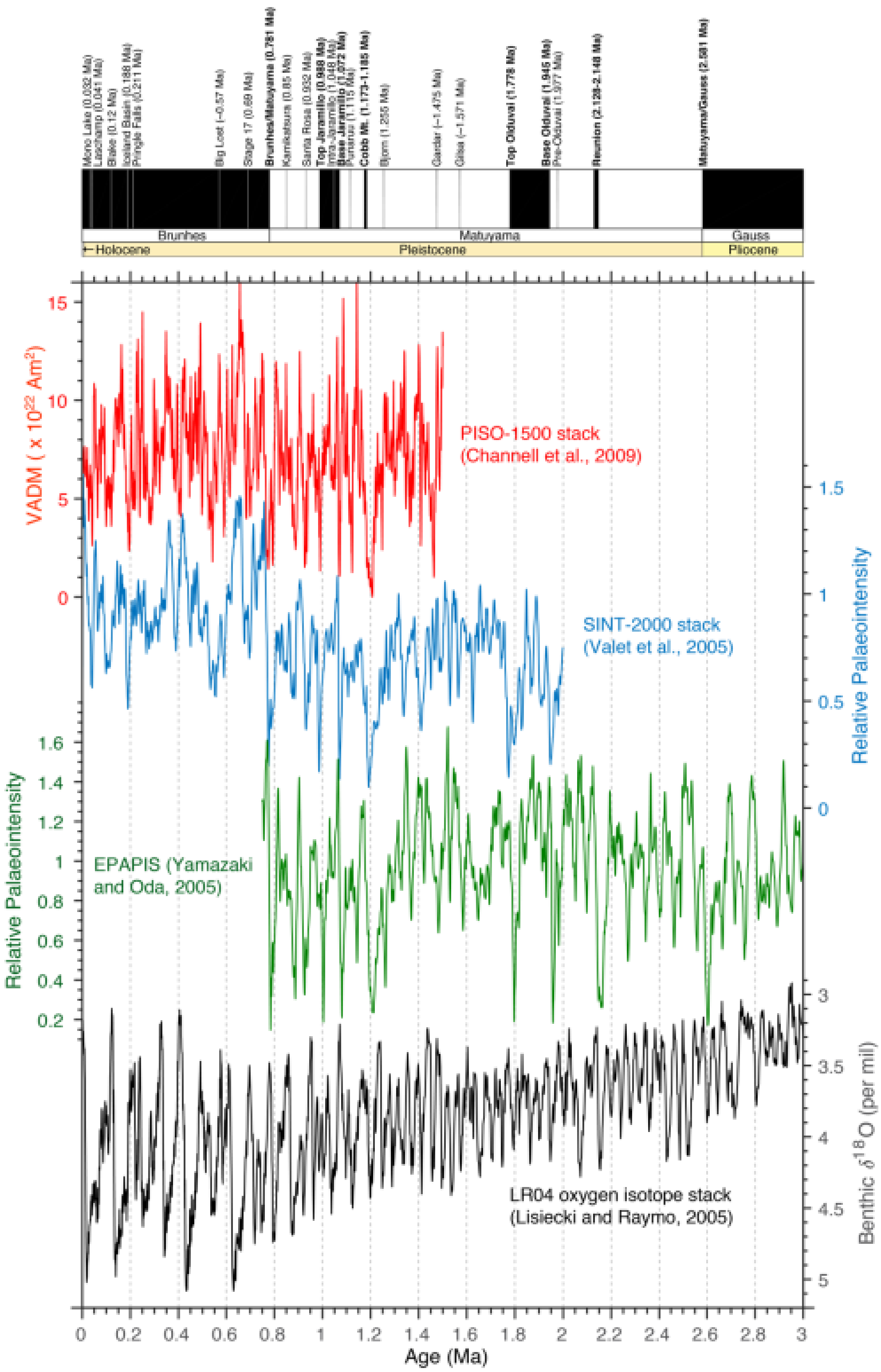


Fig 19 Top panel: geomagnetic polarity reversals (in bold) and well documented excursions of the last 3 Ma. Ages for geomagnetic reversals and excursions are based on Ogg (2012), and Laj and Channell (2015), respectively. Bottom panel: the PISO-1500 (in red, Channell *et al* 2009), SINT-2000 (in blue, Valet *et al* 2005), and EPAPIS (in green, Yamazaki and Oda 2005) relative palaeointensity stack records. The LR04 global oxygen isotope stack (in black, Lisiecki and Raymo 2005) is also shown on the bottom pane

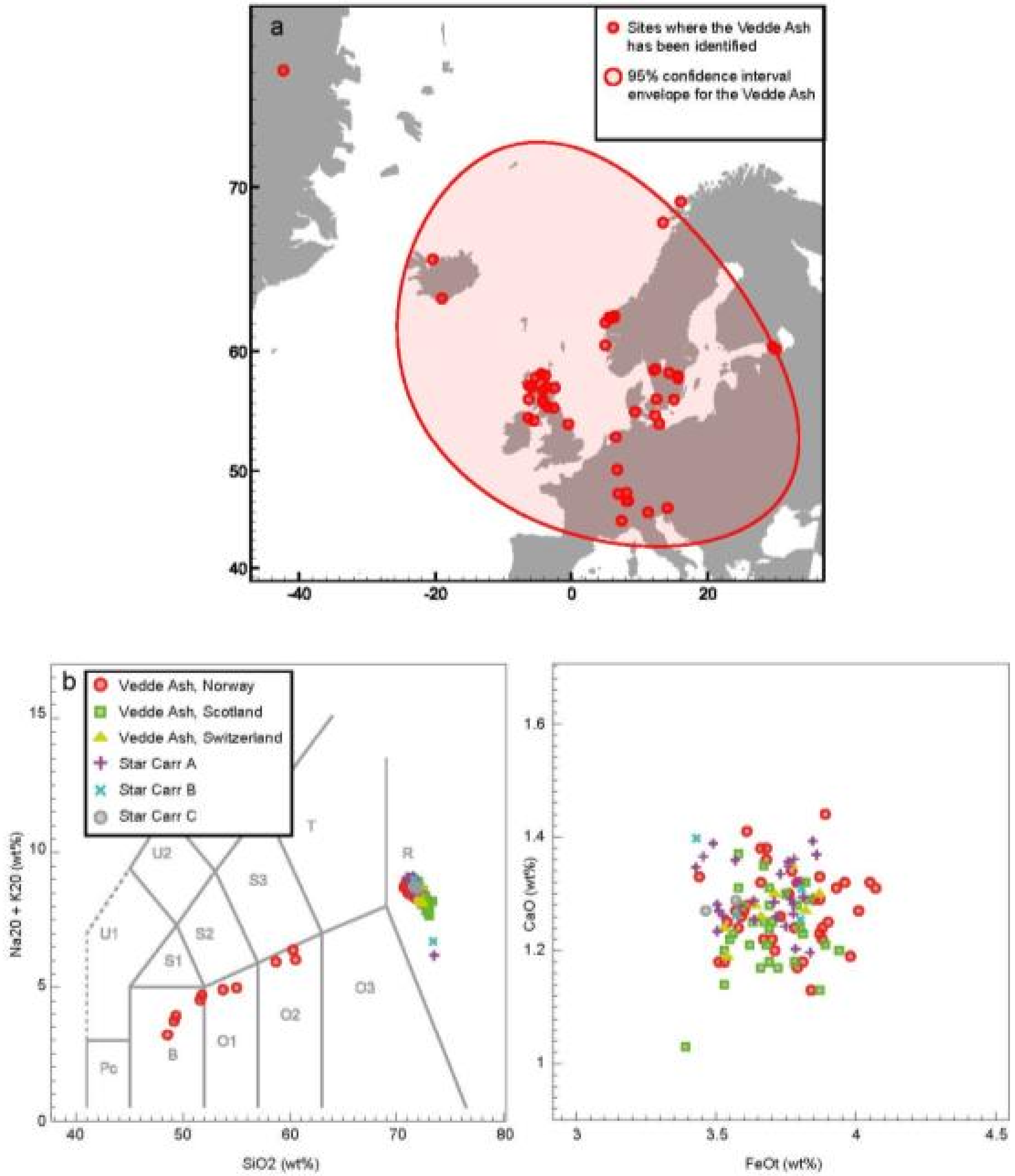


Fig 20 (a) The known distribution of ash fall from the Vedde Ash eruption of Katla, Iceland, dated to 12,023±43 cal. BP (Bronk Ramsay *et al* 2015a). While very few occurrences have been reported from England the 95% confidence distribution envelope suggest the ash may be present across the entire country. (b) Total Alkali vs Silica and FeO vs CaO bi-plots typical used to discriminate between tephra layers. Here, the chemical composition of the Vedde Ash layer reported from Star Carr, Yorkshire is shown against regional records of the same eruption (adapted from Palmer *et al* 2015)

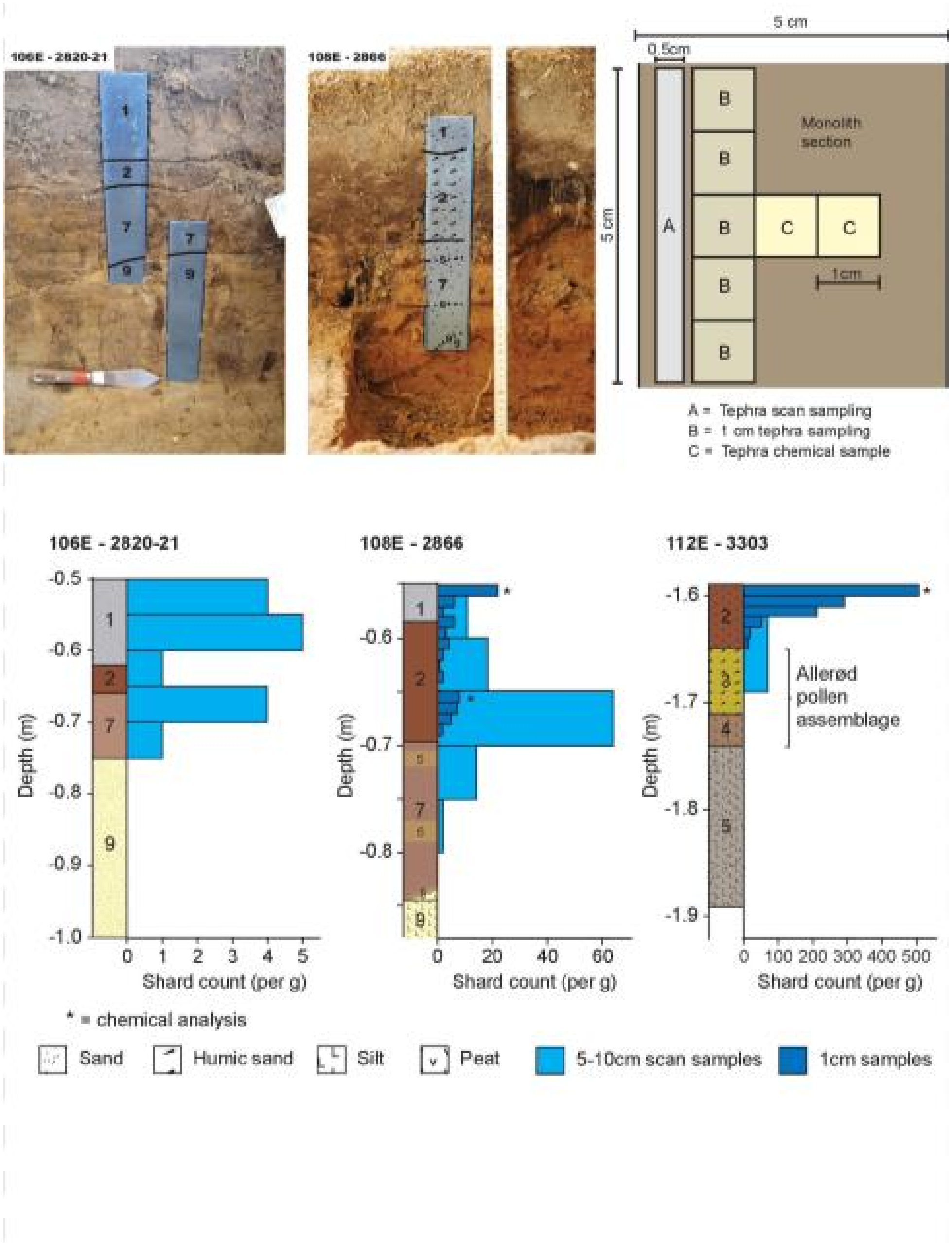


Fig 21 A suggested sampling strategy for tephra studies. The site shown here is Ahrenshöft LA 58D, north Germany, an open-air late Upper Palaeolithic site with Hamburgian and Havelte lithics (Housley *et al* 2012). Four monoliths from three sections are presented alongside a sampling schematic and subsequent shard counts. The tephra identified originated from Katla in Iceland, but similarities in chemical signatures prevent discrimination of three contenders (Suðuroy, Abernethy, Vedde Ash) showing that ambiguous results may occur where a volcano produces a series of chronologically distinct, but chemically indistinguishable, eruptions

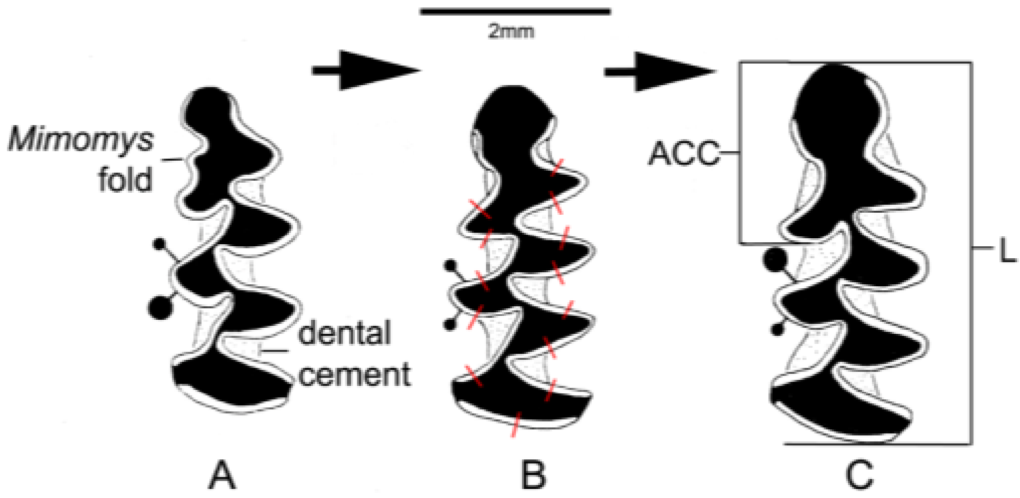


Fig 22 Evolutionary trends in *Arvicola* from the early Middle Pleistocene to the present day. A = *Arvicola terrestris cantiana*, B = transitional form, C = *Arvicola terrestris terrestris*. Arrows indicate the direction of evolution. ACC = anteroconid complex, L = length. Red lines (on B) indicate point of measurement for SDQ calculations. Redrawn with additions from Sutcliffe and Kowalski (1976)

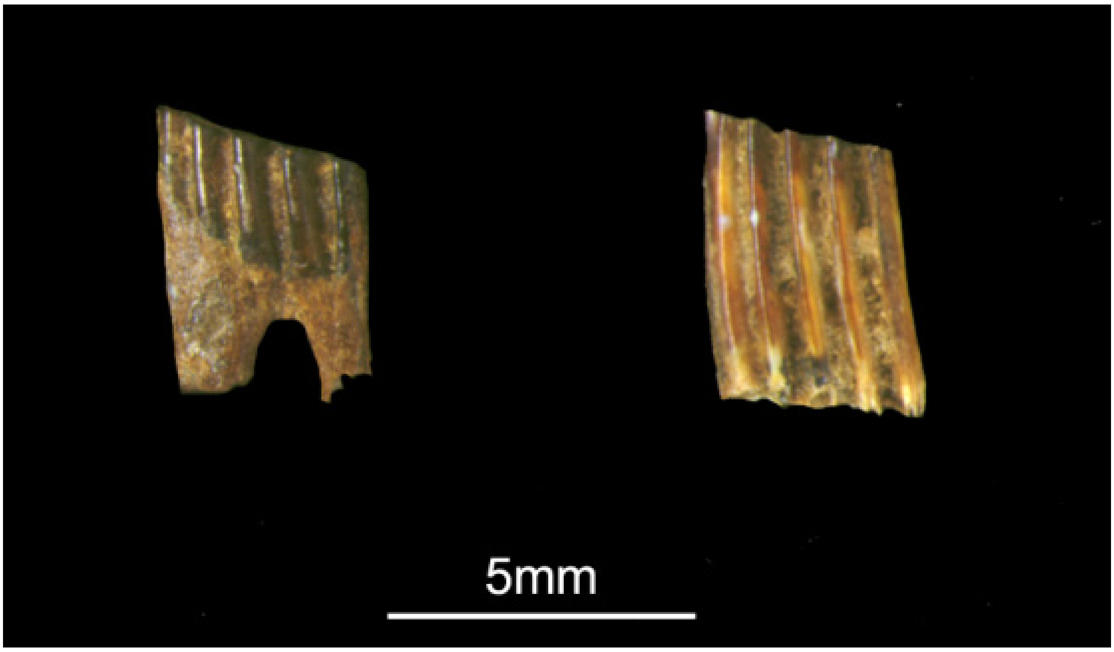


Fig 23 Lateral views of rooted first lower molar in *Mimomys savini* (left) compared to unrooted molar of *Arvicola cantiana* (right)

Fig 24 Excavations at Happisburgh Site 3 (© Mike Pitts – we have not asked him for permission to use yet)

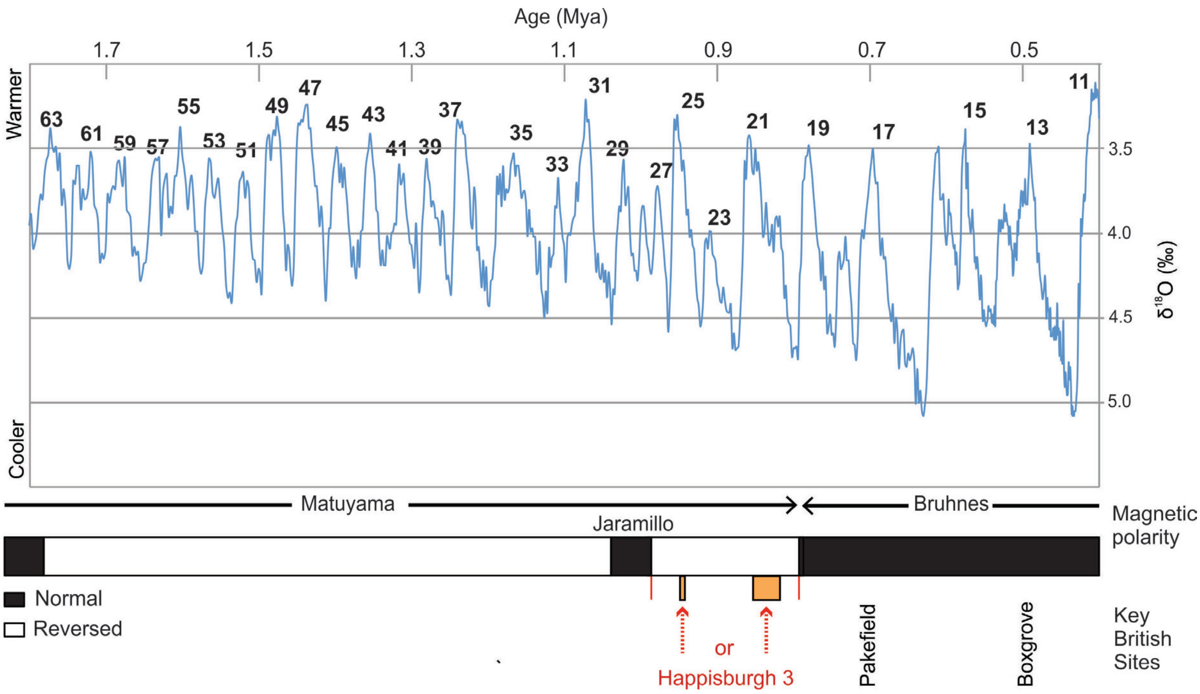


Fig 25 Suggested age of the Happisburgh 3 site, showing correlation of the MIS record (Lisiecki and Raymo 2005) and magnetic polarity record, and likely age of key English Early Palaeolithic coastal sites

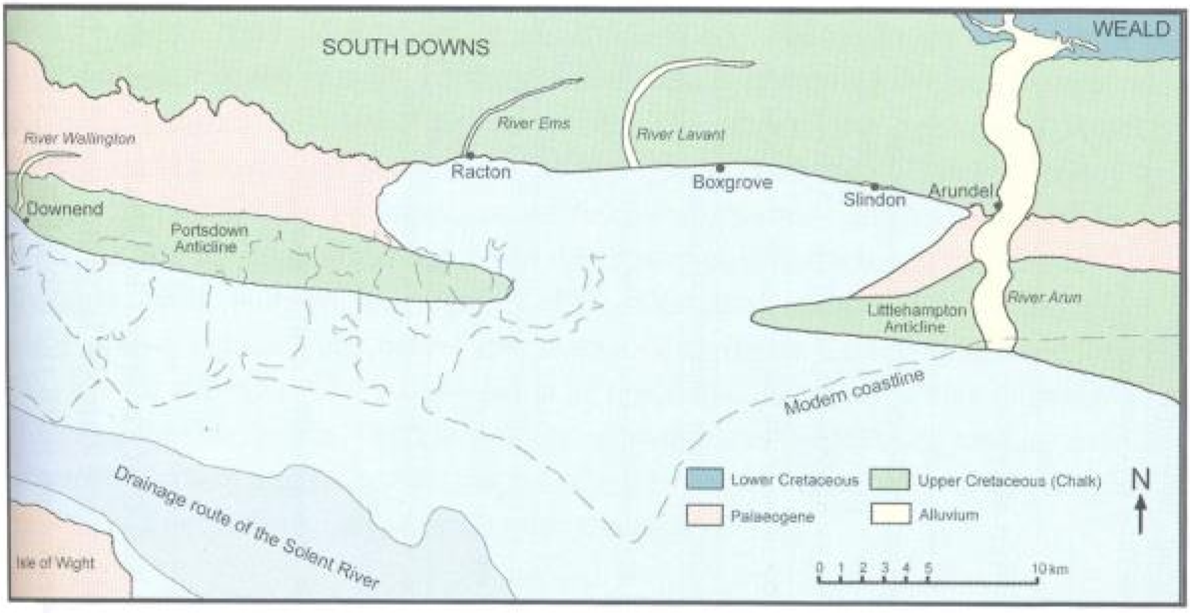


Fig 26 The position of Boxgrove relative to the contemporary coastline at the end of MIS 13 (from Roberts and Pope 2009, fig 6.4)

Fig 27 Flint scatter from the Slindon Silts (Unit 4b) (from Roberts and Parfitt 1999, fig 239)

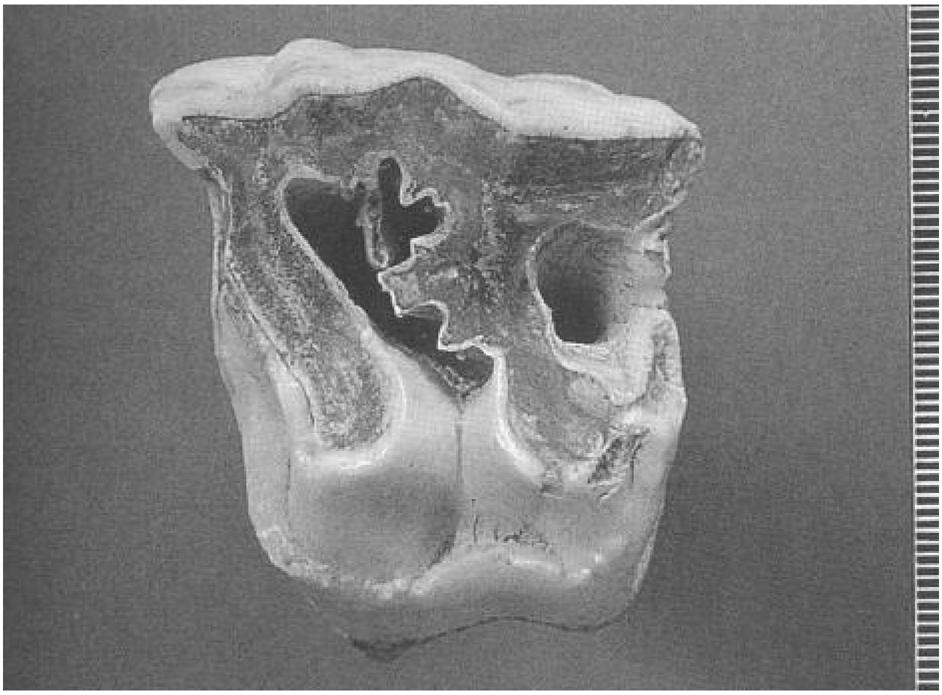


Fig 28 Upper fourth premolar of the biostratigraphical indicator *Stephanorhinus hundsheimensis* (from Roberts and Parfitt 1999, fig 154)

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2518 **Fig 29** Fluvial gravels and sands (Fortfield Farm Gravel Member), Pratt's New Pit, Broom (© R
2519 Hosfield)

2520

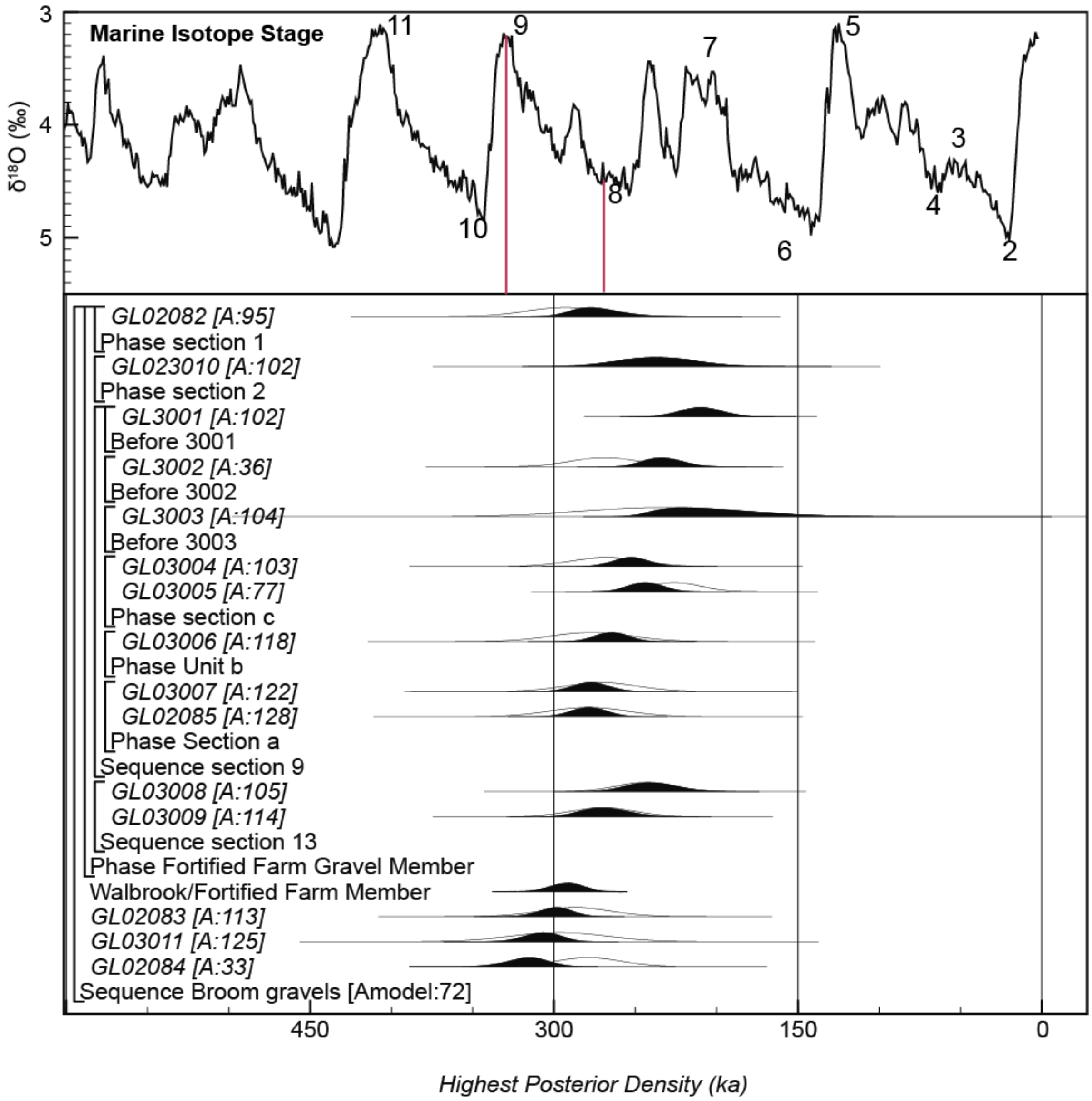

Fig 30 Probability distributions of dates from Broom. The large square brackets down the left-hand side of the diagram, along with the OxCal keywords define the overall model exactly (http://c14.arch.ox.ac.uk/). The upper panel shows the LR04 benthic $\delta^{18}O$ (‰) stack from 57 globally distributed benthic $\delta^{18}O$ records (Lisiecki and Raymo 2005)

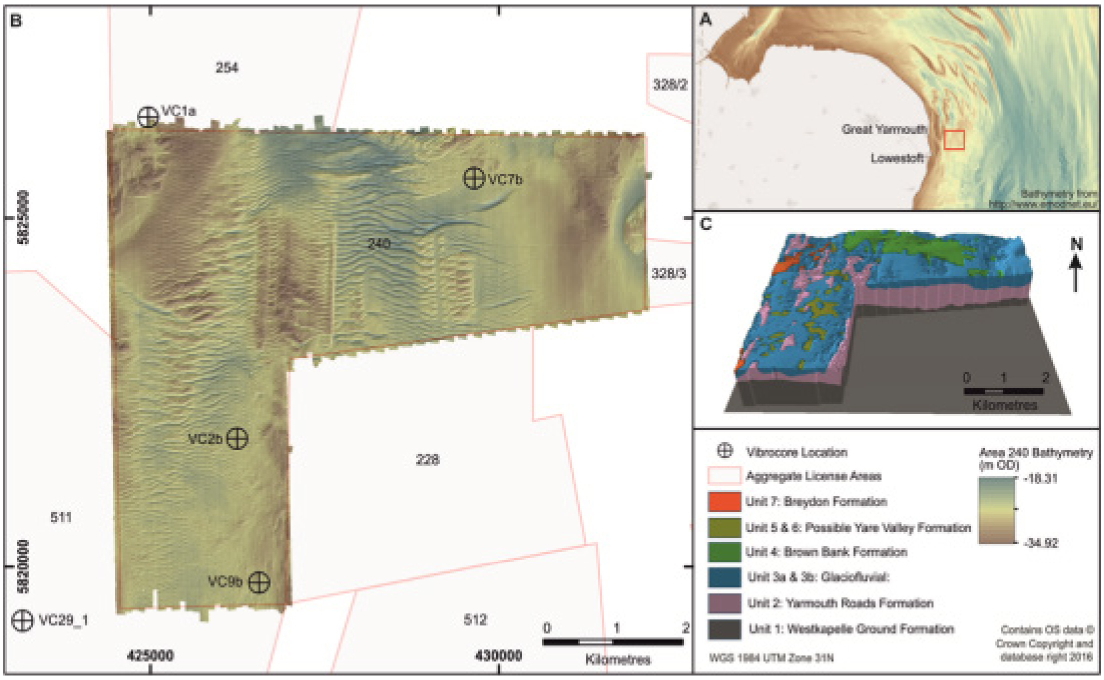

Fig 31 Location of Aggregate License Area 240. (b) Bathymetry, position of license areas, and vibrocore locations mentioned in the text. (c) 3D model of the sub-surface stratigraphy of Area 240, showing the distribution of the main stratigraphic units below the seabed (unit 8; not shown).

Fig 2 Hand-axes, flakes, and cores from Area 240 (© Wessex Archaeology)

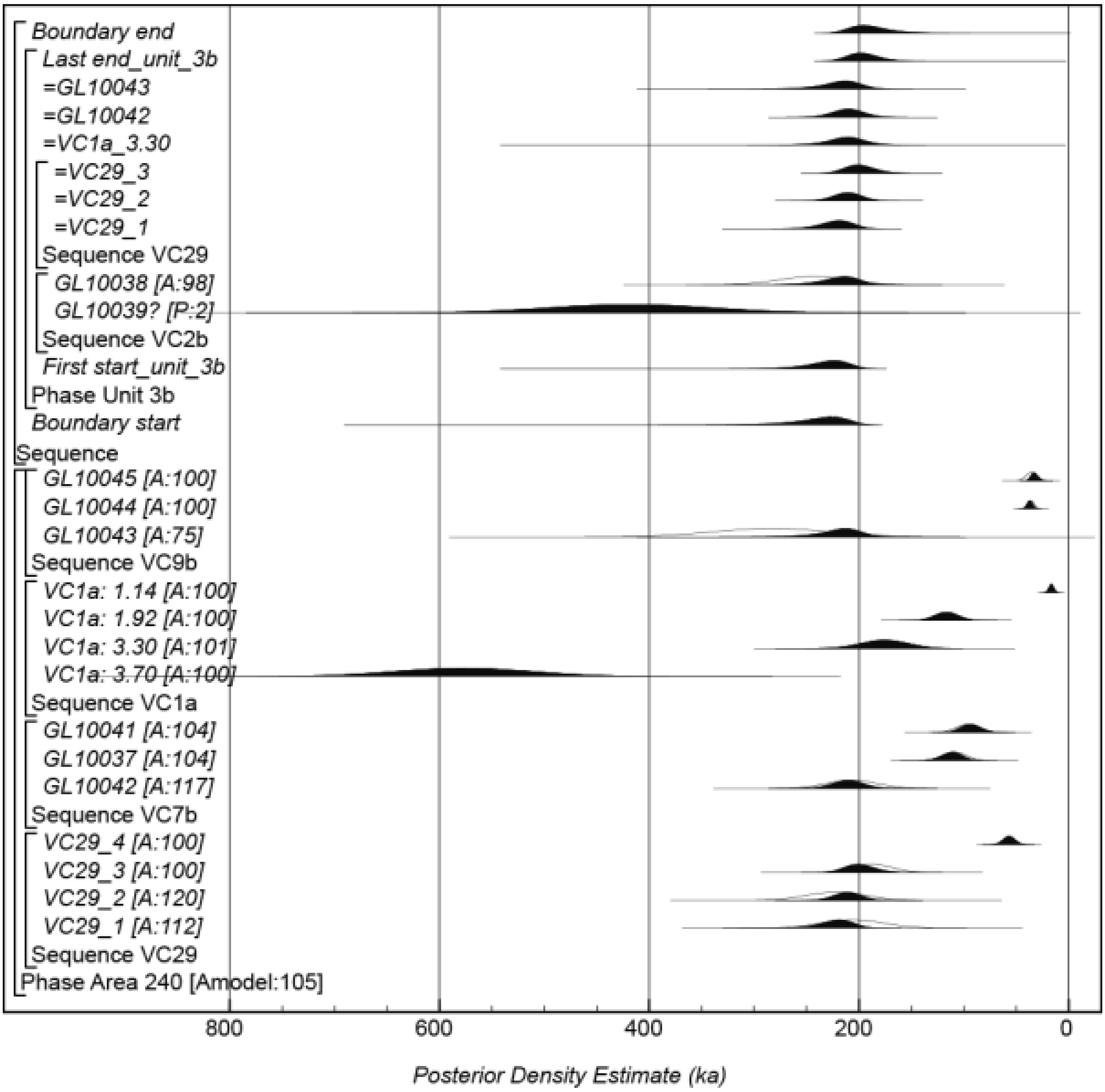

Fig 33 Probability distributions of dates from vibrocores in and around Area 240 (locations shown in Fig 31). The large square brackets down the left-hand side of the diagram, along with the OxCal keywords define the overall model exactly (http://c14.arch.ox.ac.uk/)

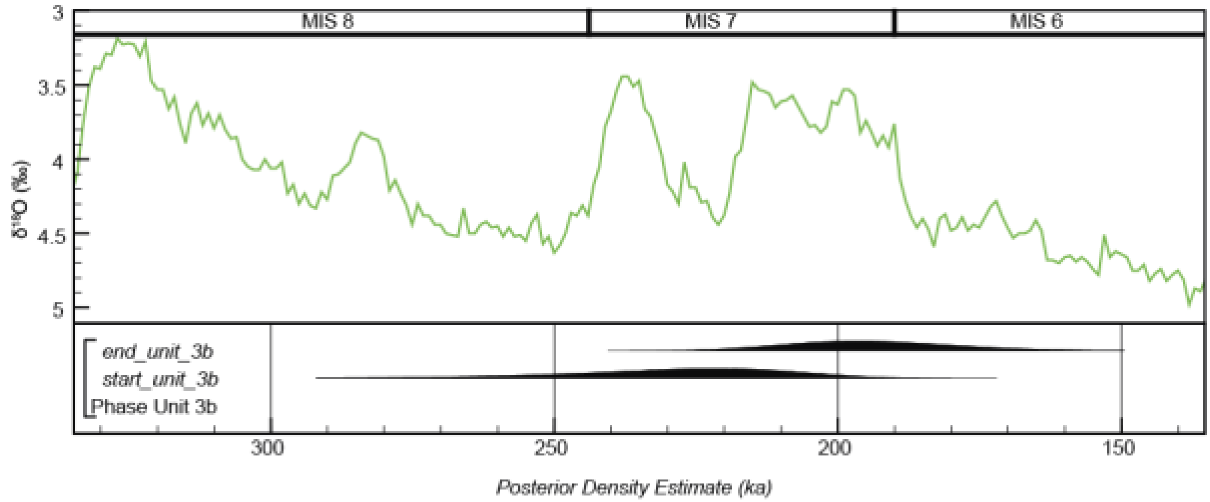

Fig 34 Probability distributions of estimates for the beginning and end of formation of Unit 3b in and around Area 240 (derived from the model shown in Fig 33). The upper panel shows the Marine Oxygen Isotope Record (Lisiecki and Raymo 2005)

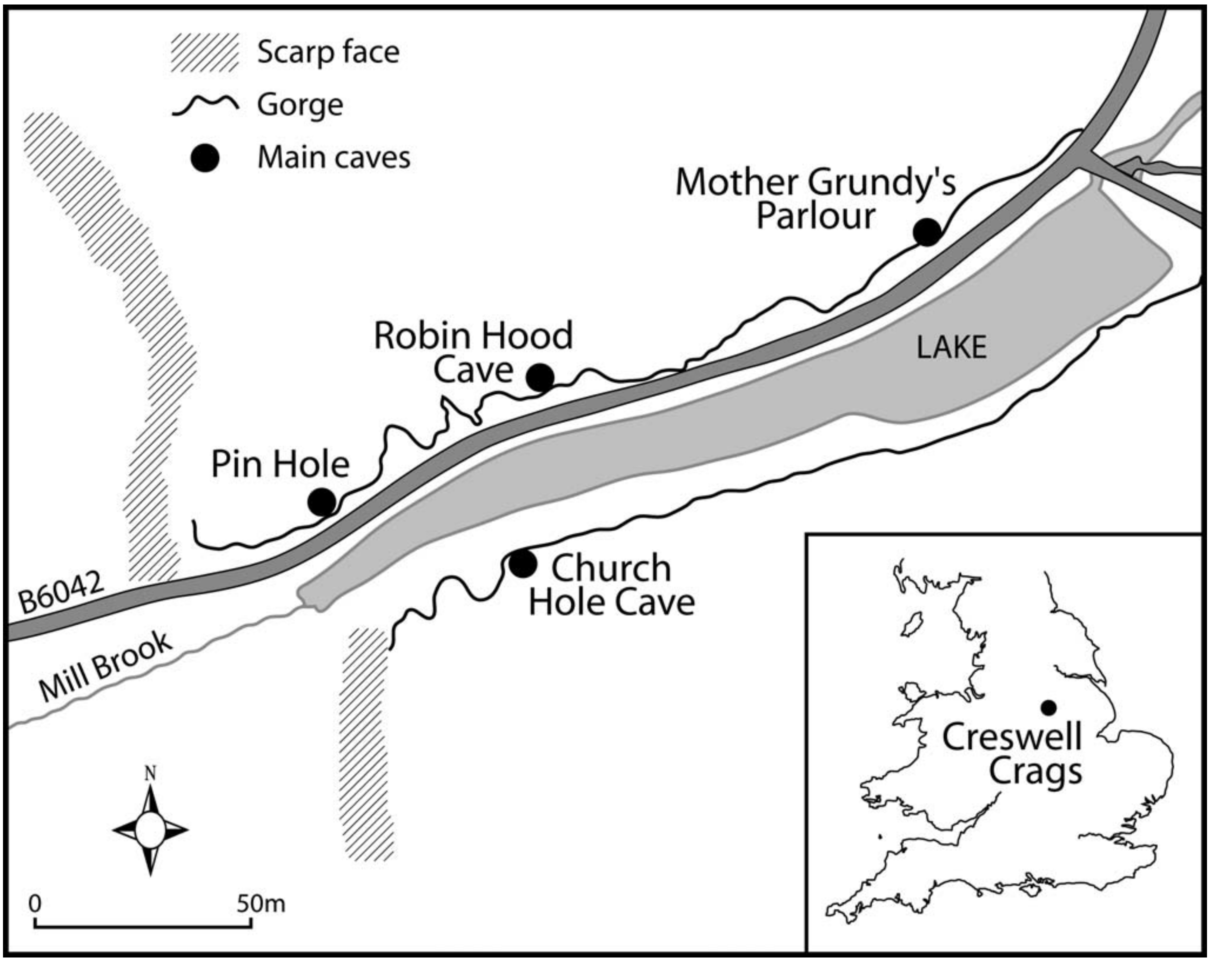

Fig 35 Location of Creswell Crags showing Pin Hole and other caves

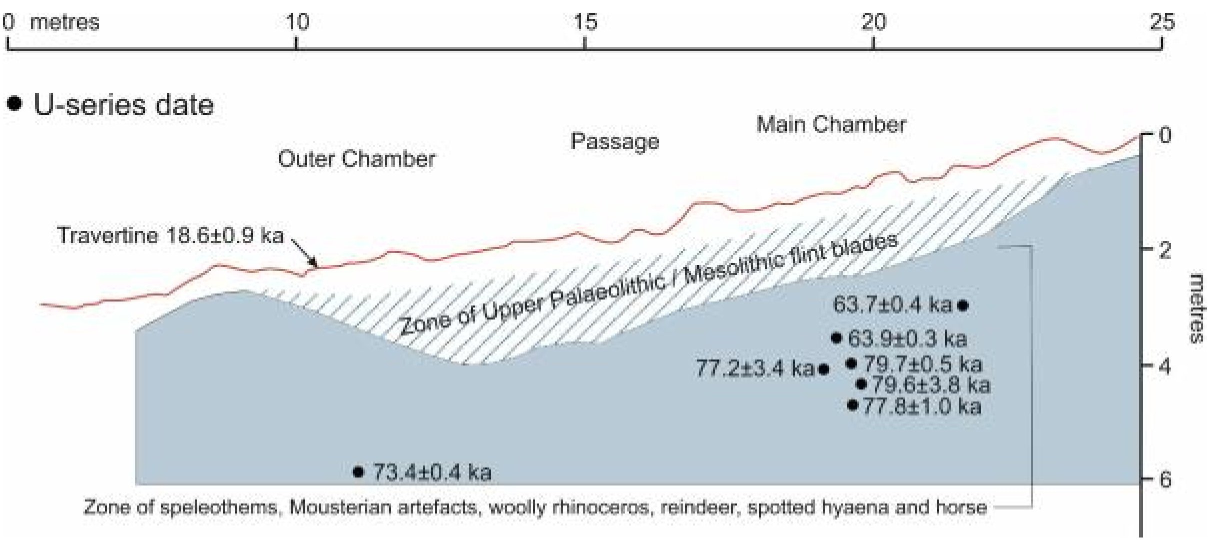

Fig 36 The reconstructed stratigraphy of Pin Hole cave showing artefact zones and dated calcite samples (after Jacobi *et al* 1998)

Fig 37 Excavation of mamouth tusk and associated flint tools at Lynford Quarry (HE Archive AA028489)

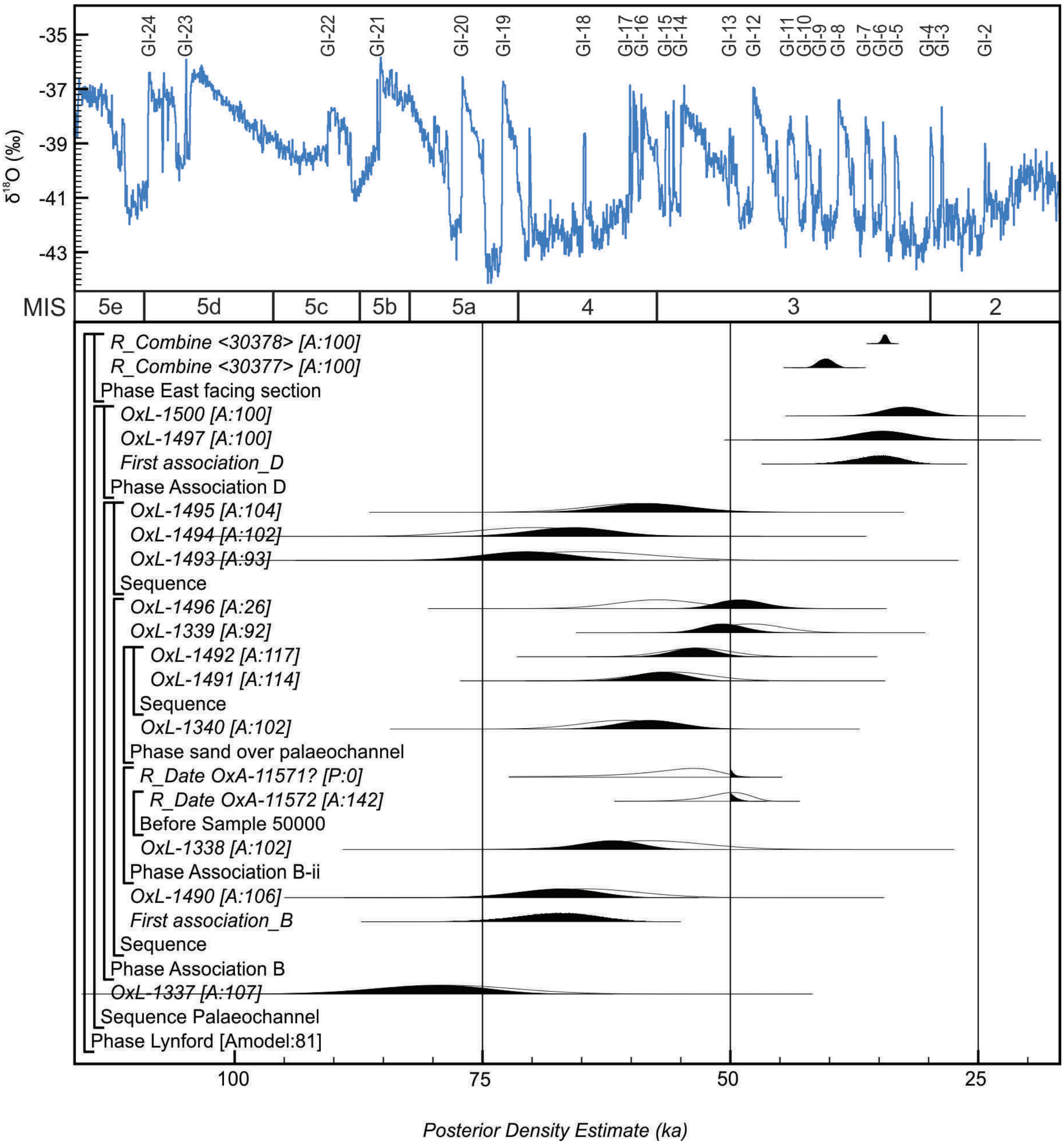

Fig 38 Probability distributions of dates from Lynford Quarry. The large square brackets down the left-hand side of the diagram, along with the OxCal keywords define the overall model exactly (http://c14.arch.ox.ac.uk/). The upper panel shows the GRIP and GISP2 ice core $\delta^{18}O$ values against the GICC05 timecale (Seierstad *et al* (2014) and Greenland event stratigraphy (onset of Greenland Interstadials (GI); Rasmussen *et al* 2014)

Fig 39 The Lateglacial sequence exposed at Gransmoor. The light coloured sediments at the base are the non-polleniferous sands and silts, while the Lateglacial Interstadial/Loch Lomond Stadial boundary coincides with the thin white band within the centre of the darker organic clays (photo courtesy of Mike Walker)

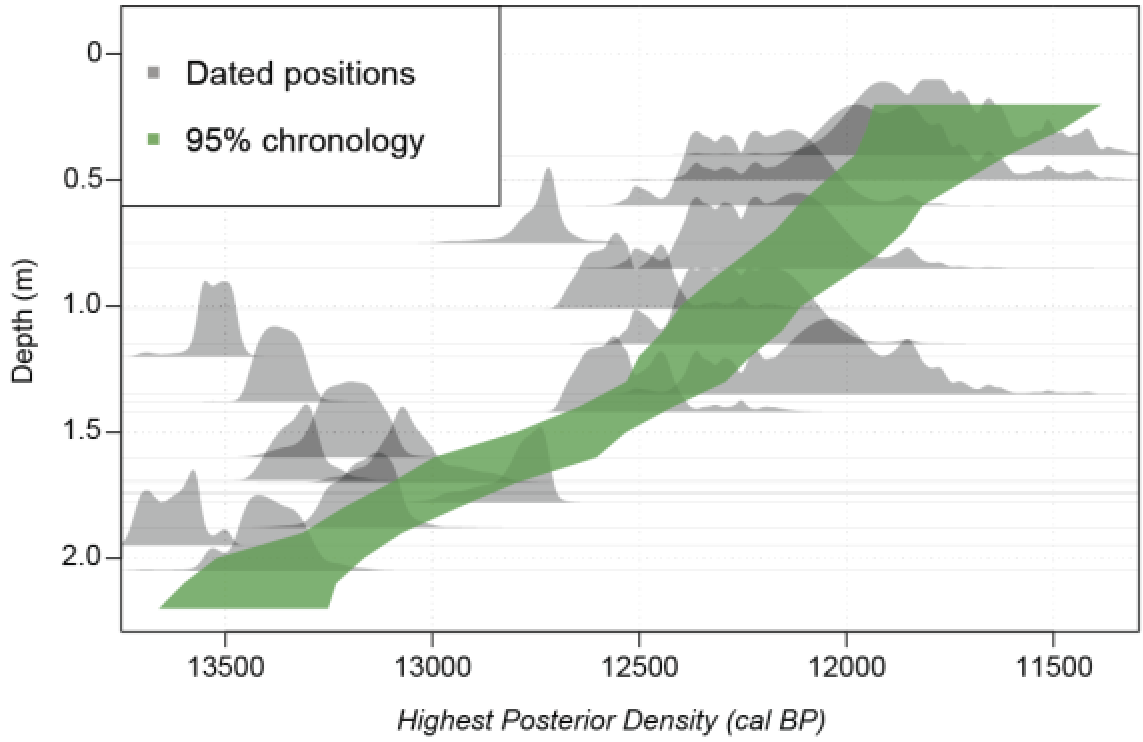

Fig 40 Gransmoor age-depth model constructed using Bchron. The 95% highest posterior density regions (HDR) indicate the uncertainty of the ages assigned to the samples between the dated depths. The probability distributions in grey represent the calibrated radiocarbon dates

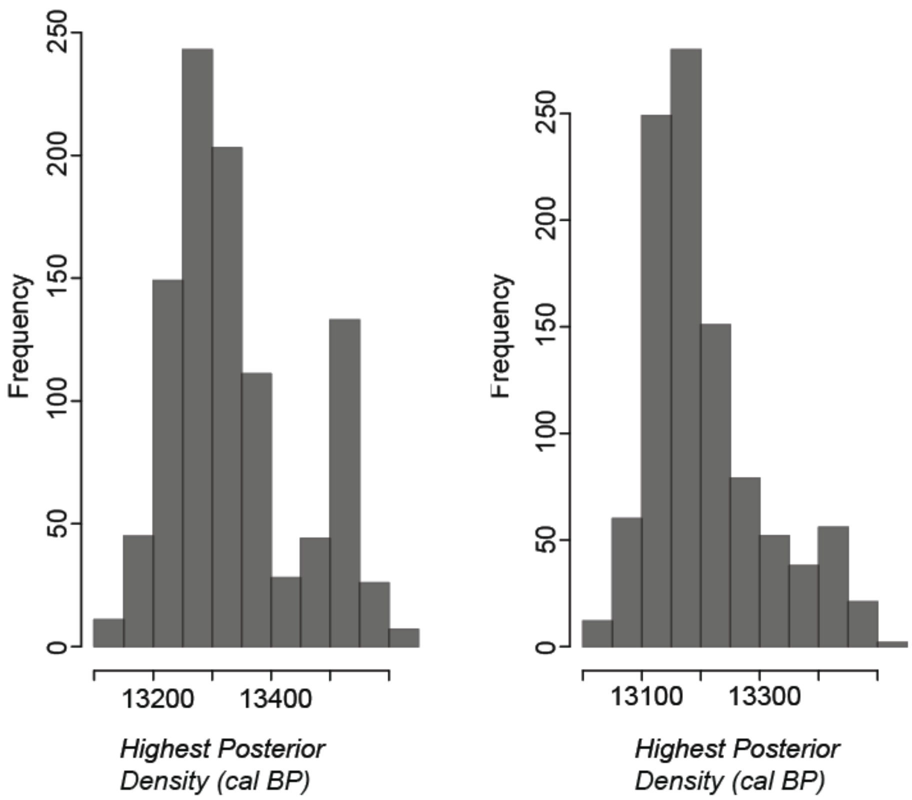

Fig 41 Histogram for the start (2.0m) and end (1.9m) of the *Betula* sp. decline, derived from the model shown in Figure 40

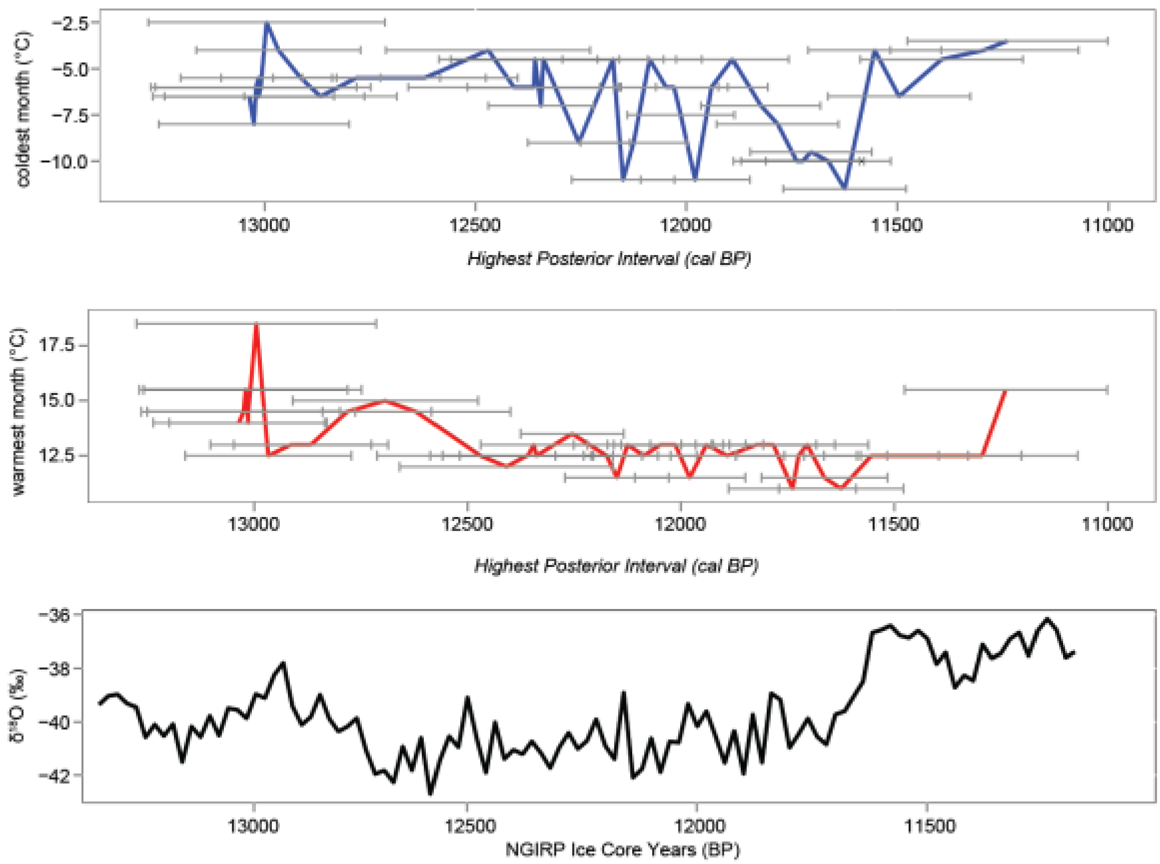

Fig 42 Late-glacial temperature changes (warmest and coldest months) from Gransmoor (data from https://c14.arch.ox.ac.uk/intimate/) and the NGRIP ice core δ^{18}O record (NGRP 2004). The chronology for late-glacial temperatures is derived from the model shown in Fig 40