

Consultation Draft

Scientific Dating of Pleistocene Sites: Guidelines for Best Practice

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1 Foreword

2 *Alex Bayliss, Historic England*

3 These guidelines provide advice on best practice for the effective use of scientific dating on
4 Pleistocene sites. They are applicable to all archaeological projects, but are aimed primarily at those
5 undertaken as part of the planning process. Pleistocene sites typically produce limited material that
6 is suitable for dating. Some of the methods that can be employed are familiar to those working in
7 later periods (eg **Radiocarbon Dating**), although special considerations for their effective use may
8 apply. Other methods (eg the '**Vole Clock**') are only used in the Pleistocene. The selection of
9 appropriate techniques, given the available types of datable material, its taphonomic relationship to
10 the archaeological objectives of the project, and the expected time-range of the site, is key. Different
11 strands of evidence can be explicitly combined using Bayesian statistical modelling, and the resultant
12 chronologies can be validated, not only by comparison to relative dating from stratigraphy, but also
13 by employing multiple scientific dating techniques. Above all, seek expert advice. All laboratories will
14 be happy to advise on applying their technique to Pleistocene deposits, and will welcome the
15 opportunity to discuss sample selection and potential methods of cross-checking their results with
16 you. It is by working together with a range of specialists that you will provide the best dating
17 possible for your site.

18 PART 1 - OVERVIEW

19 1. Introduction

20 *David R Bridgland, Durham University*

21 The Pleistocene is the geological period during which multiple ice ages, or glacials, occurred, the last
22 of which ended only c 11,700 years ago, at the beginning of the Holocene, or the post-glacial. The
23 Pleistocene and Holocene together are termed the Quaternary. The Pleistocene began 2.58 million
24 years ago, and we now know that there were numerous ice ages during this period, although those
25 of the Middle and Late Pleistocene (together accounting for the last c 0.8 million years) were more
26 severe than those occurring earlier. The Pleistocene was not continuously cold; instead there were
27 periodic warmer episodes, termed interglacials, during which conditions were similar to those of the
28 Holocene, which is generally regarded as merely the latest of numerous interglacials. This glacial–
29 interglacial oscillation is a principal characteristic of the Pleistocene and has been used as a
30 framework for dividing the Quaternary into different climatic phases (Shotton 1973a; Imbrie and
31 Imbrie 1979; Bowen 1999).

32 The sequence of alternating warm and cold Pleistocene climatic episodes is best understood from
33 long sedimentary sequences in the deep oceans and from the deepest ice cores from Antarctica,
34 both yielding their climatic signal from fluctuation in the proportion of the oxygen isotopes ¹⁸O
35 and ¹⁶O (Shackleton and Opdyke 1973; Lisiecki and Raymo 2005; **Text Box 1**). The greater resolution
36 now available, especially from ice cores, has revealed shorter-timescale climatic fluctuation
37 overprinting the glacial–interglacial cycles. Higher-resolution records of latest Pleistocene climate
38 gleaned from palaeobotanical studies from the last glacial suggest that this cold stage was
39 punctuated by several oscillations of warmer climate, albeit achieving less warmth than a full

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40 interglacial and so termed interstadials, with the term stadial used for the particularly cold parts of
41 glacial stages during which ice sheets extended beyond the present Arctic (and Antarctic) regions.
42 The distinction between interglacials and interstadials is essentially one of length and intensity, with
43 a formal definition requiring deciduous woodland in NW Europe for an interglacial rather than an
44 interstadial (Turner and West 1969).

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

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

58 The Quaternary stratigraphical framework

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

61 This classification of Pleistocene strata is based on the recognition of temperate- and (less
62 commonly) cold-climate proxies in certain deposits, taken together with other evidence for the
63 deposition of some sediments under warm (temperate) conditions and others under intensely cold
64 or even glacial conditions. In Britain, for many years, this division was primarily based on
65 palynological distinction between different interglacials (summarised by Mitchell *et al* 1973). The
66 glacial episodes were characterized by major continental ice sheets, two of which, during the
67 Devensian (*c* 110,000–11,700 years ago; equivalent to MIS 5d–MIS 2) and the Anglian (*c* 450,000
68 years ago; equivalent to MIS 12 in Fig 1), were periods when land-based ice extended across large
69 parts of Britain (Bowen *et al* 1986; Clark *et al* 2012), with the later Britain's most extensive. Together
70 these two glaciations were responsible for almost all the surface cover in Britain of the glaci-genic
71 diamicton deposits formerly called 'boulder clay'. Between the Devensian and Anglian there was
72 perhaps more than a single glacial during which ice advanced southwards across England, although
73 the evidence is preserved only where not destroyed by the later Devensian ice advances (Lee *et al*
74 2011). People are thought not to have lived in Britain during glaciations.

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

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

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

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

97 The Hoxnian is well represented in lacustrine basins formed during the preceding MIS 12 Anglian
98 glaciation. Thus the Hoxnian type locality, in Suffolk, is a kettle-hole lake overlain by fluvial deposits
99 (Ashton *et al* 2008), while the para-stratotype, at Marks Tey in Essex, is a section of subglacially
100 overdeepened valley, infilled with lake sediments. This interglacial is well represented in the Lower
101 Thames at sites in North Kent, at Dartford Heath and, in particular, at Swanscombe (Fig 4), where a
102 hominin skull fossil has been found, as well as copious numbers of artefacts and vertebrate and
103 molluscan fossils. There are three separate Lower Palaeolithic industries in superposition here: a
104 basal Clactonian, an assemblage with pointed handaxes, and an upper distinctive handaxe
105 assemblage with examples having twisted edges, thought to represent MIS 11a (Bridgland and White
106 2015).

107 Mitchell *et al* (1973) also identified by palynology an interglacial immediately prior to the Anglian
108 glaciation, the Cromerian. This is now also recognized to be an oversimplification, with the
109 Cromerian now divided into at least four different interstadials, although data from vertebrates and
110 non-marine Mollusca suggest at least five distinct warm episodes within what would once have been
111 termed 'Cromerian', probably representing isotopic substages within the range MIS 21–13. The term
112 'Cromerian Complex' is generally used for this sequence of early Middle Pleistocene interglacials and
113 the cold episodes that separate them. The oldest of these interglacials has a negative magnetic
114 polarity, indicating that it pre-dates the Matuyama–Brunhes palaeomagnetic reversal, *c* 780 ka,
115 when the Earth's magnetic north and south poles changed to their present polarity (see Fig 1).
116 Artefacts have been recovered from some, but not all, of these Cromerian Complex interglacials. Of
117 particular importance in distinguishing between these Cromerian interglacials is the change, during
118 MIS 15, in water-vole molar tooth morphology (see Section 10: The 'Vole Clock').

119 MIS 22, immediately before Cromerian Complex, coincides with the first of the intensely cold glacials
120 that have occurred only since the 100 ka climate cycles began (see above). One British
121 archaeological site is probably older than this: Happisburgh 3, where artefacts occur in reversed-

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122 magnetised sediments that have been attributed to MIS 21 or 25, late in the (reversed polarity)
123 Matuyama chron (Parfitt *et al.*, 2010). However Westaway (2011) has suggested that the reversed-
124 magnetised sediments could date from a magnetic excursion within the Bruhnes chron and date from
125 part of MIS 15; attribution by Parfitt *et al.* (2010, supplement) of the Happisburgh 3 sediments to the
126 Thames, based on their composition, renders this unlikely, as it is clear that by MIS 15 the River
127 Bytham flowed across Suffolk from west to east and entered the North Sea at Lowestoft (Parfitt *et*
128 *al.* 2005), so the Thames could not have reached Happisburgh.

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

134 Palaeogeography

135 The landscape and environment that the early occupants of Britain inhabited was, for much of the
136 time, very different to that of the present day. Notwithstanding that sea level was generally much
137 lower during the predominantly colder Pleistocene (because global water was locked up in larger
138 polar ice caps), it is clear that, prior to MIS 12, there would have been a 'British Peninsula' at the NW
139 extremity of the European continent, rather than an Island Britain (Preece 1995; Fig 5a). The timing
140 of and mechanism for the formation of the Strait of Dover is controversial, but it seems likely that
141 this took place during the Anglian (MIS 12) as a result of the overflow of a glacially dammed lake
142 in the southern North Sea basin (Fig 5b). This drained into the English Channel and thus cut the
143 earliest Dover Strait. At this time the route of the Thames moved further south, into its modern
144 valley through London, again the result of glacial-lake overflow (Bridgland 1994) and the Bytham
145 river was obliterated by the Anglian ice sheet, which engulfed its valley completely. Although parts
146 of the former valley formed the route-ways for post-Anglian drainage, that huge river system was
147 not restored, being replaced by a proto-Trent system that required a further two climate cycles and
148 another glaciation before it reached anything like its modern configuration; indeed its drainage into
149 the Humber did not come about until Devensian deglaciation (Bridgland *et al.* 2014; 2015; Fig 6). The
150 Solent river was unaffected by any glaciation, its eventual demise coming about through the
151 widening of the English Channel, probably during MIS 6, which drowned its lower reaches and
152 separated the Isle of Wight from the English mainland (Westaway *et al.* 2006).

153 Fitting the archaeological record into this dynamic landscape

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

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164 **Lynford Quarry**), with modern humans appearing slightly later, using a more sophisticated Upper
165 Palaeolithic technology.

166 Two separate lithic technologies coexisted in Britain during the latter part of the early Middle and for
167 most of the late Middle Pleistocene. These are Clactonian assemblages (Mode 1 characterised by
168 hand axes) and Acheulian assemblages (Mode 2). The distinction of these two knapping technologies
169 is far from straightforward, however, since the Acheulian or handaxe industries produce flakes and
170 cores that are identical to those in Clactonian assemblages. This means that Clactonian assemblages
171 cannot be recognized definitively unless handaxe making is not represented at all (McNabb 2007). A
172 further potential advance is the matching of handaxe typology to particular Pleistocene stages
173 (Bridgland and White 2015), which has developed out of a more reliable understanding of the
174 climato-stratigraphy and dating of Quaternary deposits across Britain. Handaxe making dwindled in
175 importance once the next development in lithic technology arose; the use of Levallois technique in
176 the knapping of prepared cores (Mode 3). This heralded the transition into the Middle Palaeolithic. It
177 has been shown that this occurred over a very wide area at the time of the MIS 9–8 transition.

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

182 Shorter-timescale division of the Late Pleistocene

183 The Late Pleistocene begins with the warming transition that led to the MIS 5e (Ipswichian)
184 interglacial (Fig 1). The preceding glacial produced the most extensive glaciation of the neighbouring
185 part of the European mainland, so, although the equivalent British ice sheet was smaller than at
186 least two earlier ones (White *et al* 2016), this episode was clearly one of severe cold. That can
187 perhaps explain why there is no compelling evidence for human occupation of Britain during either
188 MIS 6 or MIS 5e. Indeed, there is no good evidence that humans returned prior to MIS 3.

189 The level of resolution available for the various palaeoclimatic records of the Late Pleistocene is
190 significantly greater than for the Early–Middle Pleistocene, with considerable enhancement in
191 understanding during recent years thanks to evidence from ice cores, especially for fluctuations
192 during the last climate cycle (**Text Box 2**; Fig 7). The MIS 3 interstadial (generally correlated with the
193 mid-Devensian Upton Warren Interstadial), was relatively cold and rather unstable in comparison to
194 the previous warm stages of the last million years. The ice-core record shows that much of the last
195 climate cycle (since MIS 5e) has been characterised by high-frequency, high-amplitude climate
196 oscillations of the order of 500–2000 years duration (Fig 7). Known as ‘Dansgaard–Oeschger’ cycles,
197 these saw abrupt warming by 5–8°C within 50 years, perhaps as little as a decade, followed by more
198 protracted cooling. The high-resolution temperature record derived from the ice cores can be used,
199 in a similar manner to the Marine Oxygen Isotope Stages, to define late Devensian
200 chronostratigraphy. The record is divided into a series of alternating Greenland Stadial (GS) and
201 Greenland Interstadial (GI) stages, with GS-1 representing the pre-Holocene Younger Dryas (in
202 Britain called the Loch Lomond) Stadial and GI-1 representing the Bølling–Allerød (in Britain called
203 the Windermere) Interstadial (see Fig 8).

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204 2. Scientific Dating methods for the Pleistocene

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

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

215 **Bayesian chronological modelling** can be employed as an explicit methodology for combining these
216 disparate strands of evidence.

217 Certain questions must be considered before embarking on any dating application:

- 218 • Applicability: is there something dateable within the deposit that is to be dated?
- 219 • Taphonomy: how did the material being dated become incorporated into the deposit?
- 220 • Time range: is there a technique suitable for the expected time-range of the deposit (see Fig
221 9)?
- 222 • Precision/Accuracy: are the available techniques capable of providing sufficient precision to
223 resolve the archaeological problem of interest?
- 224 • Cost/facilities: is there sufficient funding and can the necessary measurements be obtained
225 within the required timescale?

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

- 227 • The application of scientific dating techniques should, wherever possible, be underpinned by
228 a thorough understanding of stratigraphy
- 229 • Some types of stratigraphy provide means of relative dating (eg biostratigraphy,
230 pedomorphology, morphostratigraphy)
- 231 • Multiple age determinations from a single stratigraphic unit should be compatible
- 232 • Independent dating techniques from the same stratigraphic unit should give concordant
233 ages
- 234 • Scientific dates should conform with the stratigraphy (ie the oldest dates at the bottom and
235 youngest at the top)
- 236 • Where deposits can be tied into the Marine Oxygen Isotope stages or the Greenland Ice Core
237 record, results should be comparable to these timescales.

238 Radiometric methods

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

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

255 Trapped Charge Methods

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

- 268 (1) **Thermoluminescence** – in which heat is used to release the trapped electrons. This was the
269 first luminescence dating technique to be used widely and is applicable as a measure of the
270 time since the firing of pottery or the heating of burnt flint recovered from hearths. It has
271 also been used to measure the exposure to daylight of wind-blown sand and silt (loess)
272 (**Luminescence Dating**).
- 273 (2) **Optically Stimulated luminescence (OSL)** – in which light is used to release the trapped
274 electrons in multiple (aliquots) or single grains of quartz sand. An important consideration
275 will be whether the grains will have been fully zeroed by the light exposure, which is why the
276 method works best for dating wind-blown sediments. (**Luminescence Dating**)
- 277 (3) **Infrared-stimulated luminescence (IRSL)** – in which the trapped electrons, often in feldspar
278 crystals, are released by infra-red radiation. This methodology has the advantage that
279 feldspar crystals can trap sufficient electrons to extend the dating interval to 1 Ma or more,
280 depending on the natural radioactivity on the site. (**Luminescence Dating**)
- 281 (4) **Electron spin resonance (ESR)** - this technique measures mineral exposure to environmental
282 radiation and is calculated based upon the signal emitted by these trapped electrons. The
283 dating range is dependent on the nature and state of conservation of the sample and the
284 surrounding environment but is between a few thousands and over a million years (**Text Box**
285 **4**).

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

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

294 Other scientific dating methods

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

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

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

310 Relative dating methods

311 There are several approaches which provide relative, rather than calendar, dating. These underpin
312 the understanding of landscape development and stratigraphy, providing a framework into which
313 other dating evidence can be inserted. A key relative dating method is biostratigraphy. This ranges
314 from the identification of particular episodes of time based on the assemblages of remains in
315 particular kinds of deposit, to the higher-resolution of climatic zonation of biological remains. An
316 important part of the method is correlation, using biostratigraphical characteristics to establish the
317 relative position of sediments in different geographic localities. Biostratigraphy may be based on a
318 single taxon, on assemblages of taxa, on relative abundances, and on specified morphological
319 features, including changes of an evolutionary nature. The latter can be the most powerful
320 biostratigraphical technique (**The 'Vole Clock'**). Mammalian faunas have proved to be the most
321 effective for dating, since they show greater change during the Quaternary than other types of
322 biological remains. This same principle is also the basis for 'archaeostratigraphy', in which diagnostic
323 archaeological artefacts (for example types of worked flint) are used to infer the age of the
324 stratigraphical unit.

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326 3. Bayesian Chronological Modelling

327 *Alex Bayliss and Peter Marshall, Historic England*

328 Bayesian statistics provide an explicit, probabilistic method for combining different sorts of evidence
329 to estimate formally the dates of events that happened in the past. The basic idea is encapsulated in
330 Bayes' theorem (Fig 10), which simply states that we analyse the new data we have collected about
331 a problem ("the standardised likelihoods") in the context of our existing experience and knowledge
332 about that problem (our "prior beliefs"). This enables us to arrive at a new understanding which
333 incorporates both our existing knowledge and our new data (our "posterior beliefs"). This is not the
334 end of the matter, however, since today's posterior belief becomes tomorrow's prior belief,
335 informing the collection of new data and their interpretation as the cycle repeats.

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

342 Figure 11 illustrates this using the assemblage of radiocarbon dates on ultra-filtered gelatin
343 extracted from human and cut-marked animal bones found in Gough's Cave, Somerset (Table 1;
344 Jacobi and Higham 2009; following their interpretation, OxA-18067 has been excluded as this related
345 to later activity). In this graph the 'raw' scientific dates are shown in outline, and the posterior
346 beliefs from the Bayesian model are shown in black. Some posterior distributions relate to particular
347 objects, for example cut-marked bone GC 1990 184 dates to *14,990–14,670 cal BP (95% probability;*
348 *OxA-18035; Fig 11), probably to 14,870–14,740 cal BP (68% probability).* Other posterior
349 distributions estimate the time of events in the past that do not relate to a particular sample, for
350 example, this model estimates that human occupation in the cave began in *15,070–14,740 cal BP*
351 *(95% probability; start Gough's Cave; Fig 11), probably in 14,950–14,790 cal BP (68% probability).*

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

355 Archaeologists have a whole range of other information that can be included as prior information in
356 Bayesian models. Relative dating can be provided by typological analysis of artefacts or, most
357 commonly, by stratigraphy. This stratigraphy can be within a single site (**Gransmoor**) or within the
358 geomorphology of sets of related features, such as river terraces (**The Axe Valley at Broom**). Often
359 an archaeological intervention will provide limited new evidence on a particular issue, but any new
360 scientific dates or limiting information will need to be interpreted within an updated chronological
361 model of the problem at hand.

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

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- 366 1. Objectives of the study: including the dating precision needed to achieve the objectives and
367 how the objectives may have been (re)cast in the light of the available material, prior
368 information, funding, etc.
- 369 2. Methodology: including a statement of the approach adopted and the statistical methods
370 and software used.
- 371 3. Sampling strategy: including a discussion of the selection of the scientific dating techniques
372 employed, the available prior information, the available pool of potential samples, the
373 results of any simulation models, and the rationale by which these elements have been
374 combined into a strategy.
- 375 4. Details of scientific dates: see the appropriate sections of these guidelines for the
376 information required for different techniques.
- 377 5. Model definition and description: each model must be explicitly defined so that it can be
378 recreated (most models can be defined using procedures provided by publicly-available
379 software packages, although models that use new statistical procedures will need
380 mathematical appendices); prior information should be described, and its strengths and
381 weaknesses assessed; the robustness of the associations between the scientific dates and
382 the prior information should be considered; the compatibility of the scientific dates, with
383 each other and with the prior information should be assessed; outliers or misfits should be
384 identified and described.
- 385 6. Sensitivity analyses: alternative models, which vary components of a model to determine
386 how sensitive the modelled chronology is to changes in the interpretations on which it is
387 based.

388 Further information on Bayesian chronological modelling can be found in Buck and Millard (2004).

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390 PART 2 – SCIENTIFIC DATING METHODS

391 4. Radiocarbon Dating

392 *Alex Bayliss and Peter Marshall, Historic England*

393 Radiocarbon (^{14}C) is a naturally occurring radioactive isotope of carbon that is formed in the upper
394 atmosphere when cosmic radiation interacts with nitrogen atoms. It is unstable, with a half-life of
395 5730 ± 40 years. It is taken up by living organisms, but decays after death so that the proportion of ^{14}C
396 in the dead organism decreases over time. By measuring the proportion that remains, the elapsed
397 time since death can be estimated.

398 In principle any organic material that was once alive can be dated, including bone, charred or
399 waterlogged plant materials, and marine shell. Radiocarbon is, however, very difficult to measure, in
400 large part because the ^{14}C concentration in living material is extremely low (about 1 in every 1
401 million million carbon atoms). This makes detecting a radiocarbon atom in a sample at the limit of
402 detection (about 50 ka) equivalent to identifying a single specific human hair that might occur on the
403 head of any of the human beings alive on earth today!

404 This means that it is much more difficult to date Pleistocene samples accurately than more recent
405 samples (which contain more radiocarbon). This is illustrated in Table 2 which shows the impact on
406 the reported radiocarbon age of modern contaminants on samples of different actual age. Since the
407 introduction of Accelerator Mass Spectrometry (AMS), which dates samples less than 1g in weight,
408 the absolute amount of contaminant needed to cause such offsets is tiny. The pressing need to avoid
409 or remove contamination in older samples has practical implications for how Pleistocene samples
410 are collected in the field and processed in the laboratory.

411 In the field extreme care should be taken that modern contaminants such as hair or hand-cream do
412 not come into contact with samples. Bone, antler, ivory, charcoal, and shell samples should be
413 wrapped in tin foil and placed in clearly labelled plastic bags. Precious artefacts are often sampled by
414 specialists from the dating laboratory to minimise intervention. Sediment samples must be securely
415 wrapped in black plastic and refrigerated as soon as possible after retrieval. Sub-sampling for
416 radiocarbon dating, either by hand-picking macrofossils using tweezers or sieving in water, should be
417 undertaken swiftly in a clean environment. Be particularly wary of fibres from paper towelling.
418 Macrofossils should be stored with a small amount of water in a glass vial with a screw lid that has a
419 foil liner and refrigerated. For all potential samples, organic consolidants, fungicides, etc must be
420 avoided.

421 Over the past decade much research has focussed on refining the chemical procedures used for
422 preparing Pleistocene samples for radiocarbon dating. Ultrafiltration of gelatin extracted from bone,
423 antler, and ivory samples of this age is now routinely applied (Brown *et al* 1988; Jacobi *et al* 2006).
424 Improved accuracy may be obtained by the implementation of an acid-base-wet oxidation (ABOX)
425 pretreatment for charcoal samples (Bird *et al* 1999), and refined pre-screening and preparation
426 methods for ornaments made from marine shell (Douka *et al* 2010).

427 Materials selected for dating must not only contain sufficient carbon and be uncontaminated, but
428 they must also have a secure association with the human activity or environmental event that is the
429 target of the dating programme. Precision may be improved if sequences of related samples can be

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430 obtained (**Bayesian Chronological Modelling**). Given the technical difficulties of accurate
431 radiocarbon dating in this period, replicate measurements should be undertaken where sufficient
432 material is available. Suitable datable material is often scarce on Pleistocene sites, but it is essential
433 that the reliability of the chronologies of this period are not undermined by dating unsuitable
434 material simply through the lack of better samples.

435 The following information must be published for each radiocarbon measurement:

- 436 • Details of the facility/facilities which produced the results and how samples were pre-
437 treated, prepared for measurement, and dated;
- 438 • Details of the radiocarbon results and associated measurements and how these have been
439 calculated; and
- 440 • Details of the material dated and the context from which it came.

441 **Bayesian Chronological Modelling** provides examples of the information that should be provided for
442 each radiocarbon date. Note that at the limit of the technique some radiocarbon ages may be
443 quoted with asymmetrical error terms (for example, GrN-12876 from Lynford Quarry, which produced
444 an age of $35,710 \pm 930 / -830$ BP), and some may produce minimum ages (for example OxA-11572 also
445 from Lynford Quarry, which produced an age of $>49,700$ BP) (**Neanderthals in Norfolk**).

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

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

456 5. Uranium-Thorium dating

457 *Alistair Pike, University of Southampton*

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

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

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468 The error on a U-Th date depends on its age. Under ideal circumstances, measurements of the
469 isotopic ratios using modern mass spectrometric methods can be made to less than $\pm 0.5\%$ (at 2σ)
470 which can lead to uncertainties of less than 100 years in 10,000. But as the sample age approaches
471 the limit of the method, the errors can get far larger. For example a 0.5% measurement error (on
472 each isotopic ratio) translates to errors of ± 1.2 ka at 100 ka and $\pm 40/-31$ ka at 400 ka. Note that the
473 errors are noticeably asymmetrical towards the limit of the technique.

474 Problems are commonly encountered from detrital contamination of the calcite (for example by
475 cave sediments and particulates) which bring with them ^{230}Th , which without correction would lead
476 to older apparent dates. The level of detritus is monitored by measurement of the common isotope
477 of thorium, ^{232}Th , usually expressed at the activity ratio $^{230}\text{Th}/^{232}\text{Th}$. High values (for example >100)
478 indicate low levels of contamination, whereas values <5 indicate severe contamination. For low and
479 moderate levels of contamination a correction can be applied using an assumed $^{230}\text{Th}/^{232}\text{Th}$ ratio for
480 the detritus with a large uncertainty which is propagated to the calculated date. For highly
481 contaminated samples, the errors on corrected ages may become so large that the dates are not
482 useful. An alternative strategy is to take multiple same-age samples (for example from a single
483 growth layer of speleothem) which allows the construction of an 'isochron' to correct for detritus.
484 Again, the errors will increase, sometimes drastically.

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

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

493 When taking samples it is worth considering the worst-case scenario; that the samples will be
494 detritally contaminated and possibly open systems, and ensuring samples are suitable for the
495 laboratory to take multiple sub-sample to construct an isochron and/or to check for open system
496 behaviour, even if these steps are not eventually required.

497 An ideal sample would be the complete sequence of growth layers of a flowstone floor that formed
498 directly over or between two archaeological layers (Fig 13). These can be detached as a block, cut
499 with a grinder, or cored with a coring drill. Photographic and other documentation of the position of
500 the sample, and especially its relation to archaeological layers, is essential, as well as indicating on
501 the sample the uppermost (youngest) layer. Where speleothem formation is very active, long
502 sequences of samples bracketing different layers can produce detailed chronologies for sites (for
503 example Hoffmann *et al* 2013). Sample storage is straightforward and can be in individual plastic
504 bags, or for small samples, clean plastic tubes.

505 Occasionally it is not possible to remove complete samples without undue damage to the
506 archaeology or the cave (for example in the case of calcite deposits on top of cave paintings: Pike *et*
507 *al* 2012). In these cases the calcite should be sampled *in situ*; this provides fewer opportunities to

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508 control for open system behaviour, contamination from the sampling equipment and other
509 complexities, so it is best to consult with a specialist and arrange for them to take the sample.

510 The minimum required data for reporting a U-Th date is: sample code; laboratory code; U
511 concentration; $^{234}\text{U}/^{238}\text{U} \pm \text{error}$; $^{230}\text{Th}/^{238}\text{U} \pm \text{error}$; $^{230}\text{Th}/^{232}\text{Th} \pm \text{error}$; uncorrected U-Th age \pm error;
512 and corrected U-Th age \pm error. There is no convention on reporting ages relative to a datum,
513 though BP (before 1950 AD) has been used, as has B2k (before 2000 AD), but most commonly no
514 datum is stated and the date is assumed as years before the publication date. Dates are in calendar
515 years and do not require further calibration. In addition, the half-lives (or published source) for the
516 date calculations should be given, along with details of the method of correcting for detrital
517 contamination and the ratios used. If isochron dating is used, the graphical plot of the isochron and
518 associated statistics (as produced by software such as *Isoplot*) should be included either in the
519 publication or as supplementary information.

520 6. Luminescence dating in the Pleistocene

521 *Geoff Duller, Aberystwyth University*

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

526 When minerals such as quartz and feldspar are exposed to radioactivity from the natural
527 environment, a small proportion of the energy is stored in the crystal structure. At some later date,
528 the energy can be released and produces light; this is the luminescence signal used for dating (Fig
529 14).

530 There are a variety of luminescence techniques, based on different minerals and different signals.
531 Quartz dating using optically stimulated luminescence (OSL) has been well established since 2000,
532 whilst infrared stimulated luminescence (IRSL) from feldspars has been revolutionised by work
533 published in 2008. Other luminescence signals are also available; each has its strengths and
534 weaknesses. Advances in methodology are constantly being made and close collaboration with a
535 laboratory is strongly recommended.

536 Luminescence methods can date the last time that the mineral grains in a sediment were exposed to
537 daylight (optically bleached) – this is normally when the sediments were deposited by a river, by the
538 wind or some other geomorphological process. When the mineral grains are exposed to daylight any
539 energy stored in them is released, and this sets the ‘clock’ to zero. Once mineral grains are buried by
540 further deposition energy starts to accumulate within them, and this continues until they are
541 collected for measurement. Sediments suitable for dating should contain either fine-silt (4–11µm) or
542 sand grains (90–300µm). Aeolian sediments are ideal, but fluvial and some colluvial materials are
543 also suitable. The key consideration is whether there is a high probability that the mineral grains
544 were exposed to daylight at, or prior, to deposition.

545 Luminescence dating can also be used to date the last heating of stones and flints. Heating to more
546 than about 250°C will release the energy stored in the mineral grains. Hearth stones, or flints that

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547 have been inadvertently burnt in hearths, have been targeted from Palaeolithic sites (for example
548 Preece *et al* 2007; Richter 2007).

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

554 For sediments a common method of sampling is to hammer a metal or plastic tube (typically 30–
555 70mm in diameter and 150–200mm in length) into the sedimentary unit. The ends of the tube
556 should be packed with plastic and sealed using tape to avoid movement of the sample during
557 transportation back to the laboratory, and to avoid moisture loss. If this is not possible then an
558 alternative approach is to use a large sheet of black plastic to exclude daylight from the section and
559 for a sample to be collected using a trowel and collected in an opaque bag that will exclude daylight.
560 Red LEDs can be used during sampling to provide limited lighting.

561 A critical part of calculating a luminescence age is to measure the natural radioactivity at the site.
562 Some measurements can be made in the laboratory, but *in situ* measurements are preferable using a
563 gamma spectrometer (Fig 15). Where *in situ* gamma spectrometry is not possible it is important to
564 consider whether the nature of the sediments varies within 300mm of the sample. Where large
565 variations are seen sub-samples of the different sediments should be collected for dose rate
566 measurements in the laboratory, and their location relative to the luminescence sample noted.
567 These dosimetry samples can be exposed to daylight since they will not be used for luminescence
568 measurements. In addition, the thickness of the overburden should be noted, and an estimate of the
569 water content during burial will be required.

570 For burnt objects the artefact should be shielded from as much light as possible, but complete
571 exclusion of light is not necessary since the inside of the artefact is normally used for measurement.
572 A representative sample of the sediment surrounding the artefact should be submitted along with
573 the artefact. The same issues about measurement of the gamma dose rate apply for burnt samples
574 as they do for sediments.

575 Luminescence can be used to date events from decades to in excess of one hundred thousand years.
576 The upper limit is determined by saturation of the luminescence signal; the point at which no
577 additional energy can be stored in the mineral grains (Duller 2008). This varies from one sample to
578 another, and the rate at which energy is delivered to the sample varies depending upon the dose
579 rate. It is common to be able to date to 100 ka, not unusual to be able to reach 200 ka, and in
580 unusual circumstances ages of 400 or 500 ka are feasible. Precision better than 5% (at 1σ) is
581 normally unrealistic because of uncertainties in the dose rate. At ages of 100 ka and above,
582 uncertainties of 10% are common.

583 Ages are normally given in kiloannum (ka) before the date of measurement. No agreed datum exists
584 for luminescence ages but it is good practice to report the date (such as 2015 CE) when a
585 luminescence age was measured (Brauer *et al* 2014). The term “BP” which is used for radiocarbon
586 ages should never be used when reporting luminescence ages. Supporting information required for
587 luminescence ages includes the mineral and analytical method used for luminescence measurement,

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588 details of any statistical analysis of the luminescence data, and the equivalent dose (D_e) for the
589 sample. Details of measurement of the dose rate must also be included: what methods were used
590 for dose rate determination, the water content used in calculation, the individual dose components
591 (alpha, beta and gamma) and the cosmic dose rate.

592 7. Amino acid racemization (AAR)

593 *Kirsty Penkman, University of York*

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

600 Amino acids are the building blocks of proteins. They are found in all living tissues and can be
601 preserved in fossil biominerals such shells or coral. Most amino acids can exist in two forms which
602 are non-superimposable mirror images of each other (Fig 16), designated left-handed (*laevo*, L-form)
603 and right-handed (*dextro*, D-form). In living organisms, proteins are almost exclusively made from
604 the L-form. However after death, a spontaneous reaction (called racemization) starts to occur. This
605 leads to a progressively increasing proportion of the D-form in direct relation to the time elapsed,
606 until the D and L forms are present in equal quantities. Depending on the amino acid, this process
607 can take thousands or millions of years and therefore is applicable over Quaternary timescales (Fig
608 17a). Different species break down at different rates, so analyses are undertaken on monospecific
609 samples (usually individual mollusc shells, 1–5mg in size). The extent of amino acid racemization
610 (AAR) in a sample is recorded as a D/L value, and its age can thus be determined based on (a) which
611 amino acid it is, (b) the species (of mollusc or other biomineral) being analysed, and (c) a baseline
612 reference framework of comparative data from independently-dated sites (an aminostratigraphy).

613 Protein degradation consists of a series of chemical reactions that are dependent not only on time,
614 but also on environmental factors (such as pH, availability of water), which can confound the time
615 signal. These difficulties in AAR's early applications have led to a focus on analysing 'closed-system'
616 protein from fossil samples (Towe 1980), where the fraction of protein analysed is physically or
617 chemically shielded from the environment. The chemically-isolated 'intra-crystalline' fraction found
618 in some biominerals forms such a closed system, meaning that the AAR within this fraction is solely
619 time and temperature dependent, and therefore predictable (Penkman *et al* 2008; Dickinson *et al*
620 2019). This technique has been particularly successful in dating carbonate and phosphate fossils
621 (shells, tooth enamel, eggshells, foraminifera, ostracods, earthworm granules), and in long-lived
622 biominerals (corals), it can be used to provide age information *within* an individual sample (Hendy *et al*
623 2012). The AAR labs have developed dating frameworks for a large number of commonly-
624 occurring 'closed-system' species, but tests can be undertaken on additional species to examine
625 whether they would be suitable for AAR dating. In a British Palaeolithic context, the most suitable
626 material for AAR dating are tooth enamel, *Bithynia opercula* and *Bithynia*, *Valvata*, *Littorina*, *Nucella*,
627 *Patella* and *Pupilla* shells. The crystal phase of calcite biominerals (such as opercula or eggshell) are
628 more stable over longer timescales and are therefore preferred for sites of Early and Middle
629 Pleistocene age.

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630 The rate of breakdown towards D/L equilibrium in the intra-crystalline fraction is still affected by
631 temperature, so comparative frameworks need to be applied from regions with a broadly similar
632 temperature history. For instance, it is not appropriate to compare D/L results from tropical material
633 to a framework based on sites from southern England, but any material from England can be
634 interpreted within the same comparative framework. In Britain analysis of amino acids in *Bithynia*
635 opercula allows correlation of deposits with the Marine Oxygen Isotope Record stages (Fig 17b), to a
636 sub-MIS level for at least the Late Pleistocene (Penkman *et al* 2011).

637 A non-specialist can collect material and/or sediment samples in the field. Sometimes molluscs or
638 other suitable remains will be directly visible, but as it is not always possible to tell whether a
639 sediment body contains suitable material for AAR dating, it may be necessary to collect a preliminary
640 sample and then subsequently assess its potential for AAR dating. Material for AAR dating is typically
641 collected from wet-sieved residues of sediment samples. The only special sampling/pretreatment
642 considerations are that the temperature-dependence of the racemisation reactions means it is
643 important that any material submitted for dating has not been treated in any way that compromises
644 its temperature history (for instance by sieving with warm water, or by drying in an oven). Suitable
645 material for AAR dating in the residues can be identified to species-level by a faunal (eg vertebrate
646 or mollusc) specialist or by the AAR laboratory.

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

654 8. Palaeomagnetism

655 *Chuang Xuan, University of Southampton*

656 The Earth's magnetic field intensity and direction are constantly changing at various temporal and
657 spatial scales. Beyond historical observations of the last few hundred years, our knowledge of past
658 field behaviour is mainly derived from natural remanent magnetisations (NRM) preserved in
659 geological and archaeological archives. These archives record palaeomagnetic field information
660 mainly through two mechanisms. Igneous rocks (eg lava, volcanic glass) and archaeological artefacts
661 acquire NRM through thermal remanent magnetisation (TRM) when magnetic minerals such as
662 magnetite in these archives cool from high temperatures to below Curie temperature. In contrast,
663 sedimentary rocks formed in a marine or lake environment record palaeomagnetic field information
664 through (post) depositional remanent magnetisation (DRM) acquisition, during which magnetic
665 particles in the sediments align themselves to ambient magnetic field during or shortly after
666 sediment deposition. Palaeomagnetic records reconstructed from geological and archaeological
667 archives play a fundamental role in revealing the dynamics and causes of geomagnetic change and
668 provide a valuable geophysical process based stratigraphic correlation and dating tool that is
669 independent from those based on palaeoenvironmental variations (eg, oxygen isotope stratigraphy;
670 **Introduction**).

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

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

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

709 RPI records are usually constructed by normalising NRM of a sample by laboratory-introduced
710 magnetisation to compensate for the ability of the sample to acquire magnetisation. Various criteria
711 have been proposed to ensure quality of the RPI records (eg Tauxe 1993). RPI records constructed
712 from different worldwide sedimentary sequences appear to record a dominantly dipolar
713 geomagnetic signal, and are generally coherent at least on a few tens of thousands-year scale. These

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714 RPI records can also be correlated to palaeointensity changes estimated using other independent
715 methods such as cosmogenic nuclides (eg Simon *et al* 2016; **Text Box 3**) and marine magnetic
716 anomaly profiles (Gee *et al* 2000). The use of RPI to constrain the chronology of a sedimentary
717 sequence is usually referred to as palaeointensity-assisted chronology (PAC). Detailed RPI stack
718 records that can be used as global or regional templates now span the entire Pleistocene (eg, Valet
719 *et al* 2005; Yamazaki and Oda 2005; Channell *et al* 2009) (see Fig 19, bottom). In addition, PSV (eg
720 declination and inclination) records have also been widely used to provide millennial scale age
721 constraints especially for late Pleistocene and Holocene sequences, usually by comparing the PSV
722 records to a regional reference curve or geomagnetic field model predictions for a location (eg Avery
723 *et al* 2017).

724 Samples used for palaeomagnetic analyses are typically oriented and can be taken in the form of
725 discrete cubes/cylinders or continuous sections/u-channels (Fig 18b–c) marked with a reference
726 orientation (eg dip/strike direction, true north, upward direction, etc.). For core samples where
727 orientation is difficult to track during coring, a straight reference line should be marked on the core
728 liner to guide subsequent cutting and splitting of the core and facilitate declination corrections later
729 on. Sediment samples are typically enclosed in plastic containers and stored in a fridge (set to ~4°C)
730 away from strong magnetic sources, to suppress any physical or chemical alternations.
731 Measurement of NRM and laboratory-introduced magnetisations of the samples are often
732 conducted on a superconducting rock magnetometer (see Fig 18d) capable of resolving weak
733 magnetisations (ie 10⁻⁵ A/m level). Samples are usually measured before and after stepwise heating
734 or alternating field (AF) demagnetisation treatment to remove secondary magnetisations
735 presumably carried by magnetic minerals with lower blocking/unblocking temperatures or lower
736 coercivity. Although geomagnetic polarity chrons, excursions, and RPI and PSV have become widely
737 used for dating Pleistocene sequences, the detailed mechanism through which sediments acquire
738 magnetisation is still poorly understood. The sediment magnetisation “lock-in” process may
739 introduce a smoothing effect and centennial to millennial scale time offsets to sedimentary
740 palaeomagnetic records (see Roberts *et al* 2013), which might define the ultimate resolution of
741 palaeomagnetism dating for Pleistocene sequences.

742 9. Tephrochronology

743 *Rupert Housley and Ian Matthews, Royal Holloway, University of London*

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

752 Tephra research is primarily stratigraphic, but calendar dating for Pleistocene sequences may be
753 acquired by two methods: direct dating of the tephra itself or dating of associated material. Direct
754 dating of volcanic deposits, through Argon-Argon, Uranium-series or Fission Track methods (Walker
755 2005), requires large amounts of material, which is usually not available in areas distant from the

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756 source volcano. England receives ash from Iceland and Continental Europe but the ash is in too low
757 concentrations and lacks the relevant mineral material to be directly dated. More commonly,
758 tephra are dated by determining the age of the layer in which they are found. Either the layer may
759 be directly dated using datable material within it, or a series of dates may be obtained for a
760 stratigraphic sequence of deposits (for example, through age-depth Bayesian modelling of series of
761 radiocarbon dates; **Gransmoor**). In some cases, it is possible to directly estimate the date of the
762 layer by counting in annually-laminated lakes and ice cores. Tephra isochrons allow this calendar
763 dating to be transferred to deposits wherever the ash is detected.

764 Tephrochronology is a viable dating technique for the entire Pleistocene period and is only limited by
765 the reference datasets available for comparison. Tephra studies have focused on the Late
766 Pleistocene, with a robust tephrochronology for Northern Europe comprising *c* 20 tephra between
767 15-11.5ka, while a developing tephrochronology of *c* 58 tephra has been established for the
768 remaining Late Pleistocene (*c* 120-15 ka) (Blockley *et al* 2014; Davies *et al* 2014). There is no reason
769 why tephra should not be detected in Early or Middle Pleistocene deposits (for example, it has
770 recently been identified in the West Runton Bed (Brough *et al* 2010)), but this earlier period has not
771 yet received the same level of research. To date, there has been only a limited number of studies
772 applying tephrochronology to English archaeological sites, but distribution maps of ash fall suggest
773 there is good potential to apply tephra studies to sites across the entire country (Fig 20a). The
774 precision and accuracy of tephra ages are limited by the dating techniques and age models used for
775 the type sites. During the Late Pleistocene, precision may be as good as 1–2% of the determined age
776 (Bronk Ramsey *et al* 2015a). When reporting tephra data, it is convention to provide the tephra
777 counts, the chemical data alongside chemical standards, the analytical conditions used, the
778 proposed correlative and how the age estimate is derived.

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

789 Cryptotephra processing (Lane *et al* 2014) involves the laboratory screening of samples *c* 300mm³ in
790 size from 50–100mm contiguous sediment blocks. If tephra is present a series of contiguous 10mm
791 samples are processed to pinpoint the highest concentration, often interpreted as the isochron (Fig
792 21). A third stage separates sufficient vitreous tephra shards for major (using EPMA (Electron Probe
793 Microanalyzer)) and trace element (using Laser Ablation Inductively Coupled Plasma Mass
794 Spectrometry (LA-ICPMS) or SIMS (Secondary Ion Mass Spectrometry)) chemical analysis (Fig 20b).
795 Databases of chemical signatures may identify correlation to known tephra horizons (TephraBase:
796 Newton *et al* 2007; RESET: Bronk Ramsey *et al* 2015b).

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797 The current application of tephrochronology to archaeology can be classified into three categories:
798 (1) wetland archaeology; (2) open-air 'dry' sites; and (3) rock shelters and caves. No formal
799 assessment has been made of the likelihood of finding tephtras in any of these kinds in Britain, but
800 recent work has demonstrated that 22% of open-air 'dry' sites and 34% of rock shelters and caves
801 produced tephtras in Continental Europe (Housley *et al* 2015). Success rates in wetlands sites are
802 likely to be higher as they are generally undisturbed.

803 10. The 'Vole Clock'

804 *Danielle Schreve, Royal Holloway, University of London*

805 Often overlooked as a source of evidence in the past, the recovery of small vertebrate remains is
806 now a recommended routine procedure when investigating sites of Quaternary age. Any calcareous
807 fine-grained deposits (generally sands, silts and clays, or seams of these within coarser gravel bodies)
808 may be suitable for sampling. The process of hand excavation with a trowel will often damage fragile
809 specimens, so the best way to proceed is for bulk samples of sediment to be extracted, either as a
810 column (in order to investigate any change up through a sequence) or as spot samples around
811 particular features of interest. The samples should be wet-sieved individually through a half-
812 millimetre mesh size before the residue is dried and then scanned under a low-power binocular
813 microscope and any bones and teeth extracted using foil tweezers. If the sample is clay-rich, air-
814 drying the sediment or soaking with a dispersant such as 1% sodium hexametaphosphate before
815 wet-sieving may help to weaken the hydrophilic bond of the clay particles, allowing the samples to
816 be processed more easily.

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

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

833 The genus *Mimomys* appeared in Europe around 4 million years ago and evolved through a number
834 of species, surviving until around 600 ka, when the final representative, *Mimomys savini*, was
835 replaced by representatives of the modern genus *Arvicola*. The key features of interest are present
836 in the first lower molar (m1), which is composed of a 'cloche hat-shaped' anterior loop (the
837 anteroconid complex, ACC, see Fig 22), followed by a series of three closed interlocking triangles and

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838 a posterior loop. At the point of transition from *Mimomys* to *Arvicola* during the early Middle
839 Pleistocene (late Cromerian Complex), an important change occurs in the switch from rooted teeth
840 to permanently-growing molars (Fig 23). This apparently rapid event forms a highly significant
841 biostratigraphic marker over western Eurasia. In Britain, the transition allows a clear separation of an
842 'old' group of early Middle Pleistocene sites such as West Runton, Norfolk and Pakefield, Suffolk that
843 are characterised by *Mimomys*, and a 'young' group of early Middle Pleistocene sites with *Arvicola*,
844 such as Westbury-sub-Mendip, Somerset and Boxgrove, West Sussex (Preece and Parfitt 2012). This
845 advantageous mutation provided *Arvicola* with extra tooth life, allowing them to extend their life
846 span and consequently their breeding opportunities, thus perpetuating the mutation.

847 Within the genus *Arvicola*, there are further trends noted over the last half million years. Two
848 subspecies are noted in the British fossil record, *Arvicola terrestris cantiana* (also known as *Arvicola*
849 *mosbachensis*) and the modern *Arvicola terrestris terrestris* (also known as *Arvicola amphibius*). As
850 well as a lengthening of the m1 and an increase in the ratio of the ACC to overall tooth length, the
851 *Mimomys* fold, an archaic feature in the ACC, also become progressively uncommon in younger
852 samples until finally disappearing (Fig 22). However, the key trend relates to the differences in
853 enamel thickness on the leading and trailing edges of the molars. *Mimomys* and early forms of
854 *Arvicola* have thicker enamel on the trailing edges of the lower molars than on the leading edges.
855 Over time, the situation reverses so that in modern populations of *Arvicola terrestris terrestris* from
856 Western Europe, the enamel is thicker on the leading edges of the lower molars (Fig 22) (Hinton
857 1926). A method known as the *Schmelzband-Differenzierungs-Quotient* (enamel differentiation ratio)
858 or SDQ was proposed by Heinrich (1982) in order to quantify this progressive trend. The method
859 uses measurements of the combined trailing edge thickness from established points on the molar,
860 divided by the combined leading edge thickness, multiplied by 100. The resulting figure (the SDQ)
861 can then be used to compare different populations of *Arvicola* in order to establish their relative age.
862 This technique has been widely applied in Britain in order to provide an independent chronology for
863 many Quaternary localities (for example Schreve 2001; Roe *et al* 2009).

864

865 PART 3 – CASE STUDIES

866

867 11. Happisburgh Site 3, Norfolk

868 *Zoe Outram and Peter Marshall, Historic England*

869 The Cromer Forest-bed formation, that formed between 2 and 0.5 million years ago along the coast
870 of Norfolk and Suffolk, is famous for its rich flora and fauna such as mammoth, rhinoceros and
871 hippopotamus that have been discovered over the last 250 years. Despite such a long history of
872 investigation it has only recently yielded evidence for hominin presence. Excavations at Happisburgh
873 Site 3, Norfolk (Fig 24), recovered an assemblage of 78 flint artefacts from the fills of a series of
874 stacked, overlapping channels (Parfitt *et al* 2010). The deposits contained a remarkable range of
875 remains for a Pleistocene site, as well as the stone tools, floral, and faunal remains that allowed a
876 detailed study of not only the hominin activities being carried out in this area, but also of the
877 environment that they occupied. Although stratigraphic evidence indicated that the site was older
878 than MIS 12 (450 ka) when the marine and freshwater deposits associated with Cromer Forest-bed
879 formation ended and sediments associated with the Anglian glaciation were laid down, determining
880 more precisely the age of the hominin activities of the site was essential in order to understand their
881 significance and place them into a broader context.

882 Samples for palaeomagnetic dating were obtained from a stratigraphic sequence of deposits below,
883 within, and above the artefact-bearing gravels. The sediments all displayed a reversed polarity
884 placing their deposition into the Matuyama chronozone (2.52–0.78 Ma). Biostratigraphic evidence
885 including the presence of key plant taxa (identified from the pollen spectra), such as *Tsuga*
886 (hemlock) and *Ostrya*-type (hop-hornbeam type) which are unknown in Northern Europe after the
887 Early Pleistocene, together with extinct mammals (mammoths, equids and voles) suggested the age
888 of the site was towards the end of the Early Pleistocene. Taken together the biostratigraphic and
889 palaeomagnetic data indicated that the hominin occupation at Happisburgh occurred towards the
890 end of the Matuyama chronozone, placing the deposits between 990 and 780 ka (Parfitt *et al* 2010).

891 Further evidence of when in this period hominin occupation took place is provided by the
892 palaeobotanical record that indicates it would have been during a phase of climatic cooling in the
893 second half of an interglacial cycle (Fig 25). Together with the other evidence, Parfitt *et al* (2010)
894 suggested that the site was occupied at the end of either MIS 21 (866–814 ka) or MIS 25 (970–936
895 ka). More recently Westaway (2011) has proposed an alternative, younger, dating for the site (MIS
896 15c; c 600 ka), based on reinterpretation of the palaeomagnetic evidence and the suggestion that
897 the pollen and faunal remains on the site are reworked from earlier deposits. Although Parfitt *et al.*
898 (2010, supplement) assign the sediments, based on their composition, to the Thames, Westaway's
899 (2011) hypothesis is unlikely, as it is clear that by MIS 15 the River Bytham flowed across Suffolk
900 from west to east and entered the North Sea at Lowestoft (Parfitt *et al.* 2005), and thus the Thames
901 could not have reached Happisburgh.

902 The evidence from Happisburgh Site 3 has redefined our understanding of the earliest known
903 occupation of Britain. If the later suggested dating is correct (Westaway 2011), Happisburgh Site 3 is
904 very much in keeping with other indications, from the European Continent, of the date when the
905 first hominins occupied this part of north-west Europe. If the earlier dating of Parfitt *et al* (2010) is

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906 accepted, then Happisburgh Site 3 has yielded the oldest hominin occupation north of Iberia and the
907 first occupation within the northern boreal zone, with important implications for our understanding
908 of populations, in terms of their movements/migrations, their behaviour, and their ability to adapt
909 and survive different environments, such as the cooler climates recorded towards the end of an
910 interglacial.

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

913 12. **Boxgrove**

914 *Danielle Schreve, Royal Holloway, University of London*

915 The site of Boxgrove is located in West Sussex, 12km north of the English Channel coast. Its modern
916 position is significant, since the Pleistocene deposits of archaeological and palaeontological interest
917 lie on top of a wave-cut platform in the Cretaceous Upper Chalk bedrock, indicating that the site
918 once lay at the northern edge of a large marine embayment (Fig 26). The marine beach associated
919 with the platform reaches a maximum height of 43.5m OD, highlighting considerable tectonic uplift
920 since the deposits were laid down. The site forms the highest (and oldest) of a flight of four marine
921 terraces that represent former sea-level high stands and which extend down to modern sea-level on
922 the West Sussex Coastal Plain. Excavated between 1984 and 1996, Boxgrove is internationally
923 renowned for its spectacular Lower Palaeolithic archaeological record, including several hundred
924 ovate bifaces (handaxes) made on flint sourced from the Chalk cliff nearby, its rich and diverse fossil
925 vertebrate assemblage, and the presence of hominin remains (two incisors and a tibia) attributed to
926 *Homo heidelbergensis*. Over 100 species of vertebrate fauna, together with invertebrates such as
927 molluscs, ostracods and foraminifera were recovered (Roberts and Parfitt 1999).

928 The deposits at the site were laid down on the wave-cut platform, and consist of a sequence of
929 marine sands (the Slindon Sands), lying beneath a series of lagoonal deposits (the Slindon Silts)
930 upon which a stable land surface developed, as witnessed by evidence for a soil (palaeosol).
931 Palaeoclimatic conditions remained temperate throughout this period. The Slindon Silts and
932 overlying land surface are the source of the majority of the archaeological and faunal remains. The
933 fine-grained nature of the sediments is such that individual episodes of handaxe knapping can be
934 identified (Fig 27) and the flakes refitted to reveal the process of manufacture. Bone and antler
935 hammers used for handaxe manufacture were also recovered, and part of the site contains evidence
936 for the presence of spring-fed pools surrounded by open grassland, which appears to have acted as a
937 focal point for human activity. This Pleistocene land surface was subsequently covered by silty
938 brickearth and gravels (the Eartham Formation), which were deposited as climate deteriorated and
939 vegetation cover became sparse. This transition to cold climate conditions is supported by the kinds
940 of ostracod and mammal remains found in the upper part of the Slindon Silts and the basal
941 sediments of the overlying Eartham Formation (Roberts and Pope 2009).

942 The site has also yielded extensive proof for large mammal butchery, including evidence for the
943 dismemberment of wild horse, red deer, giant deer, bison and three extinct Hundsheim
944 rhinoceroses. The carcasses of these animals are littered with cutmarks from stone tools, indicating
945 a complete process from skinning through to the removal of the major muscle blocks and tendons.
946 Where present, carnivore gnawmarks overlie anthropogenic cutmarks, indicating that humans had

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947 first access to the carcasses and to the complete range of body parts. Pathological evidence for a
948 trauma wound to the shoulder blade of the butchered horse is consistent with impact damage from
949 a large projectile, such as a wooden spear (Roberts and Parfitt 1999). In combination, the evidence
950 from the site provides a strong indication of hominin hunting capabilities in the Lower Palaeolithic.
951 The large size of the prey tackled and the concomitant meat yield (700kg in the case of a rhinoceros)
952 also has implications for palaeo-demography, with groups of up to 50 individuals in the immediate
953 area.

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

965 The age of the Boxgrove deposits has been controversial with different authors advancing both pre-
966 and post-Anglian (MIS 12) ages. The evidence for a post-Anglian age can now be questioned,
967 however, on the basis of scientific advances since the original studies were undertaken. For example,
968 the Amino-Acid Racemisation put forward as the strongest evidence for later dating (Bowen and
969 Sykes 1999) was not undertaken on the intra-crystalline fraction of the shells (**Amino acid
970 racemization (AAR) geochronology**). The mammalian biostratigraphy from the site, in particular the
971 presence of a large number of taxa (for example the shrews *Sorex runtonensis* and *Sorex savini*, the
972 vole *Pliomys episcopolis*, the cave bear *Ursus deningeri*, the rhinoceros *Stephanorhinus*
973 *hundsheimensis* (Fig 28) and the giant deer *Megaloceros dawkinsi* and *Megaloceros cf. verticornis*)
974 that became extinct in Britain during the Anglian glaciation, strongly imply that the Boxgrove
975 temperate climate sediments must pre-date, rather than post-date, MIS 12.

976 Further resolution in the likely chronological position of the Boxgrove deposits is provided by the
977 '**Vole Clock**'. The Cromerian Complex interglacials may be divided into an older group, characterised
978 by the presence of the archaic water vole, *Mimomys savini*, and a younger group characterised by its
979 descendant, *Arvicola cantiana terrestris*. The presence of the latter at Boxgrove therefore implies a
980 younger age within the Cromerian Complex. Furthermore, the presence of a more derived (ie
981 advanced) form of narrow-skulled vole, *Microtus gregalis*, suggests a more recent age for Boxgrove
982 within the *Arvicola* group. The preferred position of the Boxgrove Slindon Formation is therefore
983 right at the end of the early Middle Pleistocene, correlated with MIS 13, and with the cold-climate
984 Earham Formation correlated with MIS 12 (Roberts and Parfitt 1999; Roberts and Pope 2009). The
985 attribution of Boxgrove to MIS 13 also allows the timing of the earliest Acheulean in Britain to be
986 more firmly established, since handaxe sites are currently only known in association with *Arvicola*
987 (Candy *et al* 2015). These conclusions reinforce the importance of the vertebrate fossil record for
988 chronological determination at Pleistocene sites beyond the range of radiocarbon dating.

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989 13. The Axe Valley at Broom – OSL dating Middle Pleistocene fluvial 990 sediments

991 *Peter Marshall, Historic England*

992 The sand and gravel exposures at Broom, located on the River Axe along the Devon/Dorset border,
993 are of considerable significance in the context of the Lower Palaeolithic and the fluvial terrace
994 stratigraphy of southwest England (Fig 29). The deposits exposed in three working pits have yielded
995 at least 2,301 Palaeolithic artefacts; an assemblage dominated by handaxes. Like most of England's
996 river terrace Palaeolithic archaeology, the contextual information for the assemblage is incomplete.
997 The physical condition of the stone tool assemblage suggests a mixture of locally derived artefacts
998 and pieces that had been transported further by the river during the Middle Pleistocene. The
999 archaeology is of both regional importance for the understanding of the Lower Palaeolithic
1000 occupation of southwest England and of national significance with respect to the use of chert in the
1001 manufacture of the majority of the lithic assemblage (Hosfield and Green 2013).

1002 The traditional model of sediment accumulation at Broom had emphasized a tripartite sequence
1003 comprising lower gravels (Holditch Lane Gravel Member), an intervening unit comprising sands, silts,
1004 and clays (Wadbrook Member), and an upper gravel unit (Fortfield Farm Gravel Member),
1005 resonating with Bridgland's (1996) model of the typical aggradational terrace. This framework
1006 associated major fluvial aggradations and incisions with the cyclical shifts from interglacial to glacial
1007 recorded in the Marine Isotope Record (**Text Box 1**). However, the age of the sediments remained
1008 unknown.

1009 A project funded by the Aggregates Levy Sustainability Fund (ALSF), The Archaeological Potential of
1010 Secondary Contexts, was undertaken by Reading and Gloucestershire Universities. It sought to
1011 assess the interpretative potential of the secondary context archaeological resource for the Lower
1012 and Middle Palaeolithic in England, included excavations at Broom that built on a long history of
1013 research to contextualise the artefact collections and date the fluvial sediments. In order to provide
1014 an absolute chronology for the Middle Pleistocene terrace succession and the artefacts at Broom,
1015 and assess whether the River Axe's fluvial record mapped onto the classic Bridgland model, 18 OSL
1016 samples were dated (Table 4; Toms 2013). The optical age estimates from the Wadbrook Member
1017 and the Fortfield Farm Gravel Member were combined with relative dating information provided by
1018 the stratigraphic relationships among the samples to create a Bayesian chronological model (Fig 30).
1019 Age estimates from the Wadbrook Member come from a single section and were therefore defined
1020 sequentially (GL02084<GL03011<GL02083) as their relative stratigraphic position was unambiguous.
1021 The Fortfield Farm Gravel Member age estimates derived from several separate sections, and
1022 therefore formed part of a Fortfield Farm Gravel phase. The model provides an estimate for the
1023 transition from the Wadbrook Member and the Fortfield Farm Gravel Member of 312–274 ka (95%
1024 probability; *Wadbrook/Fortfield EarmMember*; Fig 30) and probably 301 ka–283 ka (68%
1025 probability). These results indicate that the Wadbrook Member formed between mid-MIS 9
1026 (interglacial) and early MIS 8 (glacial), and the Fortfield Farm Gravel Member between MIS 8 (glacial)
1027 and MIS 7 (interglacial). Combined with the stratigraphic and sedimentary evidence at Broom these
1028 dates indicate that the Axe valley's terrace stratigraphy, as evident at Broom, does not fit exactly
1029 into existing models of terrace formation, a valuable reminder that not all rivers respond in the same
1030 way to variations of climate, geology and base level. These age estimates also provide a chronology
1031 for the prolific assemblage of Acheulean (biface) artefacts recovered from the Wadbrook Member

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1032 and are particularly notable since they clearly indicate that this Acheulean dominated assemblage at
1033 Broom formed when the Palaeolithic record in south-east England contains evidence of the
1034 beginnings of the shift towards prepared core (Levallois) dominated technologies (eg at Purfleet).

1035 14. **Seeing beneath the sea – Palaeolithic finds from Aggregate Area 240** 1036 *Peter Marshall, Historic England*

1037 Between December 2007 and February 2008 gravel extraction 11km off the coast of East Anglia in
1038 Aggregate License Area 240 (Fig 31) produced an important collection of Middle Palaeolithic
1039 artefacts (Fig 32): 88 worked flints, including 33 handaxes plus faunal remains including woolly
1040 mammoth and rhinoceros, bison, reindeer and horse (Tizzard *et al* 2014; 2015). The unweathered
1041 nature of many of the hand axes indicates they probably derived from an *in situ* or a near *in situ*
1042 context before being dredged from the seabed. Although prehistoric material has been recovered
1043 from the North Sea through fishing and dredging since the 1930s, the material from Area 240 came
1044 from a known areas (dredging lanes) within Area 240. Thus unlike the majority of chance finds, the
1045 Area 240 material offered the opportunity to establish the geological and geomorphological context
1046 of the material and provide an estimate of the age of the deposits.

1047 Area 240 is situated in the lower reaches of the Palaeo-Yare river system and for most of the last 1
1048 Ma it has been part of a coastal or inland environment due to lower sea-levels. Work funded by the
1049 ALSF between 2008 and 2011 included a re-examination of geophysical and geotechnical data, new
1050 geophysical survey of the area from which the artefacts and faunal remains came, together with
1051 coring of the deposits to obtain material for dating and for reconstructing past environmental
1052 conditions (Tizzard *et al* 2015; Fig 31). This information was combined with stratigraphic information
1053 provided by the sequences from the individual cores into a Bayesian chronological model (Fig
1054 **33Error! Reference source not found.**). The model suggest that Unit 3b, from which the majority of
1055 the artefactual and faunal material is thought to derive, dates to MIS7 or possibly the beginning of
1056 MIS 6 – with the beginning of deposition starting in *248–206 ka (68% probability; start_unit_3B; Fig*
1057 *34)* and finishing in *210–178 ka (68% probability; end_unit_3B; Fig 34)*.

1058 The material from Area 240 can now be considered within the corpus of archaeological sites dated
1059 to MIS 7 within the British Palaeolithic record (White *et al* 2006). The archaeological record of MIS 7
1060 is important as it represents the final phase of Middle Palaeolithic occupation of Britain prior to the
1061 hiatus of c 120 ka years between MIS 6–3 when hominins are completely absent.

1062 Bayesian chronological modelling of the OSL dates from Area 240 (Table 5) has allowed the key
1063 depositional unit that is thought to have contained the flint artefacts to be correlated with the
1064 sequence of MIS stages (most probably MIS 7); something that could not have been achieved
1065 without the dating programme. Together with other investigations undertaken in Area 240 (Tizzard
1066 *et al* 2014; 2015) the results confirmed that submerged landscapes have the potential to preserve *in*
1067 *situ* Middle Palaeolithic artefacts.

1068

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1069 15. Uranium-series dating – constraining the age of the Middle 1070 Palaeolithic tools and fauna from Pin Hole, Creswell, Derbyshire

1071 *Alistair Pike, University of Southampton*

1072 While in ideal circumstances Uranium-series (U-series) samples would be removed in the course of a
1073 controlled excavation, caves containing intact Pleistocene deposits are rare in England. Many
1074 archaeologically important caves were excavated in the 19th or early 20th century using now-
1075 outdated methods of excavation and recording. Age constraints for the museum collections resulting
1076 from these excavations, however, can be obtained if flowstones were left *in situ* in the cave and can
1077 now be sampled and related to the excavated material, or where flowstones were collected as part
1078 of the archaeological assemblage. The latter was the case for excavations in 1925 at Pin Hole,
1079 Creswell Crags, Nottinghamshire (Fig 35) where the excavator, Leslie Armstrong, collected stalactites
1080 and stalagmites (collectively known as speleothems) believing them to be tools (Armstrong 1932).
1081 The three-dimensional position of the bones and artefacts including the calcite, were recorded by
1082 Armstrong, allowing a reconstruction of the stratigraphy (Fig 36) into two units; an upper layer
1083 containing Upper Palaeolithic or Mesolithic flint blades and a lower layer containing Mousterian
1084 non-flint artefacts along with fauna including reindeer, spotted hyaena, woolly rhinoceros, and horse
1085 as well as datable speleothems (Jacobi *et al* 1998). The U-series ages (Table 6) are scattered,
1086 reflecting the variable ages of the speleothems before they became incorporated in the
1087 archaeological layer. However, the youngest age (64 ka) provides a maximum age (*terminus post*
1088 *quem*) for the fauna and Middle Palaeolithic artefacts with which they are associated, and also a
1089 maximum age for the archaeological assemblages in the level immediately above.

1090 This study was important because the maximum age of 64 ka supported the idea that humans were
1091 absent in Britain during the preceding interglacial (Ipswichian; MIS 5e) but returned at the end of
1092 MIS 4. Additionally, the distinctive fauna at Pin Hole, chronologically constrained by these U-series
1093 dates and additional ESR and radiocarbon dates, was critical in defining a stage in the formal
1094 mammalian biostratigraphy for the Late Pleistocene of Britain (Currant and Jacobi 2001).

1095 16. Neanderthals in Norfolk: Lynford Quarry

1096 *Peter Marshall and Zoe Outram, Historic England*

1097 In 2002 an archaeological watching brief at Lynford Quarry, Mundford, Norfolk revealed a
1098 palaeochannel with a dark organic fill containing *in situ* mammoth remains and associated
1099 Mousterian stone tools and debitage buried under 2–3m of bedded sands and gravels (Fig 37). Well-
1100 preserved *in situ* Middle Palaeolithic open-air sites are very unusual in Europe and exceedingly rare
1101 in England, and thus the site was recognized as of international importance and was subsequently
1102 investigated by the Norfolk Archaeological Unit (Boismier *et al* 2012).

1103 The palaeochannel and associated deposits containing archaeological remains were excavated and
1104 recorded at a detailed level to provide a range of spatial, palaeoenvironmental, and taphonomic
1105 information concerning deposit formation and the nature of human behaviour. The lithic
1106 assemblage was dominated by Mousterian tools (handaxes and bifacial scrapers) that are
1107 characteristic of the Late Middle Palaeolithic, c 59–38 ka. The handaxes were of a form frequently
1108 associated with Neanderthals and as such obtaining dating evidence for the human activity was vital
1109 to investigate fully questions of diet, land use, and habitat. Biostratigraphic evidence from the faunal

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1110 remains suggested that the site was older than 30 ka and probably older than c 41 ka, based on the
1111 known presence of woolly mammoths (*Mammuthus primigenius*), woolly rhinoceros (*Coelodonta*
1112 *antiquitatis*) and spotted hyena (*Crocuta crocuta*).

1113 The 17 OSL (Table 7; Schwenniger and Rhodes 2005) and eight radiocarbon dates (Table 8) obtained
1114 as part of geochronological investigations of the Lynford Quarry deposits (AAR analysis failed
1115 because of poor preservation of shells), have been incorporated into a Bayesian chronological model
1116 (Fig 38). Prior information about the relationship between samples is derived from direct
1117 stratigraphic relationships and the sedimentological model for the formation of the site.

1118 The model establishes a chronological framework for fluvial activity with the infilling of the channel
1119 (Association B) estimated to have started in 76–60 ka (95% probability; *First association_B*; Fig 38)
1120 and probably in 72–63 ka (68% probability). Fine-grained organic sediments continued to be
1121 deposited in the channel until 65–52 ka (95% probability; *OxL-1340*; Fig 38) and probably 62–54 ka
1122 (68% probability) when beds of laminated sands began to accumulate.

1123 Radiocarbon measurements from two mammoth bones recovered from the organic sediments of
1124 the Association B channel were close to the reliable limits of the technique (see **Radiocarbon Dating**)
1125 and suggest that the true age of the faunal material was probably in excess of 50 ka years – the
1126 model suggests that this is the case - and highlight one of the challenges faced when investigating
1127 Middle Palaeolithic sites; the earlier part of the period lies beyond the range of radiocarbon dating.
1128 The hominin activity recorded at Lynford can therefore be placed as occurring during late MIS 4
1129 and/or MIS 3 with Neanderthals re-occupying England after a long hiatus during the cold stage of
1130 MIS 4.

1131 17. Gransmoor, East Yorkshire – a precise chronology for environmental 1132 records

1133 *Peter Marshall, Historic England*

1134 The fill of a kettle-hole in a sand and gravel quarry at Gransmoor, East Yorkshire, revealed a 2.35m
1135 sequence of minerogenic and organic-rich sediments that had accumulated following ice-sheet
1136 wastage (Fig 39). Preserved pollen and beetle remains enabled a detailed reconstruction of
1137 environmental and climatic change during this period when the sediments formed (Walker *et al*
1138 1993). The stratigraphic record for the shift from cold ('glacial') to warm ('interglacial') conditions is
1139 of great importance as it provides a unique archive of how earth and atmospheric processes interact
1140 during a period when rapid climate change occurs. The record also provides a context for better
1141 understanding the relationship between climatic, environmental, and vegetation changes at the end
1142 of the Devensian glaciation.

1143 There are 25 radiocarbon measurements from Gransmoor, 19 AMS and six conventional
1144 measurements (Table 9), obtained on terrestrial macrofossils (15), wood (1), bulked aquatic plant
1145 macrofossils (4) and bulk sediment (5). The two results from 1.70m are statistically inconsistent
1146 ($T'=44.5$, $T'(5\%)=3.8$, $v=1$; Ward and Wilson 1978) and we have preferred the terrestrial macrofossil
1147 sample (AA-12004) over the humic fraction of the bulk sediment sample (SRR-3875) as providing the
1148 best estimate for the age of this horizon as the macrofossil date shows better agreement with the
1149 sequence (Blockley *et al* 2004). The four basal samples have elevated $\delta^{13}\text{C}$ values consistent with a
1150 hard-water reservoir effect which would make their dates anomalously old. These measurements

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1151 have therefore been excluded from the age-depth model produced using Bchron (Haslett and
1152 Parnell 2008) shown in Figure 40.

1153 Bchron is like other Bayesian age-depth modelling software - rBacon (Blaauw and Christen 2011) and
1154 OxCal (Bronk Ramsey 2008, Bronk Ramsey and Lee 2013) used to produce age estimates for all
1155 depths in a sequence by combining radiocarbon, or other scientific dates with prior information
1156 about their vertical relationships. Bchron differs from both rBacon and OxCal, however, in that
1157 variability in accumulation rates cannot be controlled by the user. Its approach is based on the
1158 assumption that the accumulation rate changes, even though it may be by a very small degree, at
1159 each depth where a radiocarbon date exists.

1160 Unlike previous attempts to produce age-depth models for Gransmoor using OxCal (Blockley *et al*
1161 2004; Elias and Matthews 2013) no radiocarbon dates, apart from those with a hard water offset,
1162 have been excluded from the initial Bchron model. Bchron has sophisticated methods of handling
1163 misfits - dates that lie well beyond the standard age-depth relationship – and outliers – those that
1164 require only a small shift to come into line (Parnell *et al* 2011). Outlier probabilities are given in Table
1165 10 and reflect the weight each measurement is given in the model.

1166 Producing an age-depth model is often the first step towards estimating the age of ‘events’
1167 identified in proxy records that have not been directly dated at specific depths in a sediment
1168 sequence. For example, a feature of the pollen record from Gransmoor is the decline and
1169 subsequent recovery of *Betula* sp. (birch) values that follow an initial abrupt rise for the genus. The
1170 decline from 50% to below 20% Total Land Pollen in less than 100mm can be estimated from the
1171 age-depth model to have taken place between *13,340–13,250 cal BP (95% probability; Fig 41, left)*
1172 *and 13,250–13,130 cal BP (95% probability; Fig 41, right)*. The age-depth model can also be used to
1173 provide a chronology for the Late Glacial temperature changes derived from the beetle remains (Fig
1174 42).

1175 The sequence provided by stratigraphy at Gransmoor provides strong prior beliefs for the
1176 construction of the age-depth model and highlights the effectiveness of relative dating in the
1177 construction of Bayesian models.

1178

1179 PART 4 – PRACTICALITIES

1180

1181 18. Project Organisation and Planning

1182 *Peter Marshall, Historic England*

1183 Government guidance set out in the National Planning Policy Framework (NPPF) (Department for
1184 Communities and Local Government 2012) enshrines the principle of sustainable development in the
1185 planning process. Where archaeological projects are commissioned to inform the planning process
1186 the information sought should be proportionate to the significance of the heritage asset and the
1187 potential impacts of the proposed development. Assessments of heritage assets in advance of
1188 determinations of planning applications should therefore be sufficient to provide an understanding
1189 of the significance of heritage assets and their settings affected either directly or indirectly by the
1190 development proposals (eg desk based assessment or field evaluation where appropriate).

1191

1192 18.1 Specifications/briefs

1193 These guidelines are applicable to all archaeological projects, but are aimed primarily at those
1194 undertaken as part of the planning process. Providing an accurate price for dating as part of projects
1195 with a Pleistocene component that do not adhere strictly to management principles, such as those
1196 outlined in MoRPHE (Lee 2015; Table 11), is inherently problematic and therefore the identification
1197 of ‘contingency funds’ in overall budgets should be encouraged.

1198

1199 For Pleistocene sites scientific dating can be expected to form an important part of any project and
1200 consequently specification of a fixed percentage of the overall tender for ‘scientific contingency’
1201 (Brunning and Watson 2010) that could be spent on dating, for example, would be prudent. The use
1202 of the contingency would only take place following approval by the curator of costs resulting from
1203 the assessment. If following assessment the requirements for scientific dating are not as extensive as
1204 envisaged, then funds from the contingency budget would not be required. A practice such as this
1205 would encourage contractors to submit realistic tenders and thus avoid the tendency for very low
1206 post-excavation costs in project budgets.

1207

1208 Strategies for dating Pleistocene sites should be included in Project Designs and Written Schemes of
1209 Investigation. Definitions of briefs, specifications and project designs can be found in the Association
1210 of County Archaeological Officers’ (1993) *Model Briefs and Specifications for Archaeological*
1211 *Assessments and Field Evaluations* and the ClfA’s Standard and Guidance series (2014a–d; 2017a–b).

1212

1213 Curators who need further advice on the potential for using scientific dating on specific Pleistocene
1214 sites can obtain independent non-commercial advice from Historic England (see Appendix 1). Where
1215 advice is obtained from a commercial contractor, it is the responsibility of the commissioning body
1216 to ensure that vested interests are openly declared and that subsequent competition is fair (ClfA
1217 2014e).

1218

1219 Specifications and briefs should ask for scientific dating on Pleistocene sites to be carried out in
1220 accordance with these guidelines and as such written assurances to such an effect can be expected
1221 in Project Designs and Written Schemes of Investigation. Named specialists should be included in
1222 such documents and curators should, if necessary, ask for details of relevant experience (published
1223 papers, reports, etc) given there is no formal means of accreditation.

1224

1225 Full use should be made of all available sources of information on scientific dating potential when
1226 planning archaeological projects. Chronology is the framework for understanding all archaeological
1227 sites, particularly those from the Pleistocene and therefore the construction of reliable chronologies

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1228 should form an integral part of the initial project specification. It should not be simply seen as a
1229 contingency or luxury.

1230

1231 18.2 Desk-top assessment

1232 The purpose, definition, and standards for desk-based assessment are given in ClfA (2014c).

1233 Specialists can contribute to desk-top assessments with information and evaluation of existing

1234 scientific dating evidence from previous investigations should they exist and the potential for

1235 scientific dating to contribute to the aims and objectives of the project. Such information can be

1236 used in order to help determine the location of interventions, and appropriate sampling strategies.

1237

1238 18.3 Watching briefs

1239 The purpose, definition, and standard for watching briefs is given in ClfA (20017a). Scientific dating

1240 undertaken on samples obtained during watching briefs would only be expected in exceptional

1241 circumstances (eg completely unexpected archaeological finds).

1242

1243 18.4 Evaluation

1244 The purpose, definition, and standard for evaluations are given in ClfA (2014d). In order to

1245 understand the nature of the archaeological resource evaluations are undertaken to inform

1246 decisions on planning and mitigation strategies. In some situations an evaluation might be the only

1247 intervention undertaken. Scientific dating as part of evaluations may therefore form an important

1248 contribution to an understanding of the potential significance of the Pleistocene archaeological

1249 resource.

1250

1251 Examples of the types of questions scientific dating might be used to answer as part of evaluations

1252 include:

1253

- 1254 • What is the age of unexpected discoveries;
- 1255 • What is the age of deposits; and
- 1256 • What is the date of archaeological remains?

1257

1258 18.5 Excavation

1259 Full excavation not only presents better opportunities for the recovery of samples (eg Campbell *et al*

1260 2011) for scientific dating but more importantly for better understanding their context. Samples

1261 should ideally be retrieved by the appropriate specialist and if this is not feasible specific advice

1262 should be sort with regard to sampling methods and storage of samples.

1263

1264 18.6 Assessment

1265 Scientific dating is not a technique that falls within the typical procedures for the assessment of

1266 archaeological potential (eg environmental remains). As a minimum the following information is

1267 required by the specialist to carry out an assessment:

1268

- 1269 • Brief account of the nature and history of the site;
- 1270 • Aims and objectives of the project;
- 1271 • Summary of the archaeological results;
- 1272 • Context types and stratigraphic relationships;
- 1273 • Sample locations;
- 1274 • Assessment reports from other relevant specialists; and
- 1275 • An idea of the project timetable and budget

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1277 The primary aim of the assessment will be to ascertain the potential of the samples to address the
1278 aims and objectives of the project.

1279

1280 The assessment report should contain:

1281

- 1282 • Aims and objectives of the project to which scientific dating can contribute;
- 1283 • Specialist chronological aims and objectives;
- 1284 • Summary of potential samples;
- 1285 • Summary of potential samples to be assessed for samples suitable for dating;
- 1286 • Statement of potential – how scientific dating can contribute to site, specialist, and wider
1287 research questions;
- 1288 • Recommendations for further work, including for full analysis if applicable; and
- 1289 • Tasks, time, and outline costings for future work (analysis and publication)

1290

1291 Given the potential expense of scientific dating programmes a staged-approach may be appropriate.

1292

1293 18.7 Post-excavation Analysis

1294 Scientific dating should have been planned and, as a minimum, outline costs provided while
1295 preparing the updated project design. Scientific dating specialists will need to work closely with
1296 other specialists at all stages of the analysis stage.

1297

1298 A full report should be provided in accordance with specific guidance where it exists, eg for
1299 luminescence (Duller 2008, §9).

1300

1301 18.8 Dissemination and archiving

1302 *Historic Environment Record (HER)*

1303 In accordance with current best practice reports on any archaeological intervention, even if only an
1304 evaluation, should be deposited with the local HER as quickly as possible following completion.
1305 Chronological information may form a component of these reports and results from scientific dating
1306 methods should be recorded on Historic Environment Records.

1307

1308 *Publication*

1309 Where possible the final reports on scientific dating should be included in the main body of the
1310 publication of a project (including in electronic supplementary information where this facility is
1311 available). As it may not always be feasible to integrate individual scientific reports with the full site
1312 publication, it might be appropriate for alternative publications in, for example, archaeological
1313 science or other specialist journals.

1314

1315 *Archiving*

1316 All scientific dating reports should be included in the material deposited with the archival body, in
1317 accordance with their standards. For published overall guidelines on archive deposition see Brown
1318 (2007), Longworth and Wood (2000), Museums and Galleries Commission (1992), Walker (1990),
1319 and Archaeological Data Service (2015) and Archaeological Data Service and Digital Antiquity (2011).

1320

1321 Samples suitable for further dating are usually contained with the rest of the physical archive (eg
1322 bones, shells, etc) and do not require specialist archiving. They should be packaged and stored in
1323 accordance with current best practice. The general lack of long-term storage for soil and sediment
1324 samples means that in some circumstances sub-sampling for cold storage may need to be
1325 considered, although this has potential complications for radiocarbon dating of waterlogged plant
1326 macrofossils (Wohlfar *et al* 1998).

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1327 19. Laboratories

1328 *Michael Grant, University of Southampton*

1329 An essential part of the successful application of any dating strategy is early discussion between the
1330 field project director and the specialist undertaking the analysis. Contact details of laboratories in
1331 the United Kingdom that are equipped to undertake the types of dating discussed within this
1332 guidance are given below. Note that not all laboratories undertake all forms of analysis nor do they
1333 all provide commercial services. Under each technique, the laboratories are listed in alphabetical
1334 order based upon their location or commercial name. Details were correct at the time of writing.

1335 Radiocarbon Dating

1336 TO BE ADDED FOLLOWING CONSULTATION

1337 Uranium-Thorium Dating

1338 U-Th dating facilities are fairly common in universities with large geochemistry, oceanography or
1339 geology departments. SUERC also provide a commercial service:

1340 Radiogenic Laboratory, Scottish Universities Environmental Research Centre Rankine Avenue,
1341 Scottish Enterprise Technology Park, East Kilbride G75 0QF telephone: 01355 2233320 e-
1342 mail: director@suerc.gla.ac.uk
1343 website: <https://www.gla.ac.uk/research/az/suerc/researchthemes/isotopegeoscience/radiogenic/>

1344 The Natural Environmental Research Council (NERC) offer U-Th dates as grants-in-kind to individuals
1345 who are eligible for NERC training or research grants:

1346 BGS Geochronology and tracers facility, British Geological Survey, Environmental Science Centre,
1347 Nicker Hill, Keyworth, Nottingham, NG12 5GG telephone: 0115 936 3425 e-mail: bullock@bgs.ac.uk
1348 website: <https://www.bgs.ac.uk/sciencefacilities/laboratories/geochemistry/gtf/home.html>

1349 Luminescence Dating

1350 Aberystwyth

1351 Aberystwyth Luminescence Research Laboratory, Department of Geography and Earth Sciences
1352 Aberystwyth University Ceredigion SY23 3DB telephone: 01970 622611 e-mail: ggd@aber.ac.uk
1353 website: <https://www.aber.ac.uk/en/dges/research/quaternaly/luminescence-research-laboratory/>

1354 Cheltenham

1355 Luminescence Dating Laboratory, School of Natural & Social Sciences, University of Gloucestershire
1356 Swindon Road, Cheltenham GL50 4AZ telephone: 01242 714708 e-mail: ptoms@glos.ac.uk
1357 website: www.glos.ac.uk/luminescence

1358 Durham

1359 Luminescence Dating Laboratory, Department of Archaeology, Durham University, South Road,
1360 Durham, DH1 3LE telephone: 0191 3341100 e-mail: ian.bailiff@durham.ac.uk
1361 website: https://www.dur.ac.uk/archaeology/facilities_services/laboratories/136/

1362

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- 1363 Liverpool
- 1364 Liverpool Luminescence Laboratory, Department of Geography, Roxby Building, University of
1365 Liverpool, Liverpool L69 7ZT telephone: 0151 7942850 e-mail: rachel.smedley@liverpool.ac.uk
1366 website: [https://www.liverpool.ac.uk/geography-and-planning/research/environmental-
1367 change/facilities/osl/](https://www.liverpool.ac.uk/geography-and-planning/research/environmental-change/facilities/osl/)
- 1368 Oxford
- 1369 Oxford Authentication Ltd Doreen Stoneham Oxford Authentication Ltd Boston House, Grove
1370 Technology Park Wantage Oxfordshire, OX12 9FF telephone: 01235 770998 e-
1371 mail: info@oxfordauthentication.com website: www.oxfordauthentication.com
- 1372 Oxford Luminescence Dating Laboratory, OUCE / Dyson Perrins Building, University of Oxford, South
1373 Parks Road, Oxford, OX1 3QY telephone: 01865 285085 e-mail: richard.bailey@ouce.ox.ac.uk
1374 website: www.ouce.ox.ac.uk/research/aridenvironments/old
- 1375 Royal Holloway
- 1376 Optically Stimulated Luminescence Laboratory, Department of Geography Royal Holloway Egham,
1377 Surrey TW20 0EX telephone: 01784 276124 e-mail: simon.armitage@rhul.ac.uk
1378 website: [https://www.royalholloway.ac.uk/research-and-teaching/departments-and-
1379 schools/geography/about-us/research-and-teaching-facilities/](https://www.royalholloway.ac.uk/research-and-teaching/departments-and-schools/geography/about-us/research-and-teaching-facilities/)
- 1380 Sheffield
- 1381 Sheffield Luminescence Dating Laboratory, Department of Geography, The University of Sheffield
1382 Sheffield, S10 2TN telephone: 0114 222 7929 e-mail: M.D.Bateman@Sheffield.ac.uk
1383 website: <https://www.sheffield.ac.uk/geography/facilities/luminescence-dating>
- 1384 SUERC
- 1385 Luminescence Research Laboratory, Scottish Universities Environmental Research Centre, Rankine
1386 Avenue, Scottish Enterprise Technology Park, East Kilbride, G75 0QF. telephone: 01355 270110 e-
1387 mail: D.Sanderson@suerc.gla.ac.uk
1388 website: [https://www.gla.ac.uk/research/az/suerc/researchthemes/radiometricenvironmentalche-
1389 mistry/luminescence/](https://www.gla.ac.uk/research/az/suerc/researchthemes/radiometricenvironmentalchemistry/luminescence/)
- 1390 St Andrews
- 1391 School of Geography & Geosciences, Irvine Building, University of St Andrews, North Street, St
1392 Andrews, Fife, KY16 9AL telephone: 01334 46 3940 e-mail: earthsci@st-andrews.ac.uk
1393 website: <https://www.st-andrews.ac.uk/earth-sciences/research/facilities/>
- 1394 Amino acid racemization (AAR)
- 1395 NEaar: North East Amino Acid Racemization, Department of Chemistry, University of York,
1396 Heslington, York, YO10 5DD telephone: 01904 322574 e-mail: kirsty.penkman@york.ac.uk
1397 website: <https://www.york.ac.uk/palaeo/services/ne-aar/>

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- 1398 Tephrochronology
- 1399 Chemical analysis of tephra shards is undertaken using an Electron Probe Microanalyzer (EPMA) for
- 1400 major elements and either Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-
- 1401 ICPMS) or Secondary Ion Mass Spectrometry (SIMS) for trace elements.
- 1402 Aberystwyth (LA-ICPMS)
- 1403 Department of Geography and Earth Sciences Aberystwyth University Ceredigion SY23 3DB
- 1404 telephone: 01970 622611 e-mail: ggd@aber.ac.uk
- 1405 website: <https://www.aber.ac.uk/en/dges/research/quaternary/tephro/>
- 1406 Cambridge (EPMA)
- 1407 Cambridge tephra laboratory, Department of Geography, University of Cambridge, Downing Place,
- 1408 Cambridge CB2 3EN telephone: 01223 330242 e-mail: christine.lane@geog.cam.ac.uk
- 1409 website: <https://www.geog.cam.ac.uk/facilities/laboratories/facilities/cambridgetephralab.html>
- 1410 Edinburgh (SIMS, EPMA and LA-ICPMS)
- 1411 Tephra Analysis Unit (TAU), School of GeoSciences, Grant Institute, James Hutton Road, University of
- 1412 Edinburgh, Kings Buildings, West Mains Road, Edinburgh. EH9 3FE telephone: 0131 650 5827 e-
- 1413 mail: Chris.Hayward@ed.ac.uk website: <https://www.ed.ac.uk/geosciences/facilities/tephra>
- 1414 London (EPMA)
- 1415 The Natural History Museum, Cromwell Road, London SW7 5BD telephone 020 7942 5000 e-
- 1416 mail: j.spratt@nhm.ac.uk website: [https://www.nhm.ac.uk/our-science/departments-and-](https://www.nhm.ac.uk/our-science/departments-and-staff/core-research-labs/imaging-and-analysis/microanalysis.html)
- 1417 [staff/core-research-labs/imaging-and-analysis/microanalysis.html](https://www.nhm.ac.uk/our-science/departments-and-staff/core-research-labs/imaging-and-analysis/microanalysis.html)
- 1418 Royal Holloway (LA-ICPMS)
- 1419 Earth Sciences, Royal Holloway, University of London, Egham, Surrey, TW20 0EX telephone: 01784
- 1420 443835 e-mail: C.J.Manning@rhul.ac.uk website: [https://www.royalholloway.ac.uk/research-and-](https://www.royalholloway.ac.uk/research-and-teaching/departments-and-schools/earth-sciences/research/research-laboratories/laser-ablation-icpms-laboratory/)
- 1421 [teaching/departments-and-schools/earth-sciences/research/research-laboratories/laser-ablation-](https://www.royalholloway.ac.uk/research-and-teaching/departments-and-schools/earth-sciences/research/research-laboratories/laser-ablation-icpms-laboratory/)
- 1422 [icpms-laboratory/](https://www.royalholloway.ac.uk/research-and-teaching/departments-and-schools/earth-sciences/research/research-laboratories/laser-ablation-icpms-laboratory/)
- 1423 Oxford (EPMA)
- 1424 Research Laboratory for Archaeology and the History of Art, School of Archaeology, 1 South Parks
- 1425 Road, Oxford OX1 3TG telephone: 01865 285202 e-mail: victoria.smith@arch.ox.ac.uk
- 1426 website: [https://archit.web.ox.ac.uk/tephrochronology-and-electron-microprobe-commercial-](https://archit.web.ox.ac.uk/tephrochronology-and-electron-microprobe-commercial-services)
- 1427 [services](https://archit.web.ox.ac.uk/tephrochronology-and-electron-microprobe-commercial-services)
- 1428 Palaeomagnetism
- 1429 Edinburgh
- 1430 Rock and Palaeomagnetic Research Group, School of Geosciences, University of Edinburgh, Grant
- 1431 Institute, The King's Buildings, West Mains Road, Edinburgh EH9 3FE telephone: 0131-650-8510 e-
- 1432 mail: info@geos.ed.ac.uk
- 1433 website: <https://www.geos.ed.ac.uk/research/subsurface/palaeomagnetism/pmag.html>

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- 1434 Lancaster
- 1435 Lancaster University, Centre for Environmental Magnetism and Palaeomagnetism (CEMP), Lancaster
1436 Environment Centre, Lancaster University, Lancaster, LA1 4YQ telephone: 01524 510268 e-mail:
1437 b.maher@lancaster.ac.uk
- 1438 Liverpool
- 1439 Quaternary Environmental Change Laboratories, Department of Geography & Planning, University of
1440 Liverpool, Roxby Building, Liverpool, L69 7ZT telephone: 0151 794 3461 e-mail:
1441 Elliot.Hurst@liverpool.ac.uk website: [https://www.liverpool.ac.uk/geography-and-](https://www.liverpool.ac.uk/geography-and-planning/research/environmental-change/facilities/environmental-material-characterisation/)
1442 [planning/research/environmental-change/facilities/environmental-material-characterisation/](https://www.liverpool.ac.uk/geography-and-planning/research/environmental-change/facilities/environmental-material-characterisation/)
- 1443 Geomagnetism Laboratory, Department of Earth, Ocean and Ecological Sciences, University of
1444 Liverpool, Jane Herdman Building, 4 Brownlow Street, Liverpool, L69 3GP telephone: 0151 794 3460
1445 e-mail: maglab@liv.ac.uk website: [https://www.liverpool.ac.uk/earth-ocean-and-ecological-](https://www.liverpool.ac.uk/earth-ocean-and-ecological-sciences/research/earth-sciences/geomagnetism/)
1446 [sciences/research/earth-sciences/geomagnetism/](https://www.liverpool.ac.uk/earth-ocean-and-ecological-sciences/research/earth-sciences/geomagnetism/)
- 1447 London
- 1448 Palaeomagnetism Laboratory, Department of Earth Science and Engineering, Imperial College
1449 London, South Kensington Campus, London SW7 2AZ telephone: 020 7594 6442 e-mail:
1450 adrian.muxworthy@imperial.ac.uk website: [http://www.imperial.ac.uk/earth-](http://www.imperial.ac.uk/earth-science/research/research-groups/natural-magnetism-group/)
1451 [science/research/research-groups/natural-magnetism-group/](http://www.imperial.ac.uk/earth-science/research/research-groups/natural-magnetism-group/)
- 1452 Oxford
- 1453 Palaeomagnetism and Rock Magnetism Group, Department of Earth Sciences, South Parks Road,
1454 Oxford OX1 3AN telephone: 01865 272000 e-mail: enquiries@earth.ox.ac.uk
1455 website: <https://www.earth.ox.ac.uk/research-groups/palaeomagnetism-and-rock-magnetism/>
- 1456 Southampton
- 1457 Palaeomagnetism and Environmental Magnetism Laboratory, Ocean and Earth Science, National
1458 Oceanography Centre Southampton, University of Southampton, European Way, Southampton,
1459 SO14 3ZH telephone: 0 23 8059 6401 e-mail: C.Xuan@soton.ac.uk
1460 website: <https://www.southampton.ac.uk/oes/research/facilities.page>
- 1461 **20. Advice and Information**
- 1462 **A: Historic England**
- 1463 The first point of contact for general archaeological science enquiries, including those relating to
1464 scientific dating and Bayesian chronological modelling, within Historic England should be the Historic
1465 England science advisors, who can provide independent, non-commercial advice. They are based in
1466 the Historic England local offices.
- 1467 For contact details see [https://historicengland.org.uk/advice/technical-advice/archaeological-](https://historicengland.org.uk/advice/technical-advice/archaeological-science/science-advisors/)
1468 [science/science-advisors/](https://historicengland.org.uk/advice/technical-advice/archaeological-science/science-advisors/)

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1469 Specific advice on scientific dating and Bayesian chronological modelling can be sought from the
1470 Historic Scientific Dating Team (Alex Bayliss, Shahina Farid, Peter Marshall, and Cathy Tyers).

1471 Historic England
1472 Cannon Bridge House
1473 25 Dowgate Hill
1474 London EC4R 2YA

1475
1476 Email: alex.bayliss@historicengland.org.uk
1477 Mobile: 07584 522 333

1478
1479 Email: shahina.farid@historicengland.org.uk
1480 Mobile: 07754 776 230

1481
1482 Email: peter.marshall@historicengland.org.uk
1483 Mobile: 07584 522 816

1484
1485 Email: cathy.tyers@historicengland.org.uk
1486 Mobile: 07825 023 620

1487

1488 B. Scientific Dating Laboratories

1489 All laboratories will be happy to advise on the technical aspects of applying their technique to
1490 Pleistocene deposits, including the retrieval and selection of suitable samples, suitable storage and
1491 packaging, and the methods of sample preparation and dating used in their facility.

1492 Laboratories put a great deal of skill and effort into dating the samples sent to them accurately, they
1493 thus welcome the opportunity to provide guidance on sample selection to ensure that together you
1494 provide the best dating possible for your samples.

1495

1496 C. On-line Resources

1497

1498 Radiocarbon Datelists

1499 An Index to Radiocarbon Dates from Great Britain and Ireland can be found
1500 at https://archaeologydataservice.ac.uk/archives/view/c14_cba/. It contains basic information on
1501 more than 15,000 radiocarbon measurements. It was originally compiled by Cherry Lavell for the
1502 Council for British Archaeology and it comprehensive until 1982, with some later additions in 1991
1503 and 2001. Between 2007 and 2012 the index was updated with details of the measurements
1504 included in the Gathering Time project (Whittle *et al* 2011), and with measurements funded by
1505 English Heritage before 1993.

1506

1507 More comprehensive details of measurements funded by English Heritage can be found in the series
1508 of volumes of Radiocarbon Dates that are freely downloadable
1509 from <http://www.historicengland.org.uk/publications> (available as print-on-demand hard copy).

1510

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1511 Details of many of the measurements undertaken by the Oxford Radiocarbon Accelerator Unit can
1512 be found in their on-line database at <http://c14.arch.ox.ac.uk/results>, and published in a series of
1513 datelists in the journal *Archaeometry*.

1514

1515 Other datelists, particularly for measurements undertaken before c. 1980, can be found in the
1516 journal *Radiocarbon* (<https://www.cambridge.org/core/journals/radiocarbon>).

1517

1518 **Palaeomagnetism**

1519 GEOMAGIA50 - database providing access to published archeomagnetic/volcanic and sediment
1520 paleomagnetic and chronological data for the past 50 ka, available on-line at [http://geomagia.gfz-](http://geomagia.gfz-potsdam.de/)
1521 [potsdam.de/](http://geomagia.gfz-potsdam.de/)

1522 PINT – the Absolute Palaeointensity (PINT) Database is a catalogue all absolute palaeointensity data
1523 with ages > 50 ka which have been published in the peer-reviewed literature. It is available
1524 at <http://earth.liv.ac.uk/pint/>

1525 MagIC – Magnetic Information Consortium (MagIC) is an open community digital data archive for
1526 rock and paleomagnetic data. It is available at <https://www2.earthref.org/MagIC>

1527 **Tephrochronology**

1528 Resources containing geochemical data associated with tephra are available online. No single
1529 resource is completely comprehensive and access to original published datasets, such as within
1530 journal articles, is often required to supplement these resources.

1531

1532 RESET - Derived from the 'Response of Humans to Abrupt Environmental Transitions' (RESET)
1533 project, a database has been made available containing information on occurrences, and chemical
1534 compositions, of glass shards from tephra and cryptotephra deposits found across Europe. The data
1535 includes both information from the RESET project itself and from the published literature. In addition
1536 to this data, it also contains a series of tools for the analysis of this data, including statistical
1537 approaches to evaluate the likelihood of tephra compositions matched. The database is available
1538 at <http://c14.arch.ox.ac.uk/reset/>; described in Bronk Ramsey *et al* (2015b)

1539

1540 EarthChem - a community driven project facilitating the compilation and dissemination of
1541 geochemical data of all types, including tephra. It is a global database and therefore has much
1542 broader coverage than RESET (<https://www.earthchem.org/>)

1543

1544 GVP – The Smithsonian Institution's Global Volcanism Program (GVP) contains a comprehensive
1545 database of global volcanic activity, cataloguing Holocene and Pleistocene volcanoes, and eruptions
1546 from the past 10,000 years (<https://volcano.si.edu/>)

1547

1548 **Radiocarbon Calibration Databases**

1549

1550 The calibration curves that are currently internationally agreed are available from
1551 (<http://www.radiocarbon.org/>); and the data included in them is available from
1552 (<http://intcal.qub.ac.uk/intcal13/about.html>)

1553

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1554 A database of marine reservoir values is provided by the ¹⁴CHRONO Centre, Queen's University,
1555 Belfast (<http://calib.qub.ac.uk/marine/>).

1556

1557 **Relevant Software**

1558

1559 A variety of freely-downloadable software is available for radiocarbon calibration and Bayesian
1560 chronological modelling of radiocarbon and other scientific dates. Some packages allow a wide range
1561 of models to be constructed, others are more specialised.

1562

1563 **(a) Calibration**

1564

1565 Calib – on-line and downloadable versions available from <http://calib.qub.ac.uk/calib/>; described in
1566 Stuiver and Reimer (1993).

1567

1568 **(b) Flexible Bayesian Chronological Modelling**

1569

1570 BCal – on-line program available at <http://bcal.shef.ac.uk/>; described in Buck *et al* (1996; 1999).

1571

1572 OxCal – on-line and downloadable versions available from <https://c14.arch.ox.ac.uk/OxCal/>;
1573 described in Bronk Ramsey (1995, 1998, 2001, 2008, 2009a–b), Bronk Ramsey *et al* (2001; 2010), and
1574 Bronk Ramsey and Lee (2013).

1575

1576 ChronoModel – downloadable versions available from [https://chronomodel.com/download-
1577 chronomodel-software-mac-windows](https://chronomodel.com/download-chronomodel-software-mac-windows); described in Lanos and Phillippe (2015, 2017, 2018).

1578

1579 **(c) Specialist Bayesian Chronological Modelling**

1580

1581 rbacon – downloadable software for flexible Bayesian age-depth modelling, which runs in the R
1582 software environment (<http://www.r-project.org/>), available from [http://cran.r-
1583 project.org/web/packages/rbacon/index.html](http://cran.r-project.org/web/packages/rbacon/index.html); described in Blaauw and Christen (2011).

1584

1585 Bchron – downloadable program with routines for age-depth modelling and relative sea-level rate
1586 estimation, which runs in the R software environment (<http://www.r-project.org/>), available
1587 from <http://cran.r-project.org/web/packages/Bchron/index.html>; described in Haslett and Parnell
1588 (2008) and Parnell and Gehrels (2015).

1589

1590 **(d) Geochronology**

1591 IsoplotR– includes functions for U-Pb, Pb-Pb, ⁴⁰Ar/³⁹Ar, Rb-Sr, Sm-Nd, Lu-Hf, Re-Os, U-Th-He, fission
1592 track and U-series disequilibrium dating. IsoplotR is programmed in R and can be run (1) online, via a
1593 Graphical User Interface (GUI) that runs in a web browser on any internet-connected device; (2)
1594 offline, natively running the GUI on any computer that has R installed on it; and (3) from the
1595 command line, which allows IsoplotR to be extended and incorporated into automation scripts,
1596 available from <https://www.ucl.ac.uk/~ucfbpve/isoplotr/>; described in Vermeesch (2018)

1597

1598

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1599 **(e) Luminescence dating**

1600 DRAC – an online Dose Rate and Age Calculator (DRAC) designed to calculate environmental dose
1601 rates (\dot{D}) and ages for trapped charge dating applications. The calculations are applicable to both
1602 optically stimulated luminescence (OSL) and thermoluminescence (TL) dating and may also be useful
1603 in some electron spin resonance (ESR) applications. DRAC provides a standardised \dot{D} calculator with
1604 transparent calculation using published input variables. It is an effective means of removing the
1605 potential for miscalculation, allowing improved assessment of \dot{D} calculations and simpler inter-
1606 laboratory \dot{D} comparisons. It is available
1607 from [https://www.aber.ac.uk/en/dges/research/quaternary/luminescence-research-](https://www.aber.ac.uk/en/dges/research/quaternary/luminescence-research-laboratory/dose-rate-calculator/)
1608 [laboratory/dose-rate-calculator/](https://www.aber.ac.uk/en/dges/research/quaternary/luminescence-research-laboratory/dose-rate-calculator/); described in Durcan *et al* (2015)

1609
1610 Analyst - a Windows based program designed to view, edit and analyse luminescence data collected
1611 using a Risø automated TL/OSL reader, though other instruments may also generate datafiles that
1612 are compatible. It is available from <http://users.aber.ac.uk/ggd/>; described in Duller (2007; 2015)

1613

1614 **(g) Palaeomagnetism**

1615 Palaeomag-Tools – downloadable software for the analysis and presentation of directional data
1616 applicable to palaeomagnetism, geomagnetism and archaeomagnetism. It is available from
1617 <https://www.lancaster.ac.uk/staff/hounslow/resources/software/pmagtool.htm>

1618

1619 Matlab Tool for Archaeomagnetic dating – permits archaeomagnetic direction (declination and/or
1620 inclination) and the archaeointensity obtained from the archaeological artefact to be compared with
1621 a master palaeosecular variation curves (PSVC). The master PSVCs included with the Matlab tool are
1622 the different European Bayesian curves and those generated using both regional and global
1623 geomagnetic field models. It is available from http://pc213fis.fis.ucm.es/archaeo_dating/index.html
1624 and described in Pavón-Carrasco *et al* (2011)

1625

1626 CPLSlot – downloadable software for the correlation between ordered successions of continuous or
1627 semi-continuous data, such as geochemical data (eg isotopes), fossil abundance data (eg pollen), and
1628 directional data (eg palaeomagnetic data). It is available
1629 from <https://www.lancaster.ac.uk/staff/hounslow/resources/software/cplslot.htm>

1630

1631 **(f) Tephrochronology**

1632 GCDkit – the GeoChemical Data ToolKIT is a system for handling and recalculation of whole-rock
1633 analyses from igneous rocks, suitable for tephra-derived geochemical data, which runs in the R
1634 software environment (<http://www.r-project.org/>)// It is available from <http://www.gcdkit.org/>;
1635 described in Janoušek *et al* (2006).

1636

1637 TAS Diagram Plotter v2.0 – an Excel spreadsheet that allows fast plotting onto a TAS (total alkali
1638 silica) diagram for use differentiating tephra by chemical composition. It is available from
1639 <http://www.kaylaiacovino.com/tools-for-petrologists/>

1640

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1641 21. Glossary

1642 **Accelerator Mass Spectrometry (AMS)** counting atoms by accelerating ions in a sample to very high
1643 speeds and then separating the isotopes using powerful electric charges and magnets

1644 **Accuracy** one component of uncertainty, expresses how close a measurement comes to the true
1645 value

1646 **Alluvial** made up of or found in the materials deposited by running water, such as streams, rivers,
1647 and flood waters

1648 **Amino Acid** a simple organic compound containing both a carboxyl (—COOH) and an amino (—NH_2)
1649 group

1650 **Archaeostratigraphy** branch of stratigraphy concerned with artefacts types that are characteristic of
1651 a certain part of the typological sequence, allowing the separation (and correlation) of stratigraphic
1652 layers into approximate time periods

1653 **Acheulian biface** a techno complex of stone-tool manufacture characterised by distinctive oval and
1654 pear-shaped 'hand axes'.

1655 **Bayesian statistics** branch of statistics in which evidence about the true state of the world is
1656 expressed in terms of degrees of belief

1657 **Bayes' Theorem** express the relationship between prior and current beliefs

1658 **Biomineral** A mineral produced by the activity of living things

1659 **Biostratigraphy** branch of stratigraphy concerned with fossils and their use in dating sedimentary
1660 deposits

1661 **Cenozoic:** last Era of the Phanerozoic Eon, beginning at the end of the Mesozoic Era (end of
1662 Cretaceous period) c 65 Ma, divided into three periods: Paleogene (c 65–23 Ma); Neogene (c 23–2.6
1663 Ma) and Quaternary (c 2.6 Ma to present)

1664 **Chronology** the science of arranging events in their order of occurrence in time

1665 **Chronostratigraphy** branch of geology concerned with establishing the absolute ages of strata

1666 **Clactonian** an industry of European flint tool manufacture from bifacially working a flint core that
1667 dates from the early part of the Hoxnian.

1668 **Climatic optimum** period of highest prevailing temperatures within an interglacial

1669 **Cosmic ray** a highly energetic atomic nucleus or other particle travelling through space at a speed
1670 approaching that of light

1671 **Cretaceous** last period of the Mesozoic era, starting at the end of the Jurassic period c 145 Ma and
1672 ending at the beginning of the Paleogene period 65 Ma

1673 **Croll–Milankovitch cycle** describes orbital forcing through variations in eccentricity, axial tilt, and
1674 precession of the Earth's orbit upon the climatic patterns on Earth

1675 **Cryptotephra** volcanic ash layers invisible to the naked eye and usually comprising grains less than
1676 $125\mu\text{m}$ in size

1677 **Curie temperature (Curie point)** on heating, the temperature above which a material loses its
1678 ferromagnetic properties. The blocking temperature of a particular mineral is related to its Curie
1679 temperature but may be lower owing to such considerations as chemical impurities, crystal size and
1680 shape. Named after Pierre Curie (1859–1906)

1681 **Dansgaard–Oeschger cycles** describes rapid climate fluctuations that occurred during the last glacial
1682 (Devensian) period

1683 **Declination** the angle in the horizontal plane between the geographic north and the projection of
1684 the magnetisation vector on the horizontal plane (i.e. the direction of magnetic north). Directions to
1685 the east of geographic north are in positive values, and those to the west are in negative values

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- 1686 **(Post) Depositional Remanent Magnetisation (DRM)** a remanent magnetisation acquired during or
1687 shortly after sediment deposition. This is usually due to magnetic particles of sediment rotating to
1688 align their intrinsic magnetisations with the ambient field as they settle out of a relatively
1689 nonturbulent water solution. They then become locked into position by the weight of sediment
1690 settling above them
- 1691 **Devensian** relating to or denoting the most recent Pleistocene glaciation in Britain, identified with
1692 the Weichselian of northern Europe
- 1693 **Dosimeter** a device that measures exposure to radiation
- 1694 **Fluvial** of or found in a river
- 1695 **Glacial** an interval of time (thousands of years) marked by colder temperatures and glacier advances
- 1696 **Glacial Maximum** period within a glacial when global ice sheets reach their greatest extension; the
1697 Devensian Glacial Maximum was c 24.5 ka
- 1698 **Glaciation** the process or state of being covered by glaciers or ice sheets
- 1699 **Geological timescale:** system of chronological dating that relates geological strata (stratigraphy) to
1700 time. The largest defined unit of time are Eons, which, in turn, are divided into Eras, Periods, Epochs
1701 and Ages
- 1702 **Geomagnetic field** the Earth's spontaneously generated magnetic field. Largely due to movements
1703 of electrically conductive material in the Earth's molten outer core but with a smaller magnitude
1704 contribution from ionic movements in the upper atmosphere
- 1705 **Geomagnetic Polarity Time Scale (GPTS)** geomagnetic timescale constructed from an analysis of
1706 magnetic anomalies measured over the ocean basins and tying these anomalies to known and dated
1707 magnetic polarity reversals found on land.
- 1708 **GISP2** the second Greenland Ice Sheet Project
- 1709 **GRIP** the Greenland Ice Core Project
- 1710 **Half-life** the time required for half the atoms in a sample of radioactive material to decay.
- 1711 **Handaxe** a usually large, general-purpose bifacial Palaeolithic stone tool, often oval or pear-shaped
1712 in form and characteristic of certain Lower Palaeolithic industries
- 1713 **Heinrich events** a natural phenomenon in which large armadas of icebergs break off from glaciers
1714 and traverse the North Atlantic
- 1715 **Highest Posterior Density intervals** a range in which a certain proportion (usually 95% or 68%) of the
1716 true values of a distribution will lie
- 1717 **Holocene** second (and present) epoch within the Quaternary period, starting c 11.7 ka
- 1718 **Hominin** early human or pre-human beings: a member of the sub-family Homininae usually
1719 identified by bipedal adaptations
- 1720 **Human** members of the genus *Homo*, including *Homo habilis*, *Homo rudolfensis*, *Homo erectus*,
1721 *Homo antecessor*, *Homo heidelbergensis*, *Homo floresiensis*, *Homo neanderthalensis*, *Homo naledi*
1722 and *Homo sapiens* (modern humans)
- 1723 **Ice sheet** a layer of ice covering an extensive tract of land for a long period of time
- 1724 **Inclination** the angle between the magnetisation vector and the horizontal plane. Magnetisations
1725 pointing downward have positive inclination values, and those pointing upward have negative values
- 1726 **Interglacial** interval of warmer global average temperature lasting thousands of years that separates
1727 consecutive glacial periods
- 1728 **Interstadial** relating to a minor period of less cold climate during a glacial period
- 1729 **Isochron** a line on a diagram or map connecting points relating to the same time or equal times

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- 1730 **Isotope:** one of two or more forms of an element differing from each other in the number of
1731 neutrons present
- 1732 **Lacustrine** relating to or associated with lakes.
- 1733 **Levallios prepared core (Levallios)** a distinctive style of flint knapping, the earliest of the core
1734 preparation technologies, that initially involves preparation of a pebble into a rough shape.
1735 Subsequent stages involve, removal of cortex, platform preparation and finally removal of flakes.
- 1736 **Loess** an unstratified wind-deposited sedimentary deposit composed largely of silt-size grains that
1737 are loosely cemented by calcium carbonate
- 1738 **Morphostratigraphy** a body of sediment that is identified primarily from the surface form it displays
- 1739 **Mousterian** a techno-complex of lithic tools primarily associated with Neanderthals in Europe that
1740 largely defines the later part of the Middle Palaeolithic.
- 1741 **Natural Remanent Magnetisations (NRM)** the remanence of a natural sample as first measured in
1742 the laboratory (before any partial demagnetisation). The term implies nothing about the origin of
1743 the remanence which could be thermoremanence or depositional remanence etc.
- 1744 **NGRIP** the drilling site of the North Greenland Ice Core Project (NGRIP or NorthGRIP) near the centre
1745 of Greenland
- 1746 **Nuclide** a distinct kind of atom or nucleus characterized by a specific number of protons and
1747 neutrons
- 1748 **Orbital tuning** process of adjusting the time scale of a geologic or climate record so that the
1749 observed fluctuations correspond to the Croll-Milankovitch cycles in the Earth's orbital motion
- 1750 **Palaeolithic** the period once referred to as the Old Stone Age. It is defined by the practice of hunting
1751 and gathering and the use of chipped flint tools. This period is usually divided up into:
- 1752 • Lower Palaeolithic (pre c 250 ka): earliest subdivision of the Palaeolithic, or Old Stone Age;
1753 when the earliest use of flint tools appears in the current archaeological record. A hunter
1754 gatherer society is a defining characteristic
 - 1755 • Middle Palaeolithic (c 250–40 ka): second subdivision of the Palaeolithic or Old Stone Age.
1756 Characterized by the fine flake tools of the Mousterian tradition and economically by a
1757 hunter gatherer society
 - 1758 • Upper Palaeolithic (c 40-11.5 ka): third and last subdivision of the Palaeolithic or Old Stone
1759 Age; characterized by the development of projectile points made from bony materials and
1760 the development of fine blade flint tools
- 1761 **Palaeointensity-Assisted Chronology (PAC)** the use of Relative Palaeointensity (RPI) to constrain the
1762 chronology of a sedimentary sequence
- 1763 **Palaeosecular Variation (PSV)** short-period secular variations, in both direction and magnitude,
1764 capable of providing decadal to millennial age resolutions
- 1765 **Palynology** The recovery and study of ancient pollen grains for the purposes of analysing ancient
1766 climate, vegetation, and diet
- 1767 **Pedostratigraphy** study of the stratigraphical and spatial relationships of surface and buried soils
- 1768 **Pleistocene:** first epoch within the Quaternary period, between c 2.58 Ma and 11.7 ka
- 1769 **Pliocene** last epoch of the Tertiary period, between the Miocene and Pleistocene epochs, between c
1770 5.3 and 2.6 Ma
- 1771 **Post-glacial** relating to or occurring during the time following a glacial period
- 1772 **Posterior beliefs** our state of understanding a problem after considering new data
- 1773 **Posterior density estimate** a function that describes the likelihood of a date occurring at a particular
1774 point in time

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- 1775 **Pretreatment** physical and chemical processing of a sample to purify it before combustion
- 1776 **Prior beliefs** our state of understanding a problem before considering new data
- 1777 **Precision** one component of uncertainty and indicates the degree to which measurements are
- 1778 repeatable and reproducible
- 1779 **Racemization** the transformation of one-half of the molecules of an optically active compound into
- 1780 molecules that possess exactly the opposite (mirror-image) configuration
- 1781 **Radiocarbon calibration** the process of converting a radiocarbon measurement into a distribution,
- 1782 or range, of possible calendrical dates, expressed as cal AD, cal BC or cal BP
- 1783 **Radioactive decay** the spontaneous disintegration of atoms by emission of matter and energy.
- 1784 **Radioactivity** the emission of radiation from a radionuclide during radioactive decay
- 1785 **Radioactive decay** spontaneous transformation of a radionuclide towards a more stable state with a
- 1786 lower atomic number, resulting in the release of radiation in the form of alpha particles, beta
- 1787 particles or gamma rays
- 1788 **Radionuclide** an atom that has excess nuclear energy, making it unstable and subject to radioactive
- 1789 decay
- 1790 **Relative Palaeointensity (RPI)** the record of relative geomagnetic intensity variations measured
- 1791 from normalised natural remanent magnetization of sedimentary samples. The normalisation is
- 1792 typically done by a laboratory-introduced magnetisation to compensate for the ability of the sample
- 1793 to acquire magnetisation
- 1794 **Stable isotope** an isotope that does not undergo radioactive decay.
- 1795 **Stadial** relatively cold period during glacials
- 1796 **Stratigraphy** study of the order and relative position of strata / archaeological material
- 1797 **Stratotype** designated exposure of a named layered stratigraphic unit or of a stratigraphic boundary
- 1798 that serves as the standard of reference (type site)
- 1799 **Taphonomy** the circumstances and processes of fossilisation.
- 1800 **Tephra** fragments of rock that are produced when magma or rock is explosively ejected by a volcano
- 1801 **Tertiary** first period of the Cenozoic era, between the Cretaceous and Quaternary periods, c 65-2.6
- 1802 Ma
- 1803 **Thermal Remanent Magnetisation (TRM)** a remanent magnetisation acquired after a substance has
- 1804 been heated then cooled in an ambient magnetic field.
- 1805 **Ultrafiltration** filtration using a medium fine enough to retain colloidal particles, viruses, or large
- 1806 molecules
- 1807 **Virtual Geomagnetic Pole (VGP)** a point on the Earth's surface at which a magnetic pole would be
- 1808 located if the observed direction of remanence at a particular location was due to a geocentric
- 1809 magnetic dipole field
- 1810 **Quaternary** most recent period of the Cenozoic era, starting c 2.6 Ma. It follows the Tertiary period,
- 1811 and is subdivided into the Pleistocene and Holocene epochs
- 1812 **Vitreous** like glass in appearance or physical properties
- 1813

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2240 23. **Acknowledgements**

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2246 24. Text Boxes

2247 TEXT BOX 1: OXYGEN ISOTOPES IN OCEAN SEDIMENTS

2248 The modern-day record for Quaternary glacial–interglacial climatic fluctuation is derived from
2249 oceanic sediments, which arguably provide a continuous sequence. Palaeo-climatic fluctuation
2250 during the deposition of these sediments has been reconstructed from the study of the oxygen
2251 isotope content of the calcium carbonate tests of foraminifera, specifically the ratio of the
2252 isotope ^{18}O to ^{16}O (for example Shackleton and Opdyke 1973). Changes in the relative abundance of
2253 these isotopes in foraminifera run parallel with the isotopic composition of seawater, which varies
2254 according to the amount of global ice. The lighter isotope ^{16}O represents a slightly greater
2255 proportion of the oxygen in water evaporated from the oceans (and thus entering the global
2256 hydrological cycle) in comparison with the sea water from which it originates, so when larger
2257 amounts of global water are locked up in enlarged icesheets, as occurs during glacials, the world's
2258 oceans become relatively enriched in the heavy isotope (^{18}O). Thus the oxygen-isotope signature of
2259 oceanic sediments records global ice volume. It can be expressed as $\delta^{18}\text{O}$, or the ratio of ^{18}O to ^{16}O ,
2260 and is generally presented, plotted against time, as a curve (Fig 1). The extremes (peaks and troughs)
2261 in this curve represent the warmest (interglacial) and the coldest (glacial) episodes. Some 60–70% of
2262 the Pleistocene is seen to fall between the two, although such intervals were significantly colder
2263 than the Holocene.

2264

2265 TEXT BOX 2: OXYGEN ISOTOPES IN ICE CORES

2266 Ice cores drilled from the Arctic and Antarctic shelves provide a high-resolution record of $\delta^{18}\text{O}$, which
2267 varies according to the temperature of the ocean. Ice is deposited in these archives as a series of
2268 annual layers, which can be counted from the present. This is not a straightforward process, and
2269 missing and false layers lead to a cumulative counting error, but this is in the order of a few hundred
2270 years at MIS 2 and a few thousand years at MIS 5e. The $\delta^{18}\text{O}$ ratios from the Greenland ice cores
2271 show that much of the last climate cycle (since MIS 5e) has been characterized by high-frequency,
2272 high-amplitude climate oscillations (Alley 2000; Bond *et al* 1993; Dansgaard *et al* 1993; Seierstad *et*
2273 *al* 2014; Rasmussen *et al* 2014; Fig 7). These 'Dansgaard–Oeschger' cycles saw abrupt warming by 5–
2274 8°C within 50 years, perhaps within as little as a decade, followed by more protracted cooling. Each
2275 cycle lasted in the order of 500–2000 years. There are 25 such cycles evident in the ice-core record
2276 between c 122 and 25 ka, the latter coinciding with the Last Glacial Maximum (MIS 2). Although it
2277 required the exceptional resolution of the ice cores to reveal this cyclicity, which could probably
2278 never have been determined from fragmentary terrestrial records, recent studies of vegetation
2279 change across Europe have revealed a degree of synchrony between palaeoclimate reconstructions
2280 from that particular terrestrial proxy and from ice-cores (Fletcher *et al* 2010). The high-resolution
2281 temperature record derived from the ice cores can be used, in a similar manner to the Marine
2282 Oxygen Isotope Stages, to define late Devensian chronostratigraphy. The record is divided into a
2283 series of alternating Greenland Stadial (GS) and Greenland Interstadial (GI) stages (Fig 8).

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2285 **TEXT BOX 3: COSMOGENIC NUCLIDE DATING**

2286 There are two contrasting approaches to using cosmogenic nuclides for age estimation: exposure
2287 dating and burial dating.

2288 Exposure dating measures the time when rock surfaces became exposed to cosmic radiation. It has
2289 been used to date past glaciation, for instance by dating ice-moulded bedrock and erratic boulders
2290 (eg Ballantyne 2010). ^{36}Cl , ^{10}Be and ^{26}Al isotopes, between them cover timescales from a few ka to 4
2291 Ma. The amount of these isotopes built up, in the uppermost few cm of exposed rock, is
2292 proportional to the length of time elapsed since the initial exposure of the rock surface.

2293 Burial dating is based on the differential decay of at least two nuclides, where at least one of them is
2294 a radionuclide, which can indicate the time elapsed since they were sealed from cosmic-ray
2295 bombardment (Dunai 2010). The nuclide pair $^{26}\text{Al}/^{10}\text{Be}$ is frequently employed for this method, both
2296 being readily produced in quartz by the action of cosmic rays at a ratio that is essentially
2297 independent of latitude and altitude. Burial dating using these isotopes depends on the quartz
2298 having been exposed to cosmic rays for a period during which they accumulate in the sediment. This
2299 must then have been rapidly buried at sufficient depth to prevent further cosmogenic nuclide
2300 production. As they decay at differing rates, and the surface concentration ratio is well understood,
2301 the ratio of the buried sample can be measured and dated.

2302

2303 **TEXT BOX 4: ELECTRON SPIN RESONANCE (ESR)**

2304 Electron spin resonance (ESR) is a technique related to the luminescence group, in that it measures
2305 mineral exposure to environmental radiation (Duval 2016; Rixhon *et al* 2017). The materials that can
2306 be dated include phosphates, carbonates and silicates, with fossil (including teeth) and optically
2307 bleached quartz grains being the most common applications to Pleistocene deposits in Britain. The
2308 main difference from luminescence dating is that the equivalent dose (electrons stored in traps in
2309 the crystal lattice) is obtained using ESR spectroscopy, which requires the aging of the samples
2310 artificially at increasing doses in order to describe the behaviour of the studied signal. A wide range
2311 of different analytical techniques can be used and correction is typically applied for the density of
2312 the material, its geometry and water content. Quoted errors are typically 15% of the estimated age

2313

2314 25. Tables

2315 **Table 1:** Radiocarbon ages and associated measurements on ultra-filtered gelatin from Gough's Cave, Somerset (see Jacobi and Higham 2009, table 1 for
 2316 further measurements from this site)

2317

Laboratory Number	Material and context	Radiocarbon Age (BP)	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)	%C	CN ratio	Gelatin yield (mg)
OxA-18065	M.49797, <i>Equus ferus</i> , 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, <i>Cervus elaphus</i> , 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, <i>Cervus elaphus</i> , 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, <i>Canis cf familiaris</i> , 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, <i>Equus ferus</i> , 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, <i>Equus ferus</i> , 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, <i>Equus ferus</i> , 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, <i>Cervus elaphus</i> , 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, <i>Lynx lynx</i> , 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)	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)	%C	CN ratio	Gelatin yield (mg)
	Natural History Museum excavation (1987–9).						
OxA-17846	GC 1987 25, bevel-based rod of <i>Mammuthus primigenius</i> 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, <i>bâton percé</i> of <i>Rangifer tarandus</i> 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, <i>Equus ferus</i> 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, <i>Equus ferus</i> 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

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2318 **Table 2:** The affect of contamination by modern carbon on samples of varying radiocarbon age
 2319

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

2320
 2321 **Table 3:** Example of calcite sample suitable for U-Th dating. For the hypothetical archaeological
 2322 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

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2325 **Table 4:** Broom Optical Stimulated Luminescence dates (Toms 2013)

Laboratory Code	Depth (m)	Mean Age (ka) BP	Minimum Age (ka) BP	<i>Highest Posterior Density Interval – ka (95% probability)</i>
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	-	-

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2328 **Table 5:** Optical Stimulated Luminescence dates from in and around Area; Toms (2011) and Wessex
 2329 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

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2332 **Table 6:** Uranium-series TIMS data. Numbers in parentheses are the errors (1 SD) in the last one or
 2333 two decimal places. Sample number is Armstrong's find co-ordinate. Mid-and upp refer to middle
 2334 and upper layers, respectively, of calcites with more than one growth phase, separated by hiatuses

Sample number	$^{238}\text{U}(\mu\text{g g}^{-1})$	$[\frac{^{230}\text{Th}}{^{232}\text{Th}}\text{h}]$	$[\frac{^{234}\text{U}}{^{238}\text{U}}]$	$[\frac{^{230}\text{Th}}{^{238}\text{U}}]$	$[\frac{^{230}\text{Th}}{^{234}\text{U}}]$	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

2335 **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	

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2337 **Table 8:** Lynford Quarry radiocarbon measurements

Laboratory Code	Sample number	Material & context	Radiocarbon Age (BP)	$\delta^{13}\text{C}$ (‰)	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± 930 830	-28.0	41,800–38,900
GrN-28396	30377	Peat, humin - as GrN-28395	35,800±200 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± 620 570	-27.8	
OxA-11571	50137	Tooth, <i>Mammuthus primigenius</i> , anterior fragment of molar DM ₃ or M ₁	53,700±3100	-21.2	-
OxA-11572	50000	Animal bone, <i>Mammuthus primigenius</i> , part of mandible attached to molar DM ₃	<49,700	-21.1	-

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2340 **Table 9:** Gransmoor Quarry radiocarbon dates (Lowe *et al* 1995; Walker *et al* 1993)

Laboratory number	Material & depth	$\delta^{13}\text{C}$ (‰)	Radiocarbon Age (BP)	Highest Posterior Density interval cal BP (95% probability)
AA-13299	Terrestrial plant macrofossils, mainly <i>Carex</i> and Cyperaceae, from 0.40m	-28.6	10,150±80	11,615–11,985
AA-13298	Terrestrial plant macrofossils, mainly <i>Carex</i> and Cyperaceae, from 0.50m	-29.5	10,215±90	11,735–12,050
AA-13297	Terrestrial plant macrofossils, mainly <i>Carex</i> and Cyperaceae, from 0.60m	-29	10,355±75	11,825–12,130
AA-13296	Terrestrial plant macrofossils, mainly <i>Carex</i> and Cyperaceae, from 0.70m	-27.5	10,835±80	11,875–12,170
AA-13295	Terrestrial plant macrofossils, mainly <i>Carex</i> and Cyperaceae, from 0.85m	-29.2	10,340±85	11,980–12,260
AA-13294	Terrestrial plant macrofossils, mainly <i>Carex</i> and Cyperaceae, from 0.95m	-28.9	9745±85	12,040–12,315
AA-13293	Terrestrial plant macrofossils, mainly <i>Carex</i> and Cyperaceae, from 1.01m	-28.8	10,565±75	12,125–12,385
AA-13292	Terrestrial plant macrofossils, mainly <i>Carex</i> 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 <i>Carex</i> 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 <i>Carex</i> and Cyperaceae, from 1.42m	-29.5	10,575±80	12,450–12,685
AA-12005	Terrestrial plant macrofossils, mainly <i>Carex</i> 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	<i>Carex</i> 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	<i>Carex</i> fruits, from 1.78m	-26.2	10,905±75	12,910–13,345
AA-12002	<i>Carex</i> 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	<i>Carex</i> 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	$\delta^{13}\text{C}$ (‰)	Radiocarbon Age (BP)	<i>Highest Posterior Density interval cal BP (95% probability)</i>
AA-11997	Aquatic macrophytes and sedge remains from 2.26m	-10.2	12,445±90	-

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2341 **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

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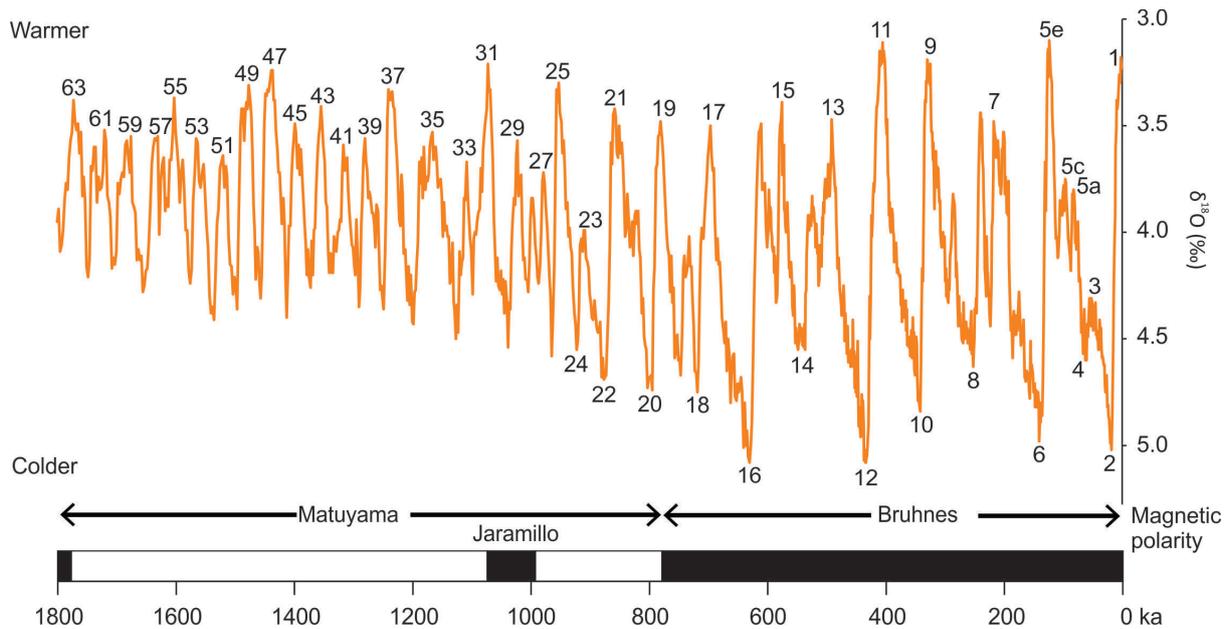
2343 **Table 11:** Summary of stages of project planning for Pleistocene scientific dating under MoRPHE (Lee
2344 2015) with examples of activities at each stage

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.
	<i>NB There may be several iterations of this stage in more complex projects</i>
Closure	Produce publication
	Review achievements and lessons learnt

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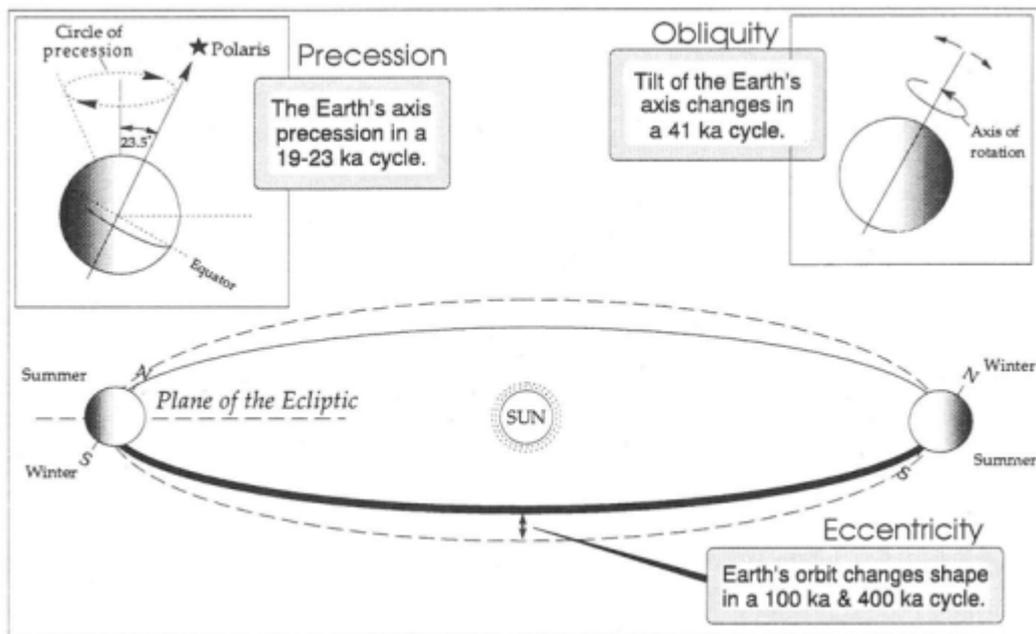
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2347 26. Figures
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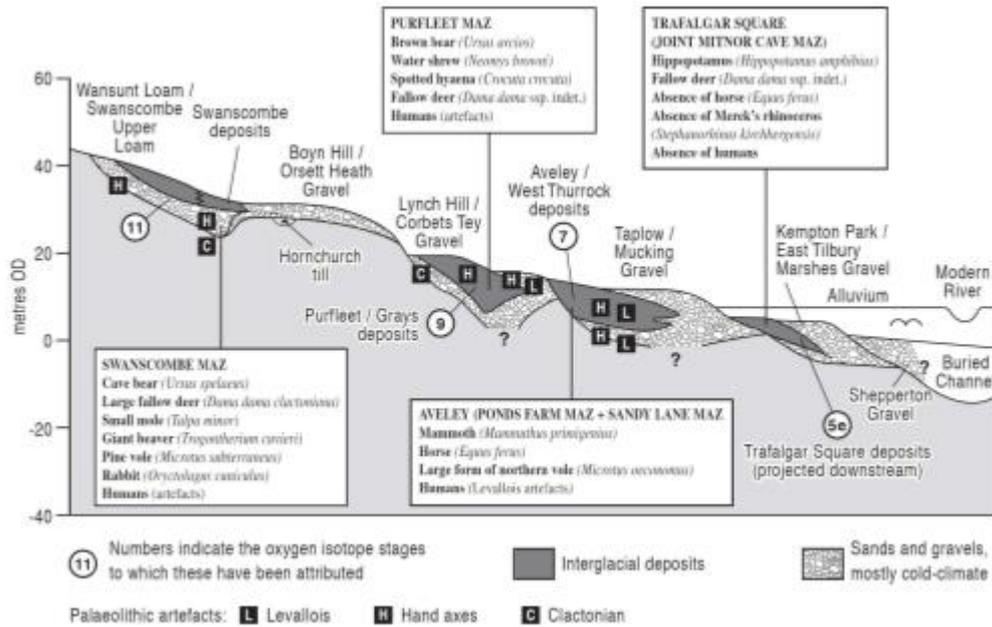
Fig 1 The Marine Oxygen Isotope Record from deep marine sediments, for the last 1.8 Ma, based on the LR04 benthic $\delta^{18}O$ stack constructed by Lisiecki and Raymo (2005) by the graphic correlation of 57 globally distributed benthic records. The record of palaeomagnetic polarity is shown below the graph, with main intervals named



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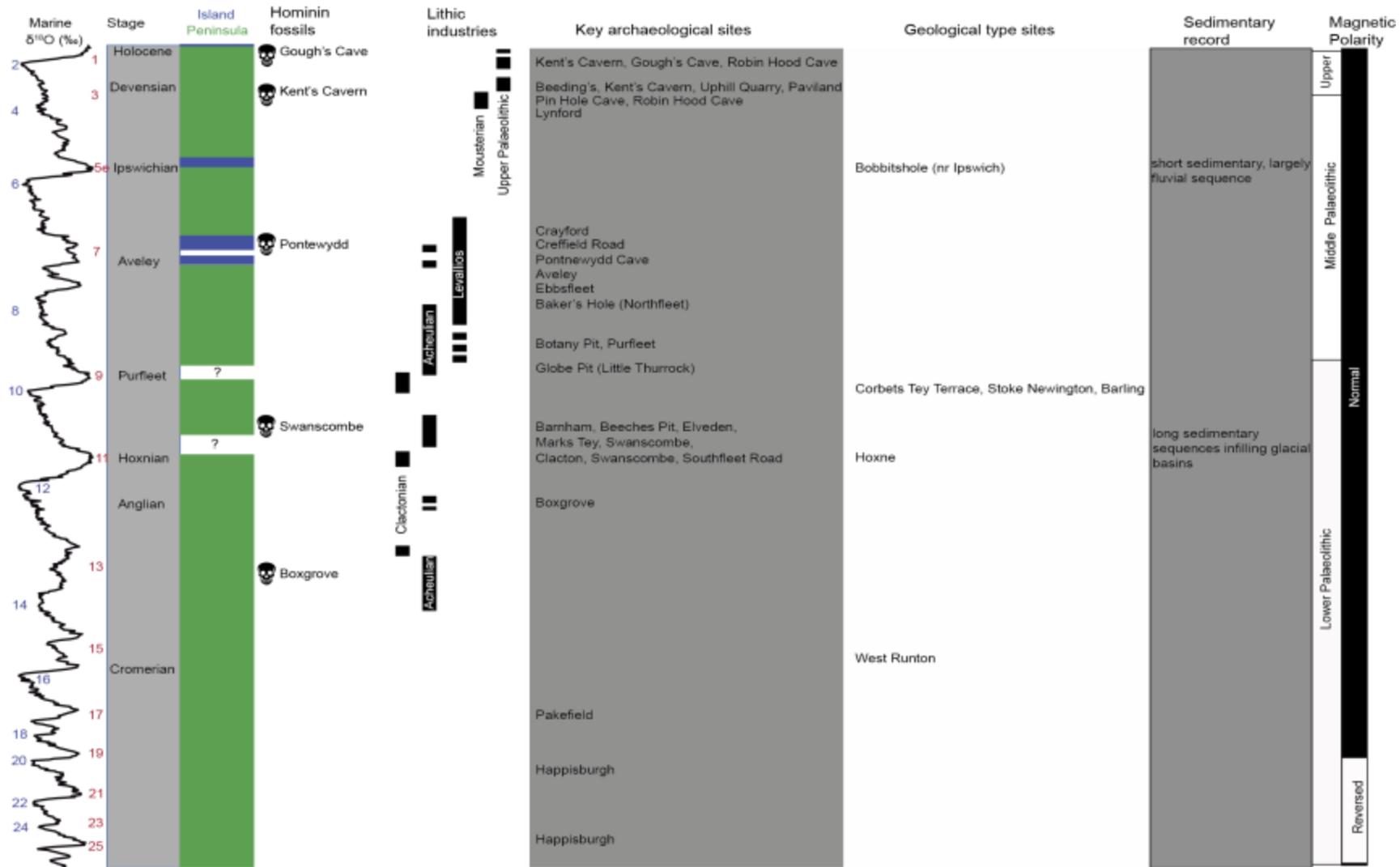
Fig 2 Summary of astronomical cycles (orbital eccentricity, obliquity, and precession) involved in solar input and climate variation

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2358 **Fig 3** Idealised transverse profile of the Lower Thames terrace staircase, showing the mammalian
 2359 assemblage zones (MAZ) and the distribution of main Palaeolithic artefact types (after Bridgland *et*
 2360 *al* 2014). Marine Oxygen Isotope stage attributions of the interglacial components of this sequence
 2361 are indicated

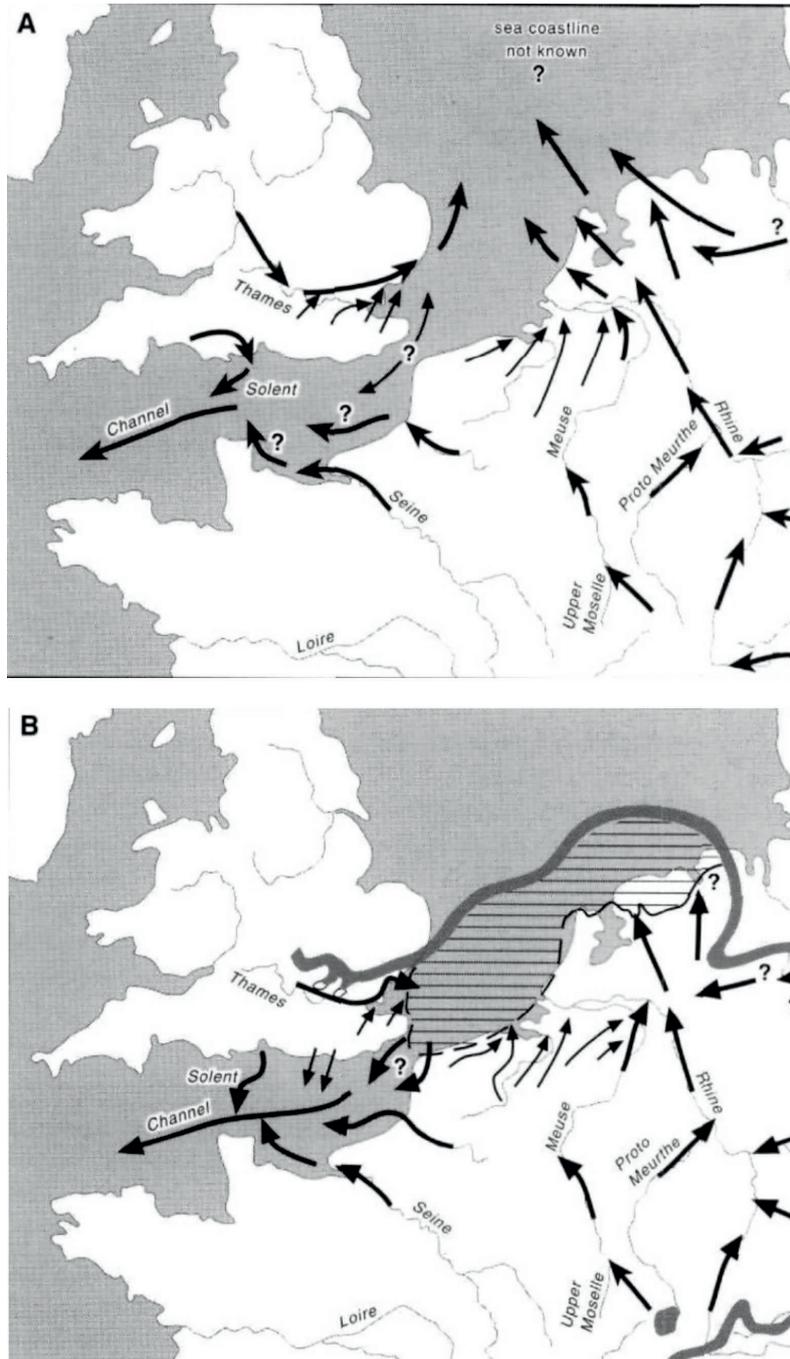


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Fig 4 Clmato-stratigraphy, paleogeography and human occupation of Britain during the Quaternary (modified from ahobproject.org/Downloads/Chart.PDF)

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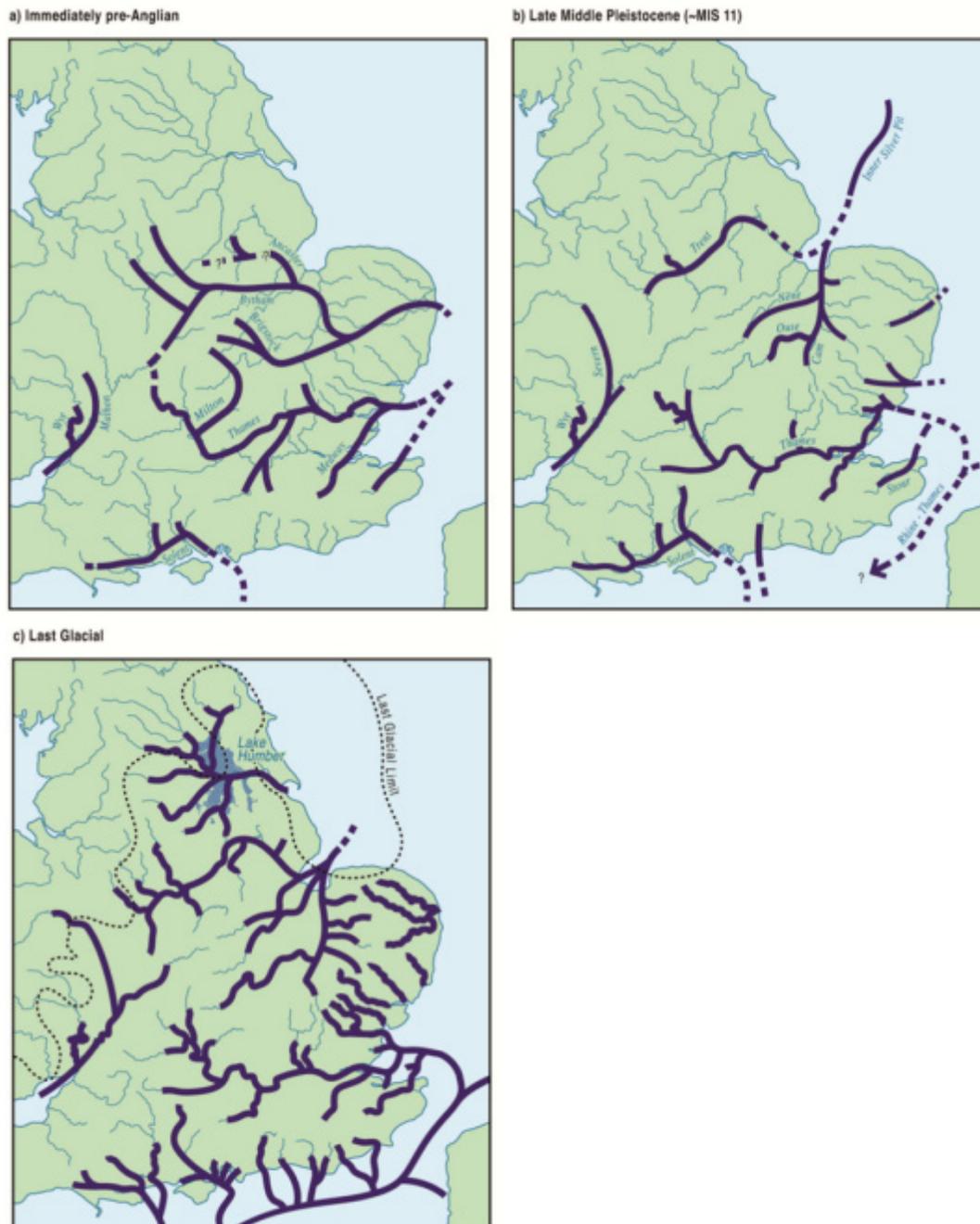
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Fig 5 Evolution of the southern North Sea – English Channel and the glacial diversion of the Rhine–Thames during MIS 12. (A) Drainage of the southern North Sea region in the Cromerian Complex. (B) The same area during the MIS12 glacial maximum, showing 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)

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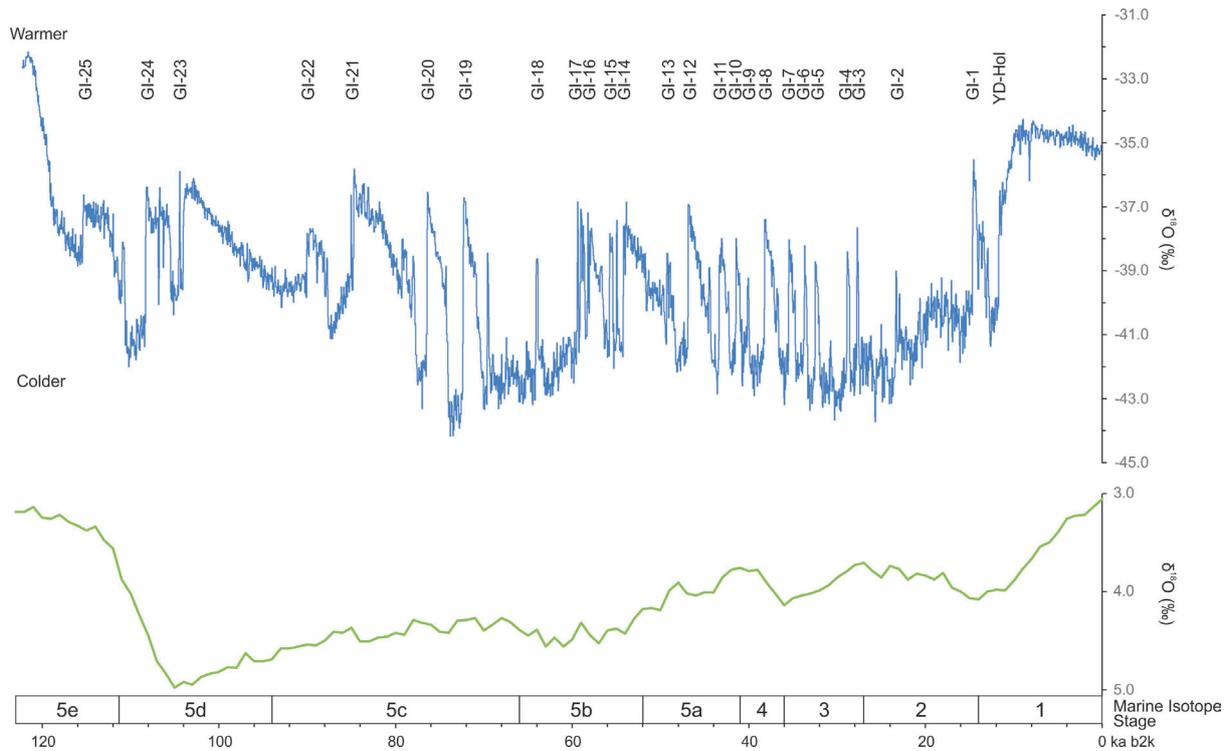
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Fig 6 Key elements of British Quaternary drainage evolution: (a) Drainage systems that existed immediately prior to the Anglian (MIS 12) glaciation. (b) Drainage systems in the late Middle Pleistocene, with emphasis on data from MIS 11, although extensions 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)

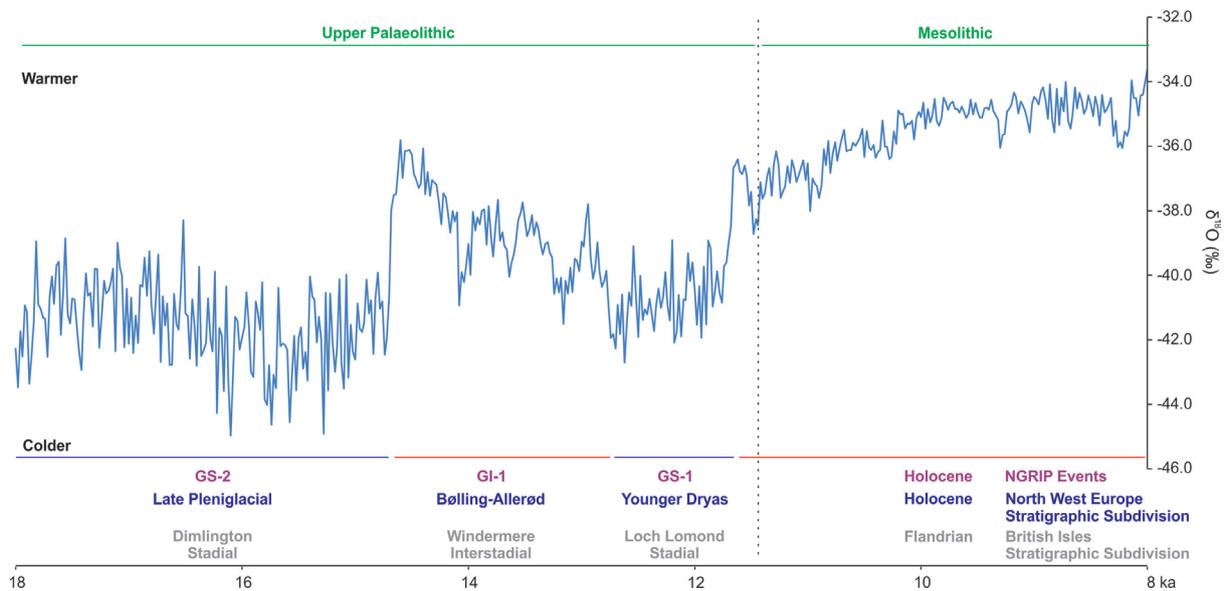
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2386 **Fig 7** Ice Core Chronology for the Late Pleistocene-Holocene. NGRIP, GRIP and GISP2 ice core $\delta^{18}\text{O}$
 2387 record against the GICC05 timecale (Seierstad *et al* 2014) and Greenland event stratigraphy (onset of
 2388 Greenland Interstadials (GI); Rasmussen *et al* 2014). "YD-Hol" marks the Younger Dryas-Holocene
 2389 transition (see Walker *et al* 2009). Below this, the Marine Oxygen Isotope Record (Lisiecki and
 2390 Raymo 2005), with ages for the start of each MIS derived from Lisiecki and Raymo (2005) except MIS
 2391 1 which is derived from the Holocene GSSP (Walker *et al* 2009)

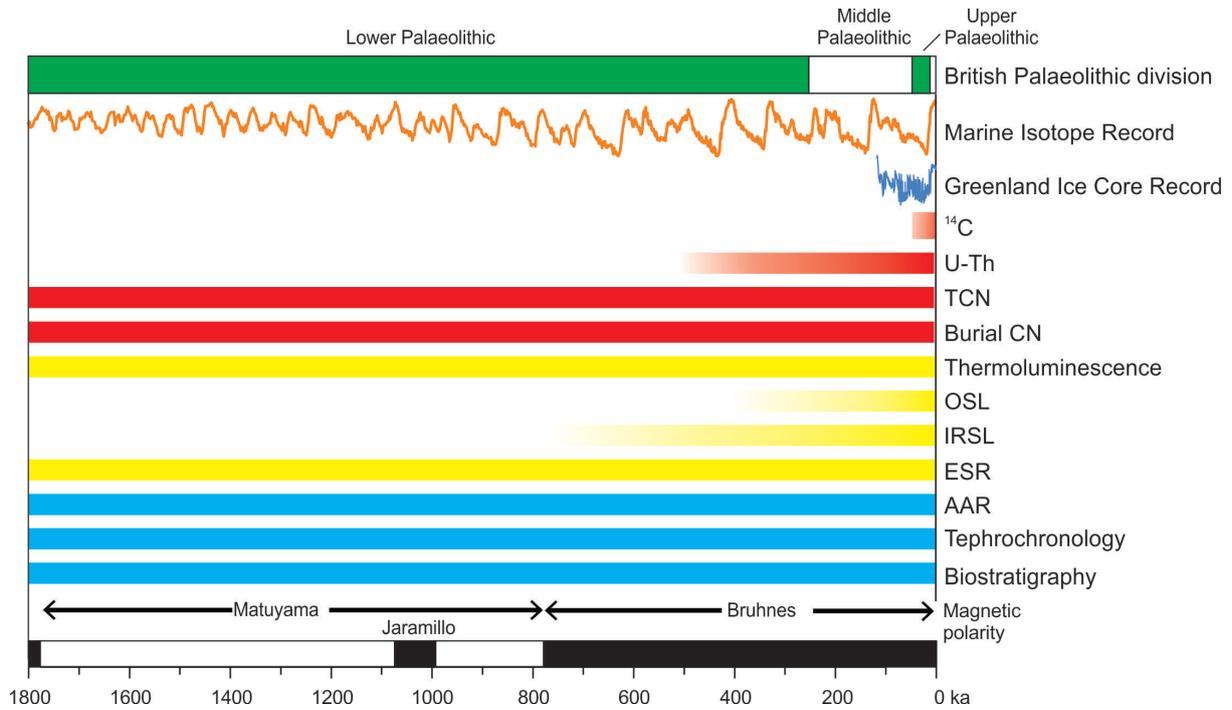
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2393 **Fig 8** Late Glacial event stratigraphy derived from the NGRIP, GRIP and GISP2 ice core $\delta^{18}\text{O}$
 2394 record against the GICC05 timecale (Seierstad *et al* 2014), with stratigraphic subdivisions of the Late Glacial
 2395 in north-west Europe and the British Isles, archaeological periods in the British Isles, based upon
 2396 Walker (2005, fig 1.5). GI = Greenland Interstadial; GS = Greenland Stadial

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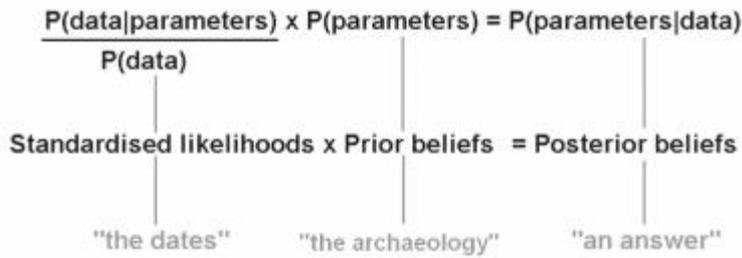
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2400 **Fig 9** Timespans at which dating methods mentioned in this guidance are applicable. Maximum age
 2401 limits are determined by material being dated, local environmental conditions and presence of
 2402 suitable reference material (for example known dated tephra's or equivalent chrono-biostratigraphic
 2403 information). Marine Oxygen Isotope Record from Lisiecki and Raymo (2005) and Greenland Ice Core
 2404 Record from Seierstad *et al* (2014)

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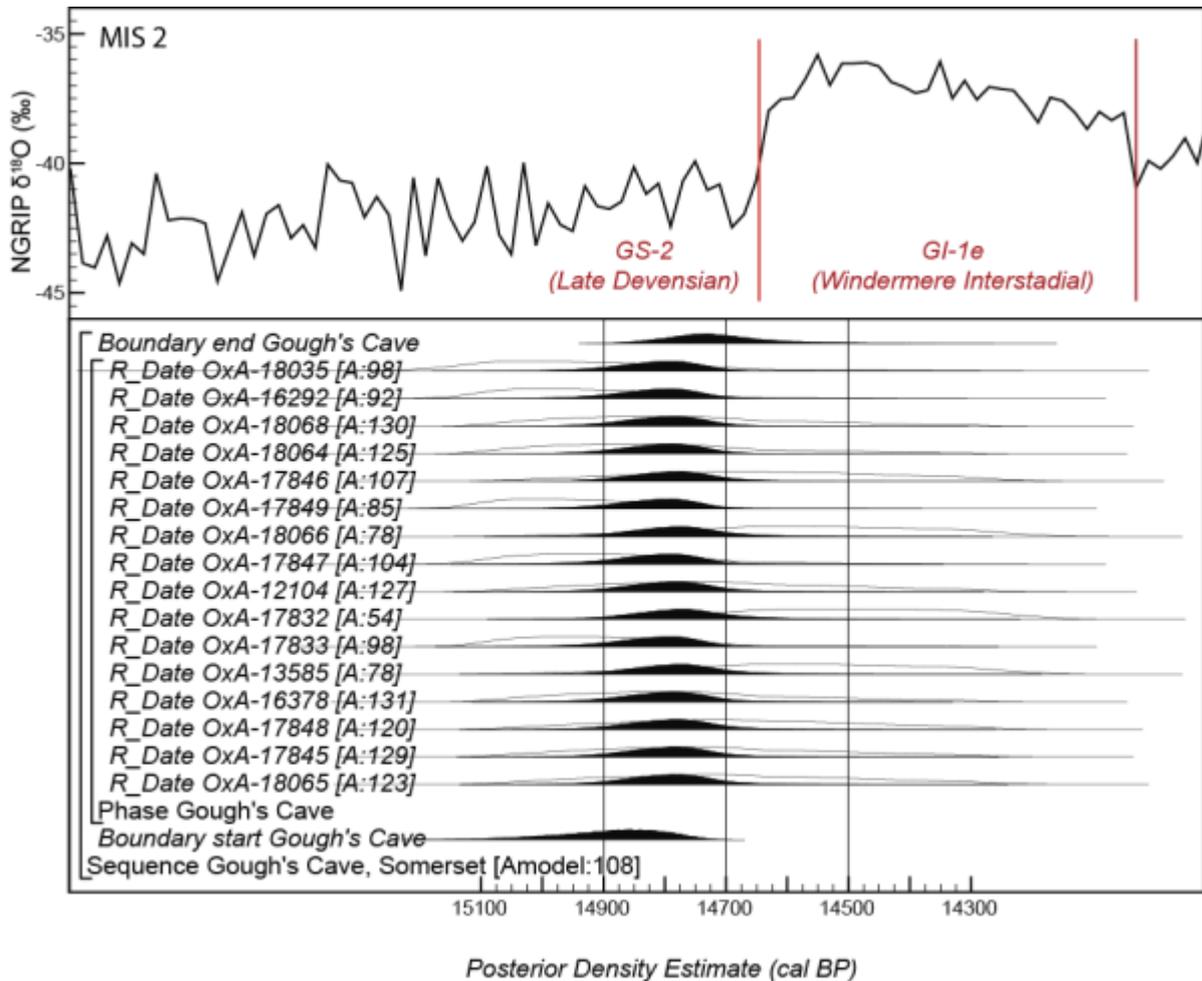
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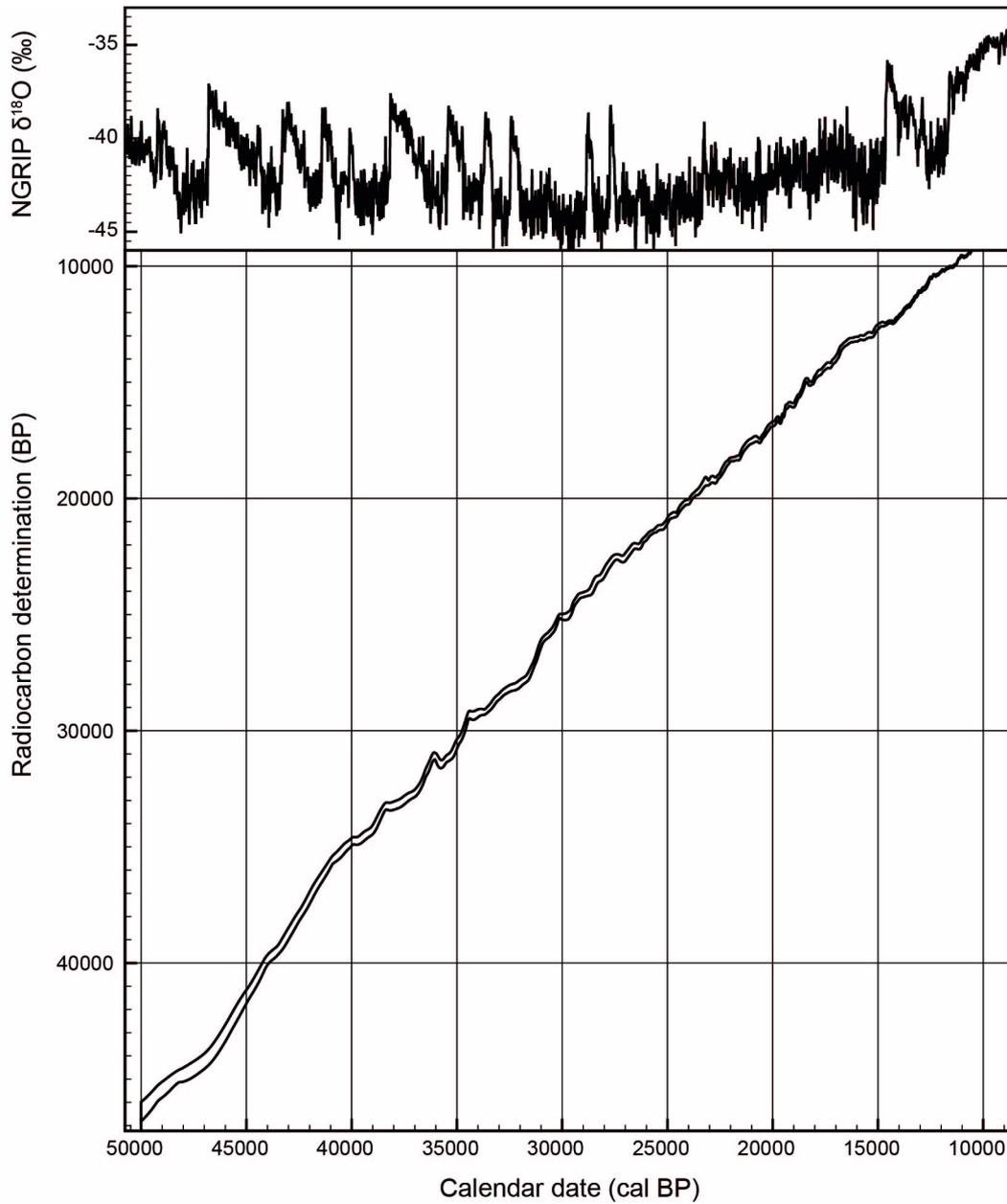
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2408 **Fig 10** Bayes' theorem



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2410 **Fig 11** Probability distributions of dates from Gough's Cave, Somerset. Each distribution represents
 2411 the relative probability that an event occurs at a particular time. For each of the dates two
 2412 distributions have been plotted: one in outline, which is the result of simple radiocarbon calibration,
 2413 and a solid one, based on the chronological model used. Other distributions correspond to aspects
 2414 of the model. For example, the distribution 'start Gough's Cave' is the estimated date when people
 2415 began to occupy the site. The large square brackets down the left-hand side of the diagram, along
 2416 with the OxCal keywords, define the overall model exactly (<http://c14.arch.ox.ac.uk/>). The upper
 2417 panel shows the correlated NGRIP, GRIP and GISP2 ice core $\delta^{18}\text{O}$ record against the GICC05 timecale
 2418 (Seierstad *et al* 2014)



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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 $\delta^{18}\text{O}$ record (Seierstad *et al* 2014)

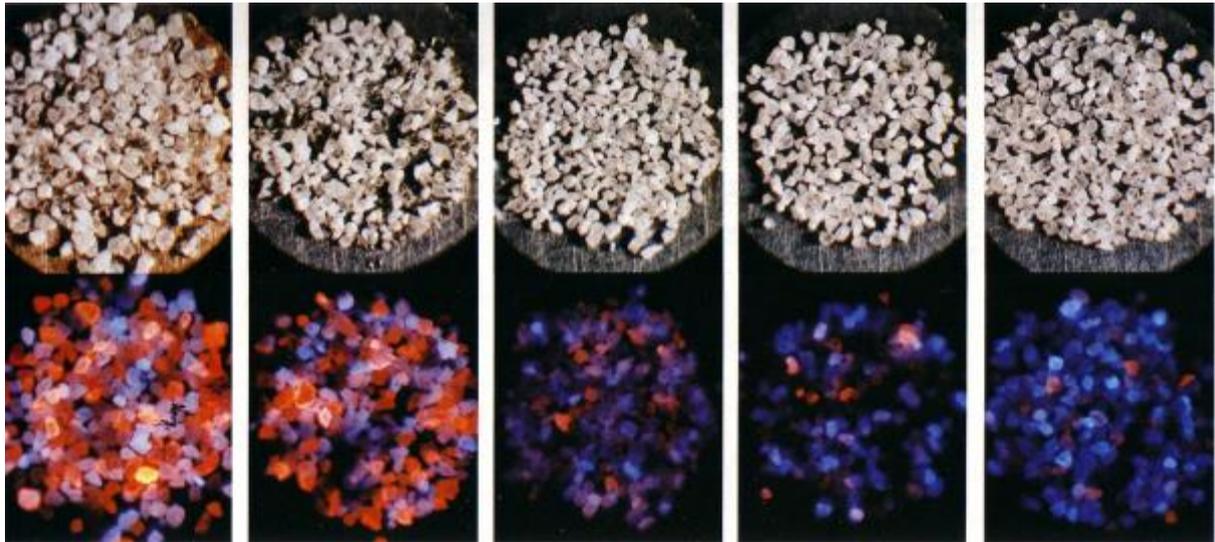


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2425 **Fig 13** Block of flowstone removed from a cave for U-Th dating

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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



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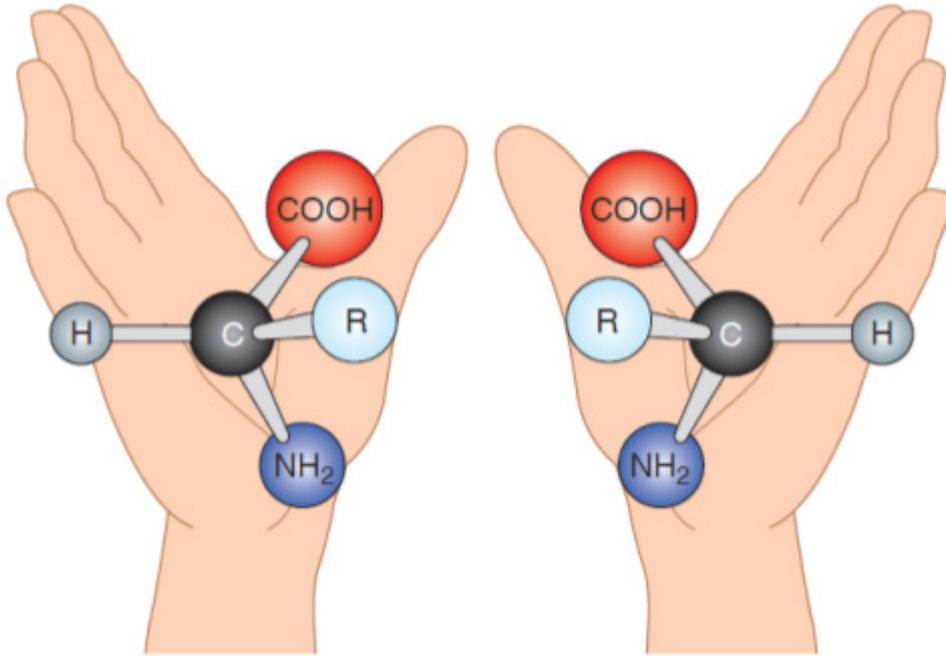
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Fig 15 Three samples for luminescence dating have been collected from this Palaeolithic site at Broom using plastic tubes. A portable gamma spectrometer is being used to measure the radioactivity on the right hand side of the image. See Brown *et al*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

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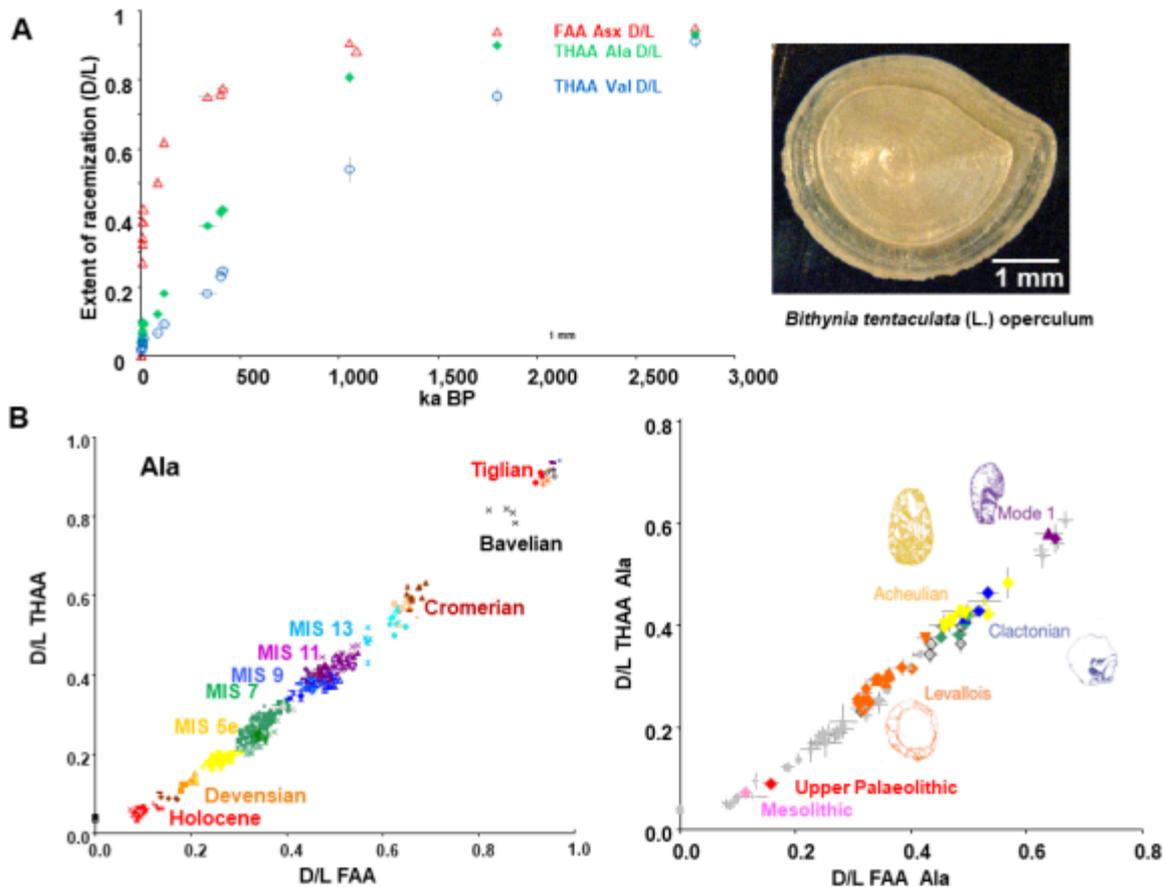


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2437 **Fig 16** Most amino acids have no plane of symmetry, just like hands, so their mirror images are non-
2438 superimposable and therefore distinct from each other. The breakdown of left-handed molecules to
2439 the right-handed form over time provides a mechanism for estimating age of fossil material
2440 (modified from Crisp 2013)

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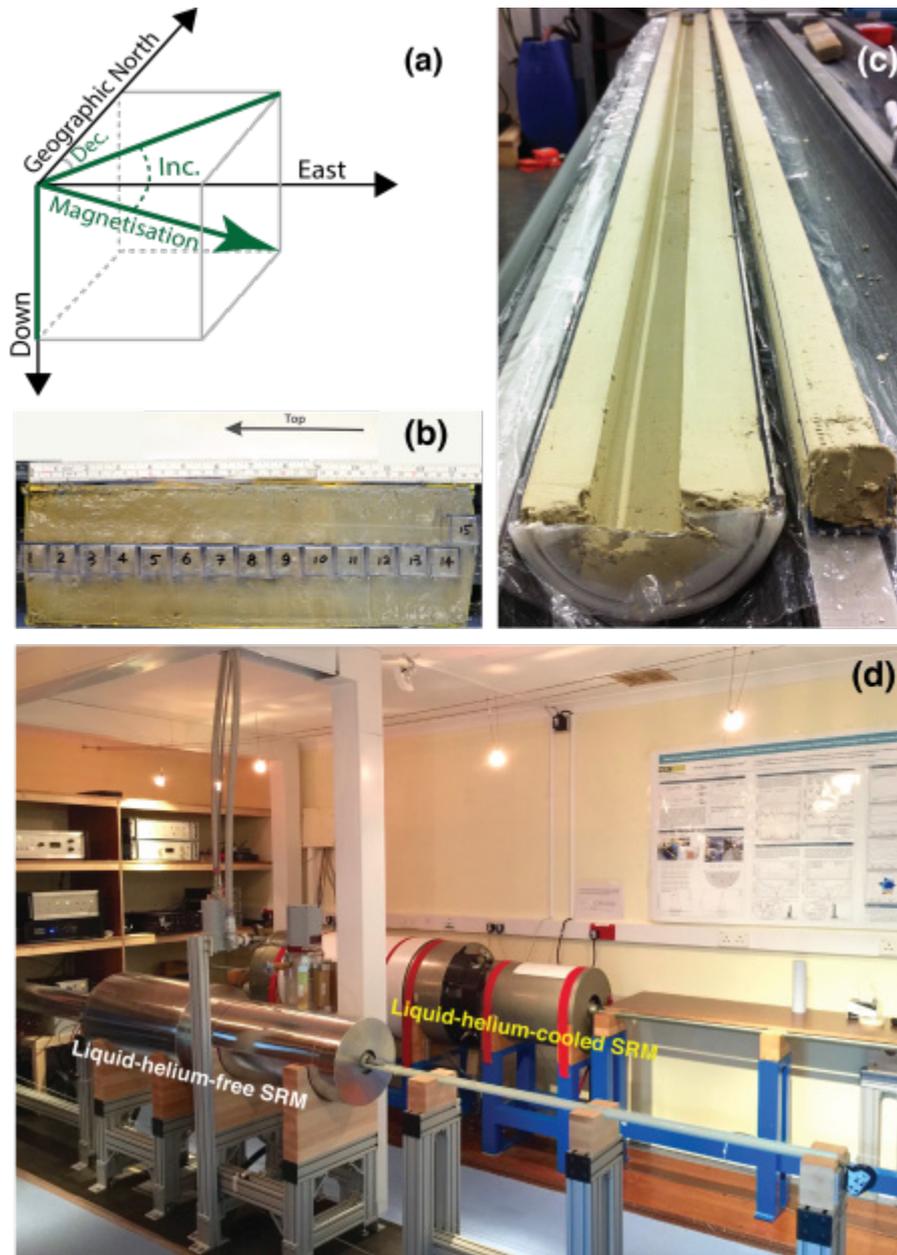


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2443 **Fig 17** A) The increase in racemization in *Bithynia* opercula with age for the free amino acid (FAA)
2444 aspartic acid (Asx) and the total hydrolysable amino acids (THAA) valine (Val) and alanine (Ala). Asx
2445 racemises rapidly and is therefore most valuable for separating sites younger than MIS 7. Val, in
2446 contrast, racemizes more slowly and is able to differentiate between sites back to the Pliocene, but
2447 provides poorer resolution for young sites. Utilizing multiple amino acids with different rates of
2448 degradation therefore enables greater time depth and age resolution. B) Mean THAA D/L vs FAA D/L
2449 for alanine in *Bithynia* opercula from British sites, with colours representing the independent
2450 evidence of age for each site (left). These two measures of breakdown should be highly correlated in
2451 a closed-system, and so this plot forms an aminostratigraphic framework, where young samples fall
2452 towards the bottom left and old samples lie towards the top right of the graph. These frameworks
2453 allow temporal exploration of the archaeological record (right): data from British archaeological
2454 sites, coloured by occurrence of technology (green signifies occurrence of both Clactonian and
2455 Acheulian at a site). Modified from Penkman *et al* (2011)

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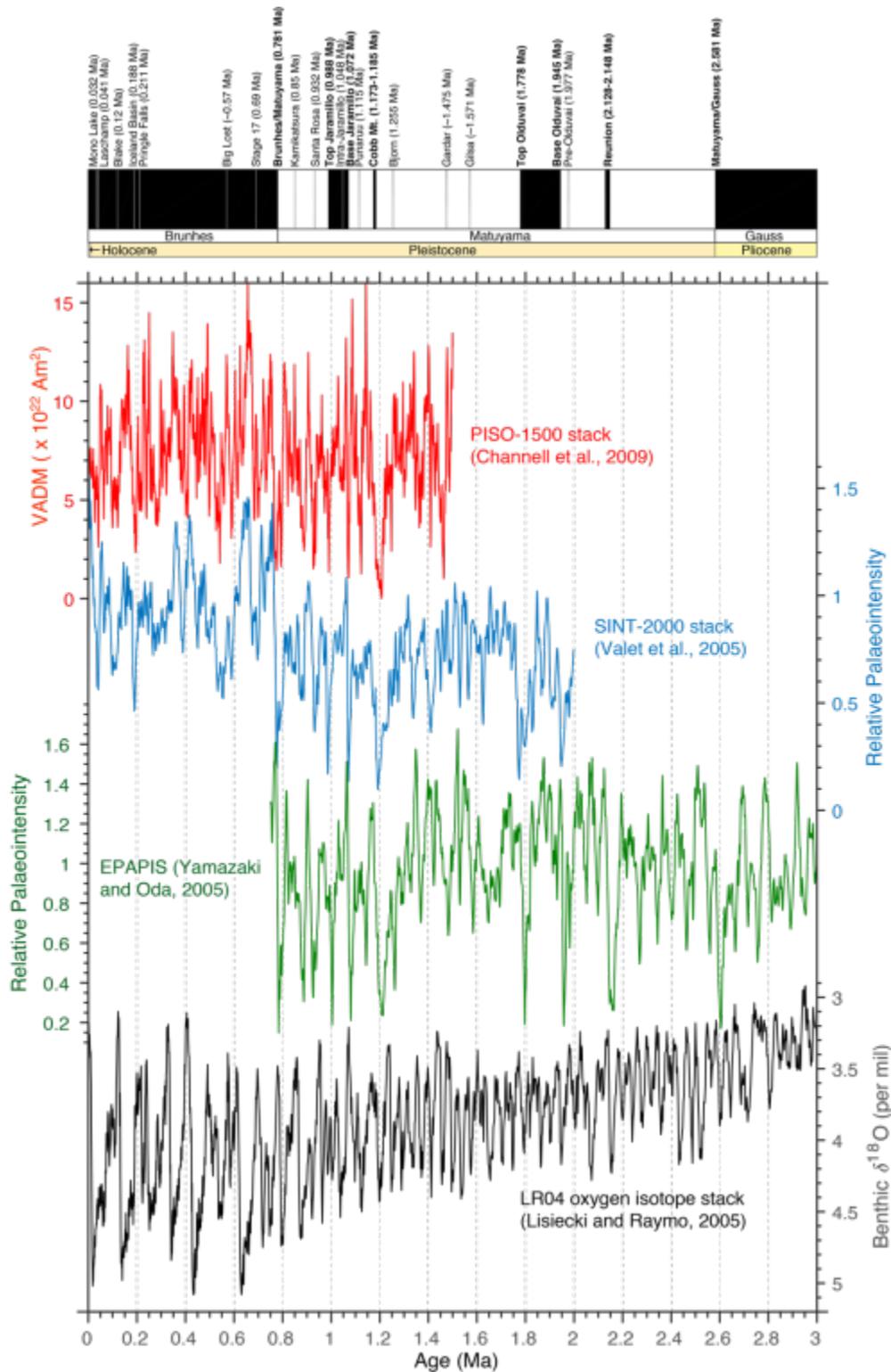
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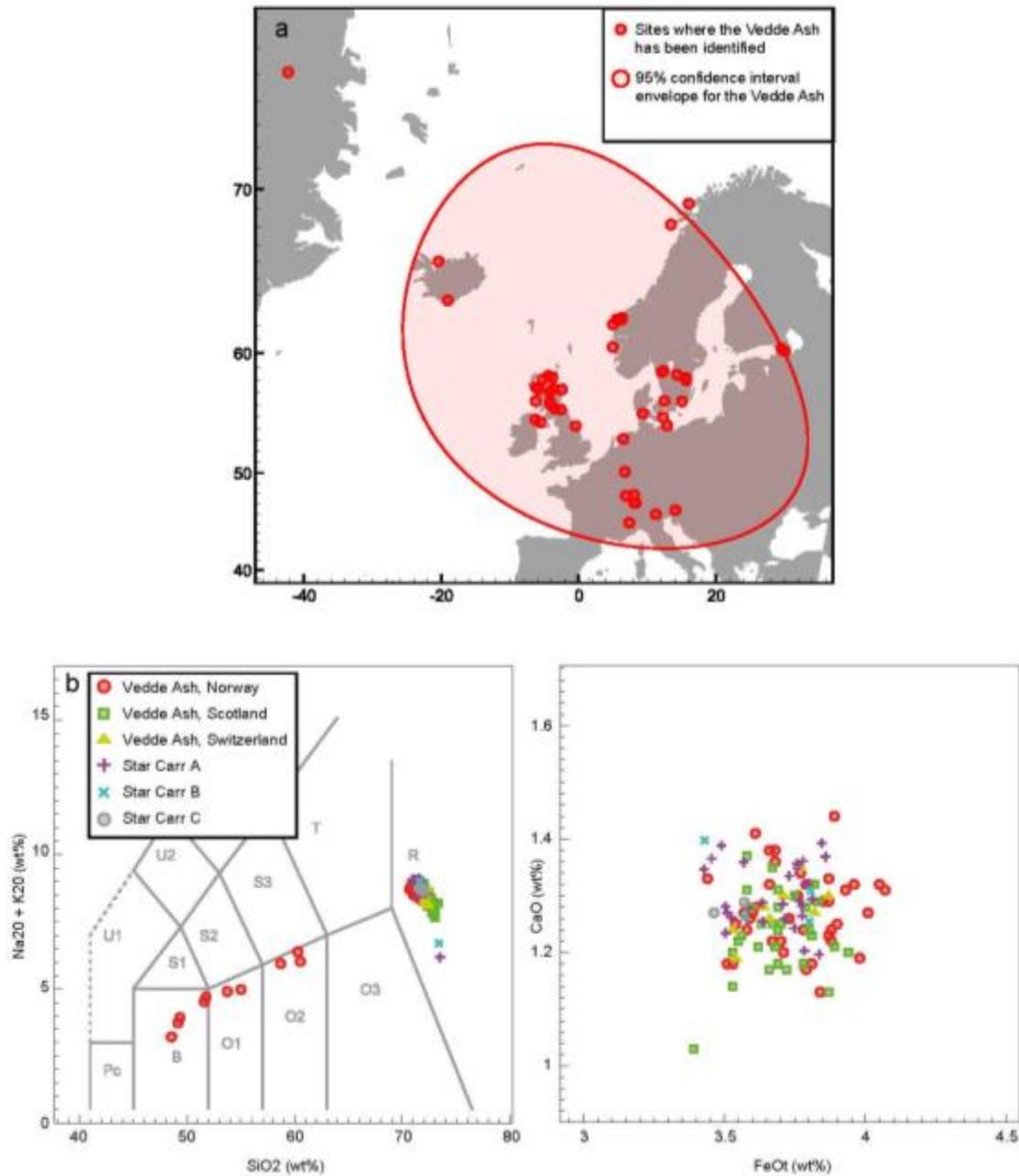
Fig 18 (a) Definition of declination (Dec.) and inclination (Inc.) of a remanent magnetisation signal (green arrow). Examples of (b) discrete and (c) continuous sampling of sedimentary sequences for palaeomagnetic analyses. Samples are typically taken from the centre part of cores that are usually less 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**



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2466 **Fig 19** Top panel: geomagnetic polarity reversals (in bold) and well documented excursions of the
 2467 last 3 Ma. Ages for geomagnetic reversals and excursions are based on Ogg (2012), and Laj and
 2468 Channell (2015), respectively. Bottom panel: the PISO-1500 (in red, Channell *et al* 2009), SINT-2000
 2469 (in blue, Valet *et al* 2005), and EPAPIS (in green, Yamazaki and Oda 2005) relative palaeointensity
 2470 stack records. The LR04 global oxygen isotope stack (in black, Lisiecki and Raymo 2005) is also shown
 2471 on the bottom pane

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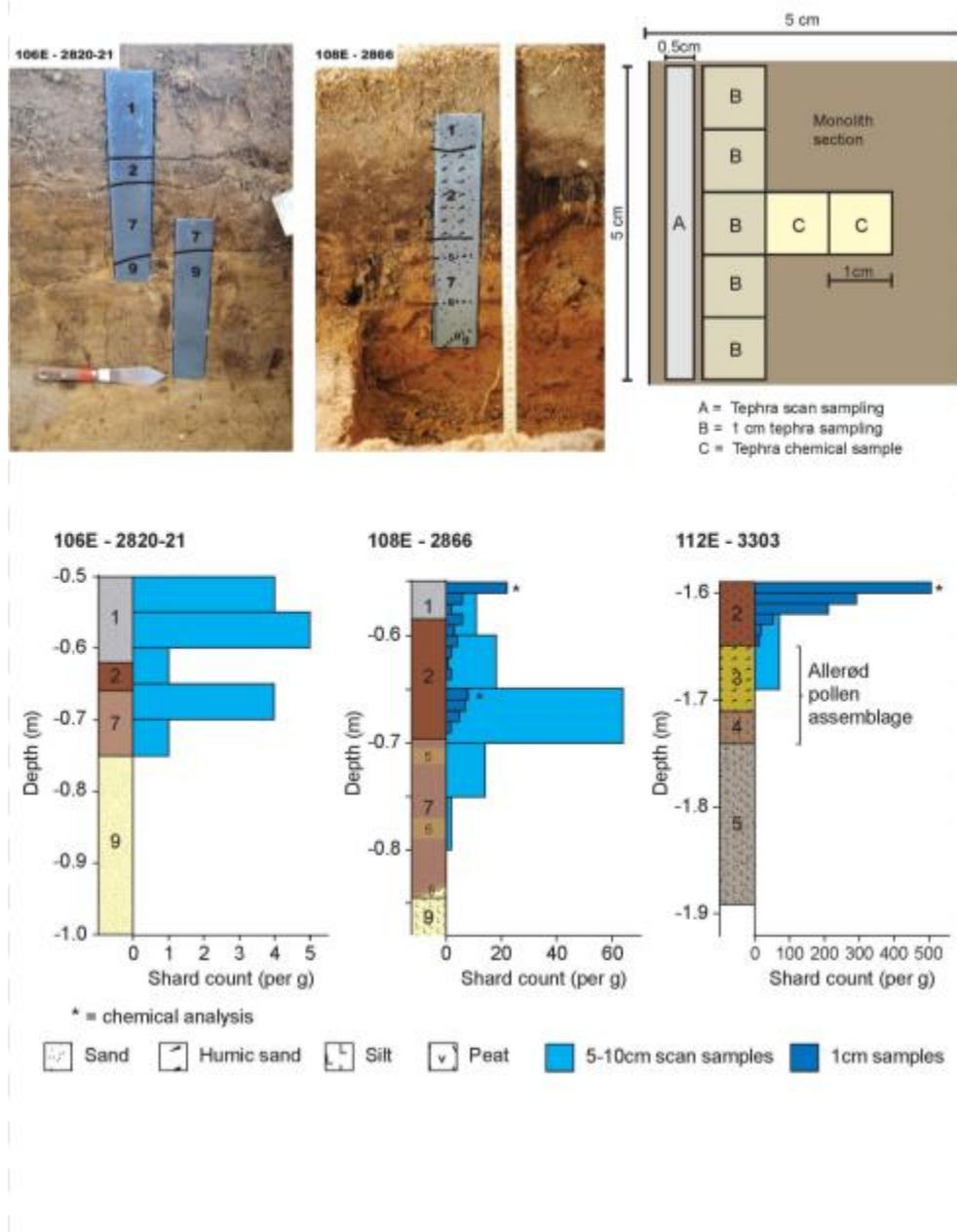
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Fig 20 (a) The known distribution of ash fall from the Vedde Ash eruption of Katla, Iceland, dated to $12,023 \pm 43$ cal. BP (Bronk Ramsay *et al* 2015a). While very few occurrences have been reported from England the 95% confidence distribution envelope 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)

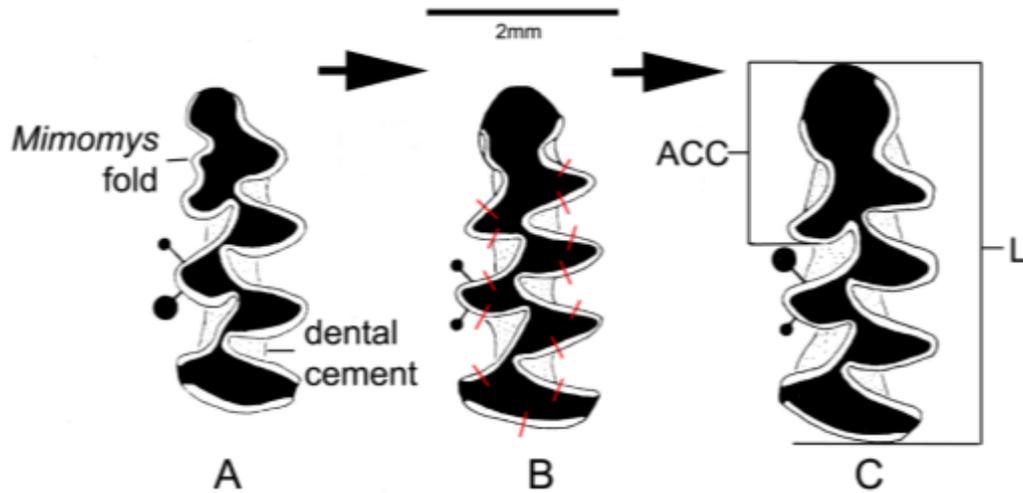
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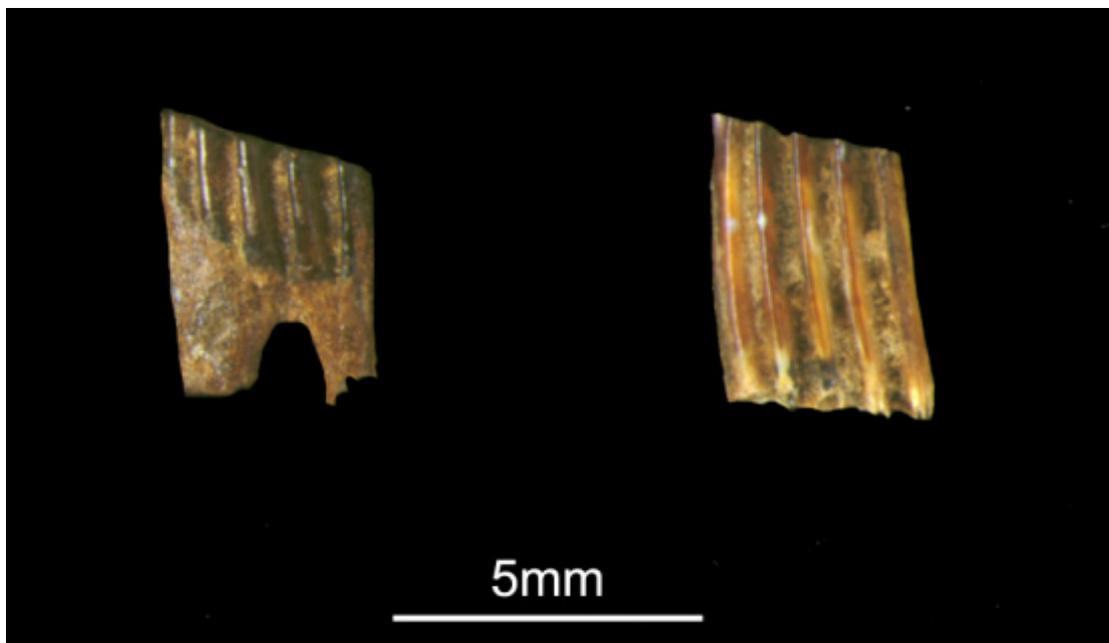
2481 **Fig 21** A suggested sampling strategy for tephra studies. The site shown here is Ahrenshöft LA 58D,
 2482 north Germany, an open-air late Upper Palaeolithic site with Hamburgian and Havelte lithics
 2483 (Housley *et al* 2012). Four monoliths from three sections are presented alongside a sampling
 2484 schematic and subsequent shard counts. The tephra identified originated from Katla in Iceland, but
 2485 similarities in chemical signatures prevent discrimination of three contenders (Suðuroy, Abernethy,
 2486 Vedde Ash) showing that ambiguous results may occur where a volcano produces a series of
 2487 chronologically distinct, but chemically indistinguishable, eruptions

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2490 **Fig 22** Evolutionary trends in *Arvicola* from the early Middle Pleistocene to the present day. A =
 2491 *Arvicola terrestris cantiana*, B = transitional form, C = *Arvicola terrestris terrestris*. Arrows indicate
 2492 the direction of evolution. ACC = anteroconid complex, L = length. Red lines (on B) indicate point of
 2493 measurement for SDQ calculations. Redrawn with additions from Sutcliffe and Kowalski (1976)



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2495 **Fig 23** Lateral views of rooted first lower molar in *Mimomys savini* (left) compared to unrooted
 2496 molar of *Arvicola cantiana* (right)

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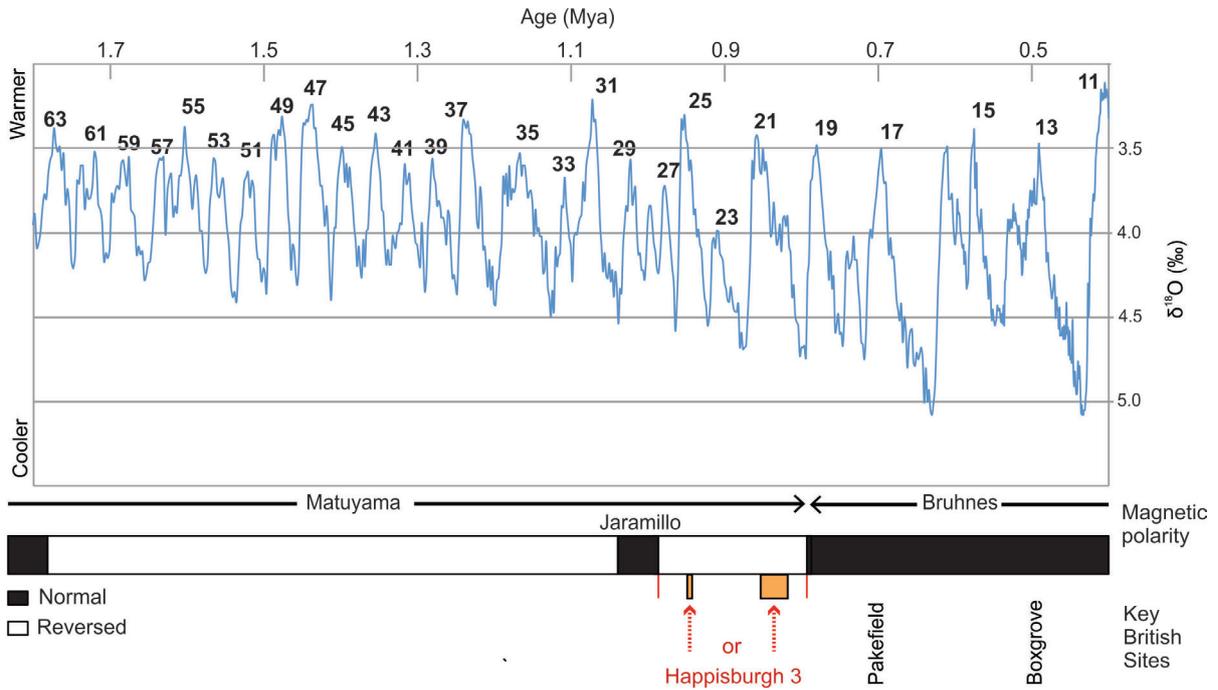
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2500 **Fig 24** Excavations at Happisburgh Site 3 (© Mike Pitts – we have not asked him for permission to
2501 use yet)



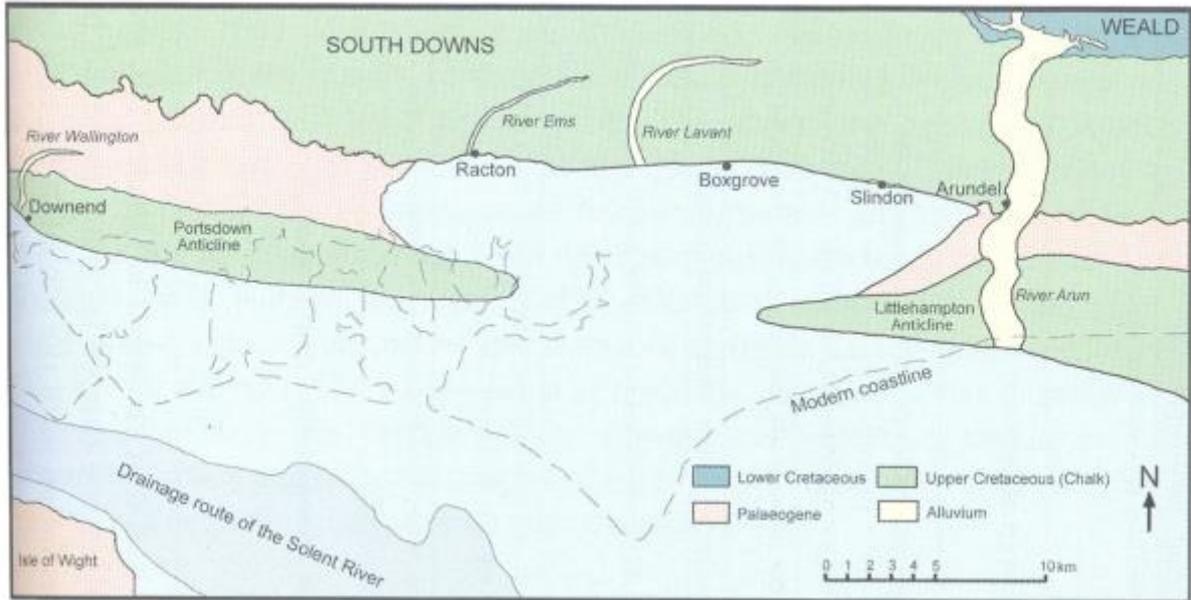
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2504 **Fig 25** Suggested age of the Happisburgh 3 site, showing correlation of the MIS record (Lisiecki and
2505 Raymo 2005) and magnetic polarity record, and likely age of key English Early Palaeolithic coastal
2506 sites

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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)

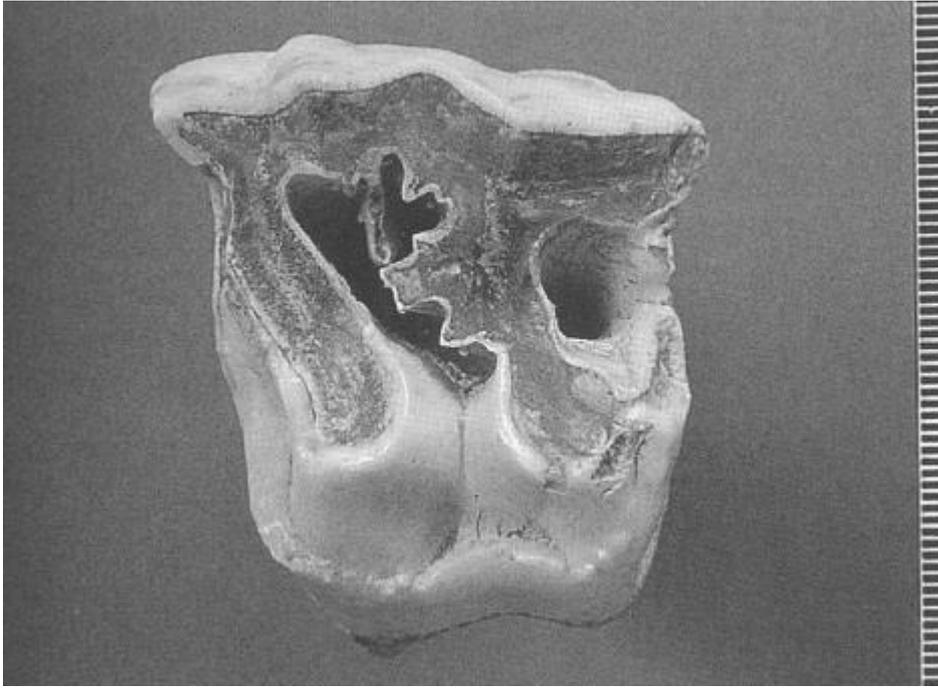


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Fig 27 Flint scatter from the Slindon Silts (Unit 4b) (from Roberts and Parfitt 1999, fig 239)



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

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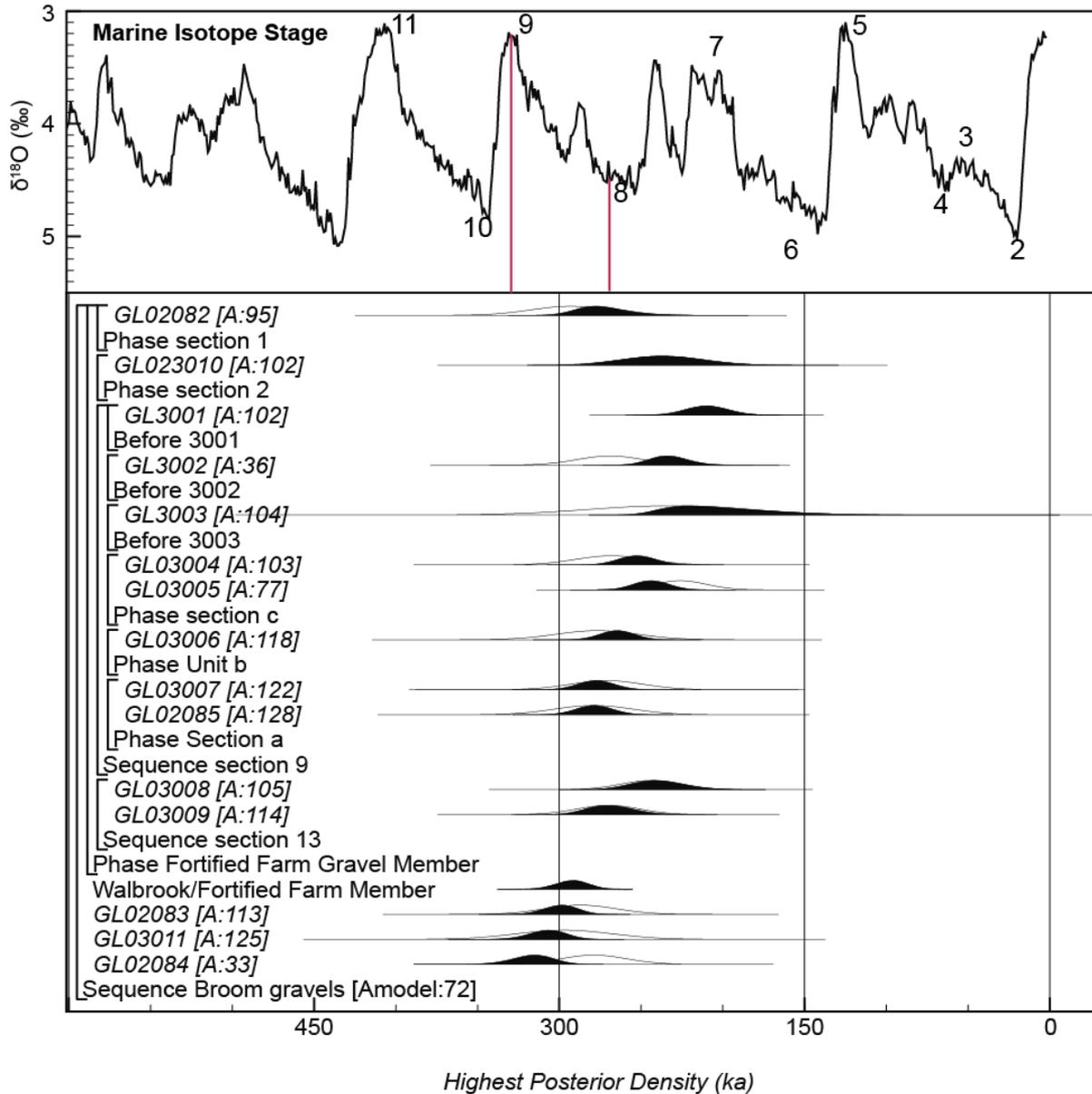


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2518 **Fig 29** Fluvial gravels and sands (Fortfield Farm Gravel Member), Pratt's New Pit, Broom (© R
2519 Hosfield)

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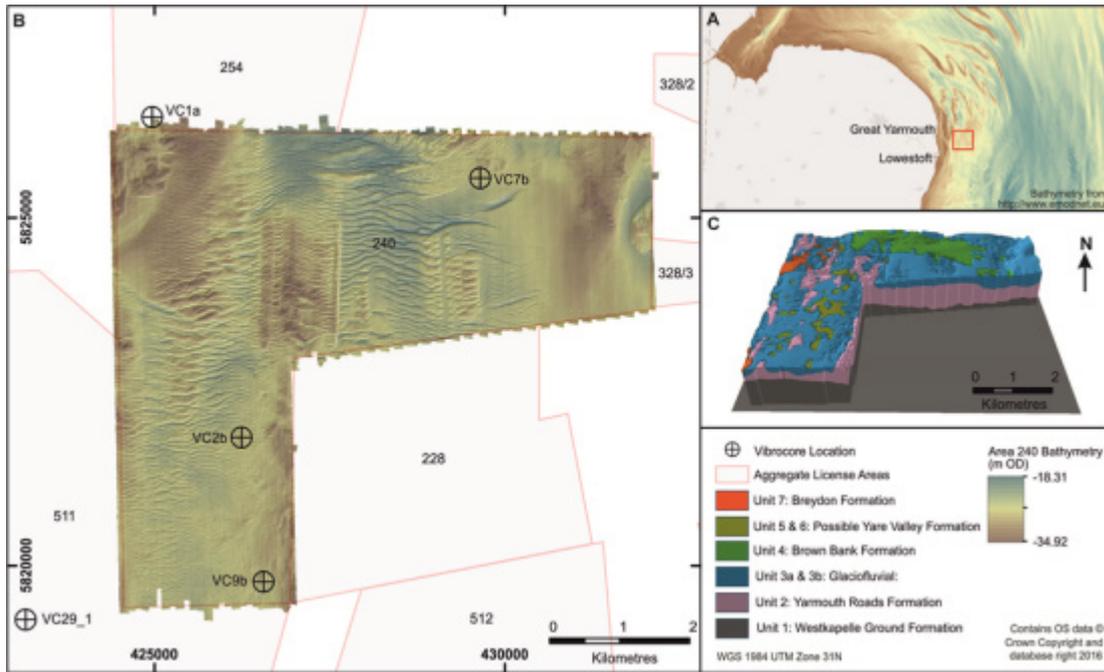
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2522 **Fig 30** Probability distributions of dates from Broom. The large square brackets down the left-hand
 2523 side of the diagram, along with the OxCal keywords define the overall model exactly

2524 (<http://c14.arch.ox.ac.uk/>). The upper panel shows the LR04 benthic $\delta^{18}\text{O}$ (‰) stack from 57
 2525 globally distributed benthic $\delta^{18}\text{O}$ records (Lisiecki and Raymo 2005)

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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).



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2533 **Fig 2** Hand-axes, flakes, and cores from Area 240 (© Wessex Archaeology)

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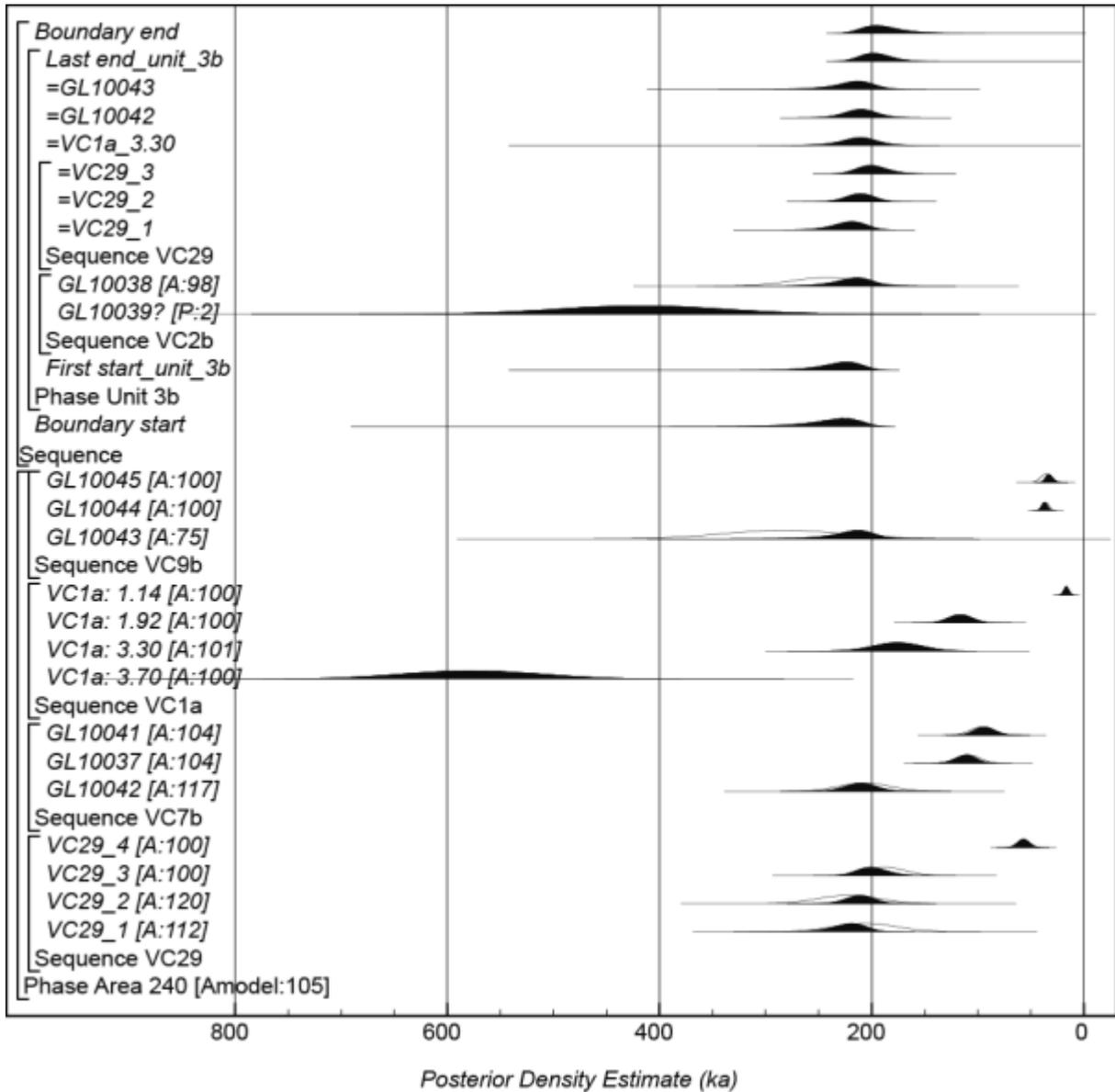
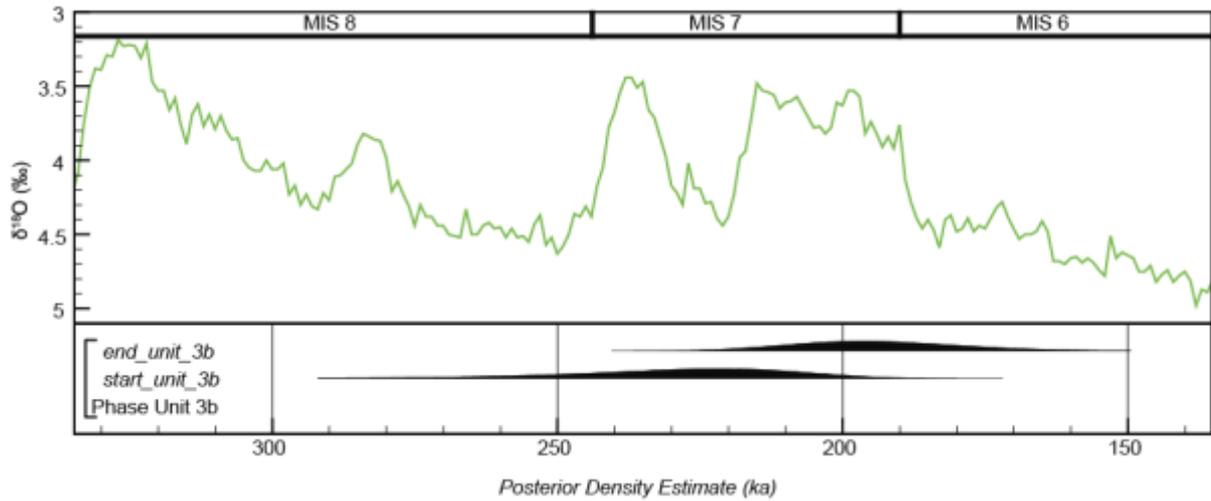


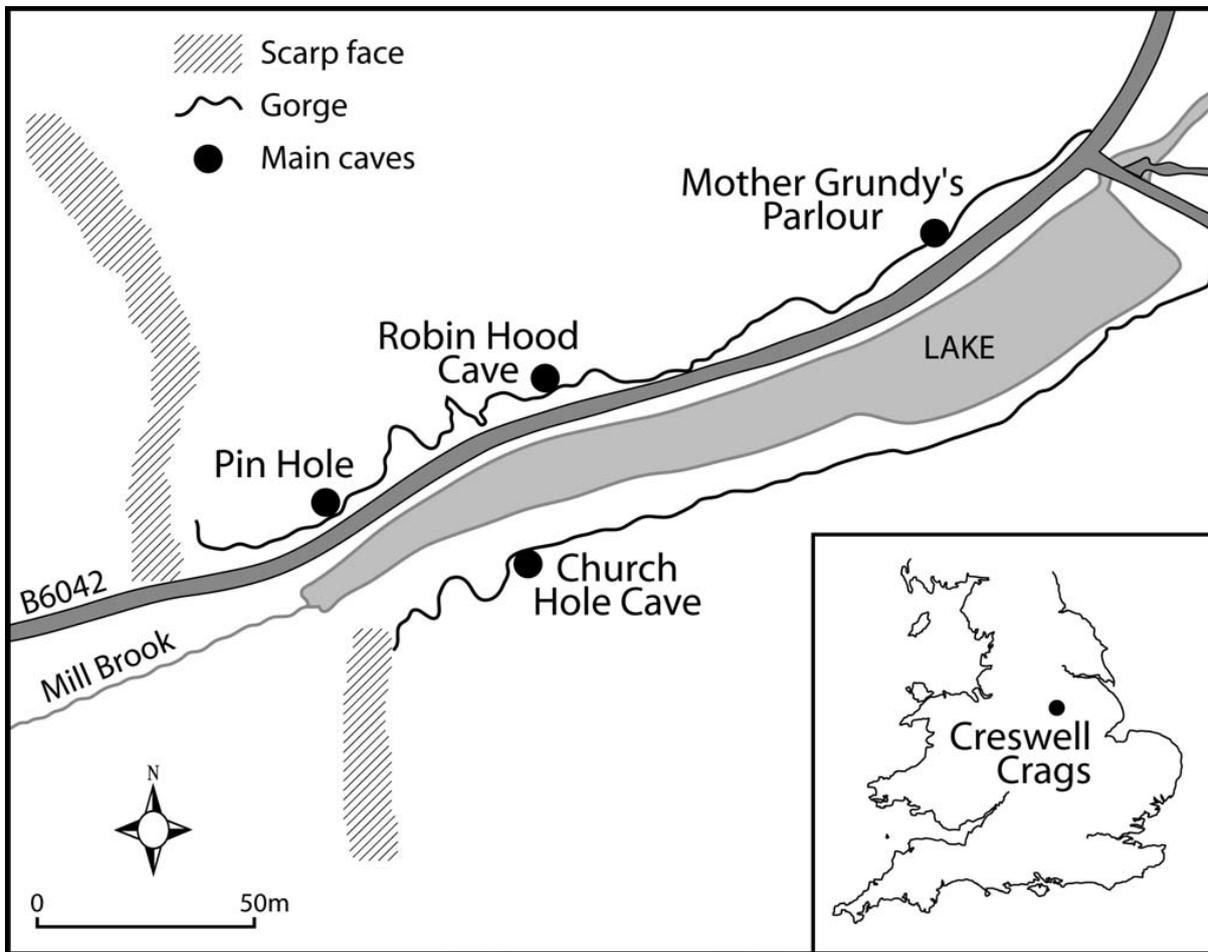
Fig 33 Probability distributions of dates from vibrocores in and around Area 240 (locations shown in Fig 31). The large square brackets down the left-hand side of the diagram, along with the OxCal keywords define the overall model exactly (<http://c14.arch.ox.ac.uk/>)

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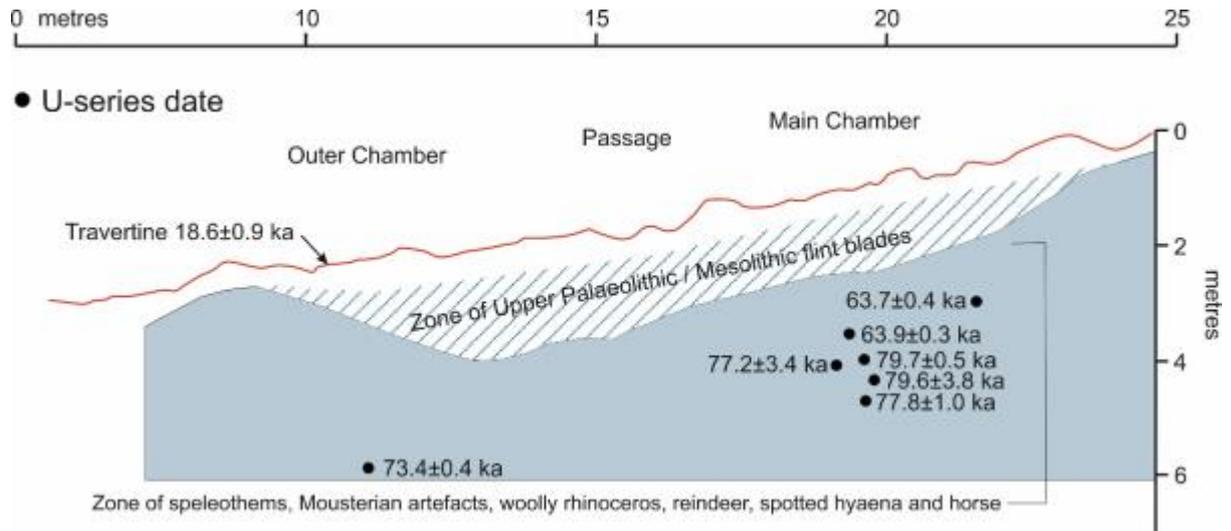
Fig 34 Probability distributions of estimates for the beginning and end of formation of Unit 3b in and around Area 240 (derived from the model shown in Fig 33). The upper panel shows the Marine Oxygen Isotope Record (Lisiecki and Raymo 2005)



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

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



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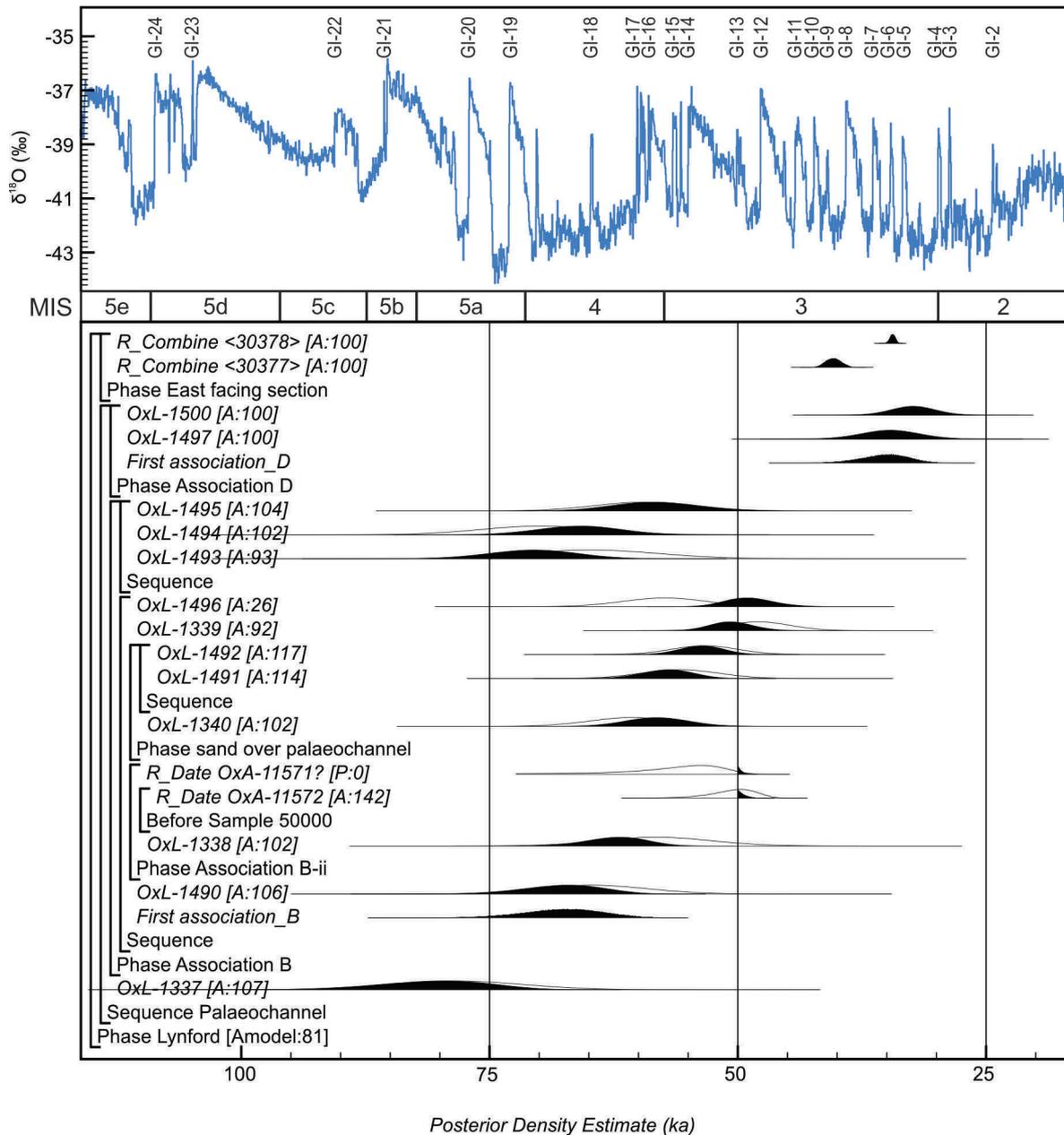
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Fig 37 Excavation of mammoth tusk and associated flint tools at Lynford Quarry (HE Archive AA028489)

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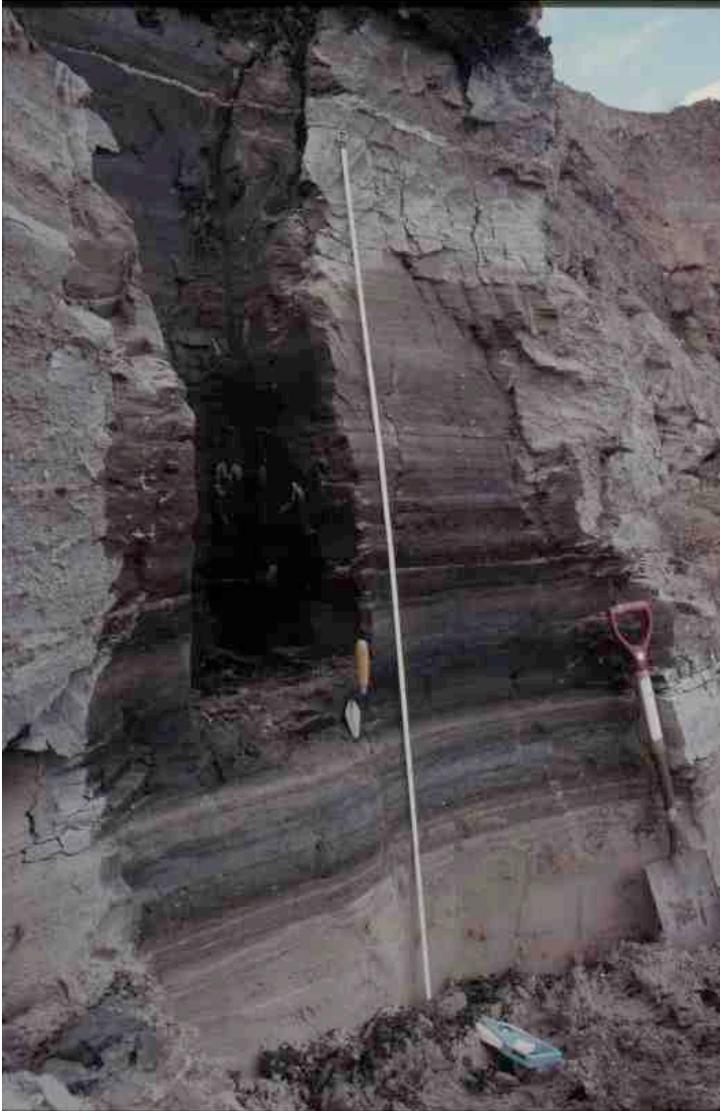
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Fig 38 Probability distributions of dates from Lynford Quarry. The large square brackets down the left-hand side of the diagram, along with the OxCal keywords define the overall model exactly (<http://c14.arch.ox.ac.uk/>). The upper panel shows the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

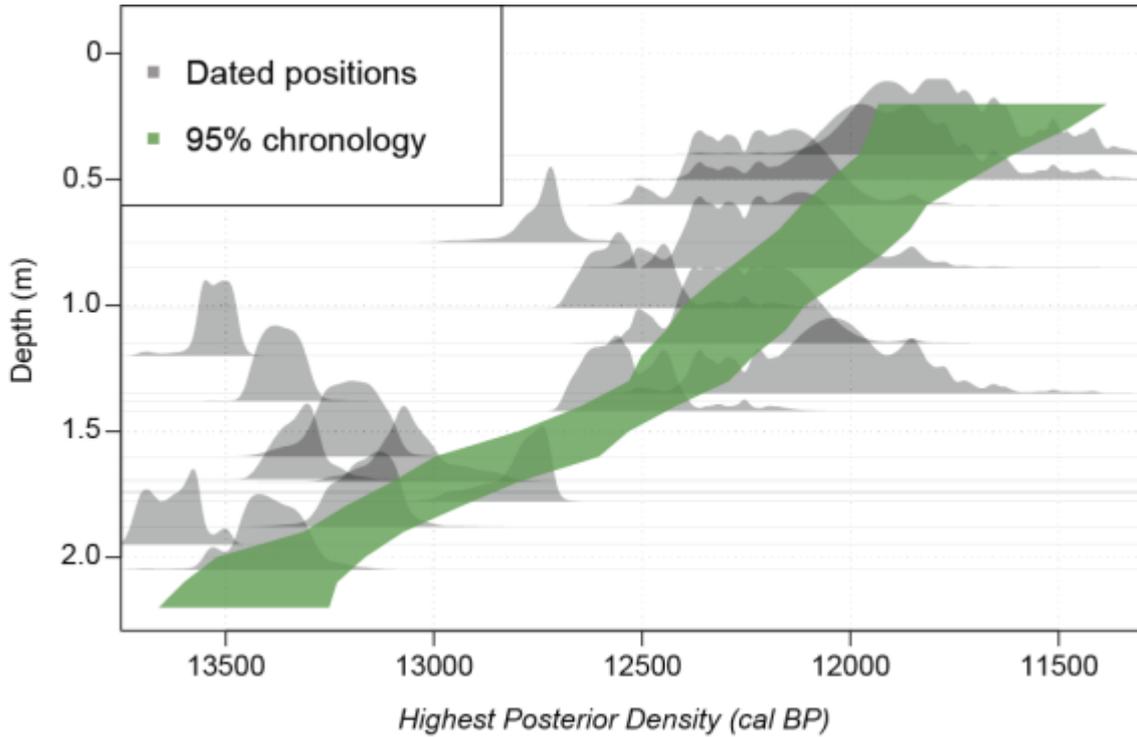


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2562 **Fig 39** The Lateglacial sequence exposed at Gransmoor. The light coloured sediments at the base are
2563 the non-polleniferous sands and silts, while the Lateglacial Interstadial/Loch Lomond Stadial
2564 boundary coincides with the thin white band within the centre of the darker organic clays (photo
2565 courtesy of Mike Walker)

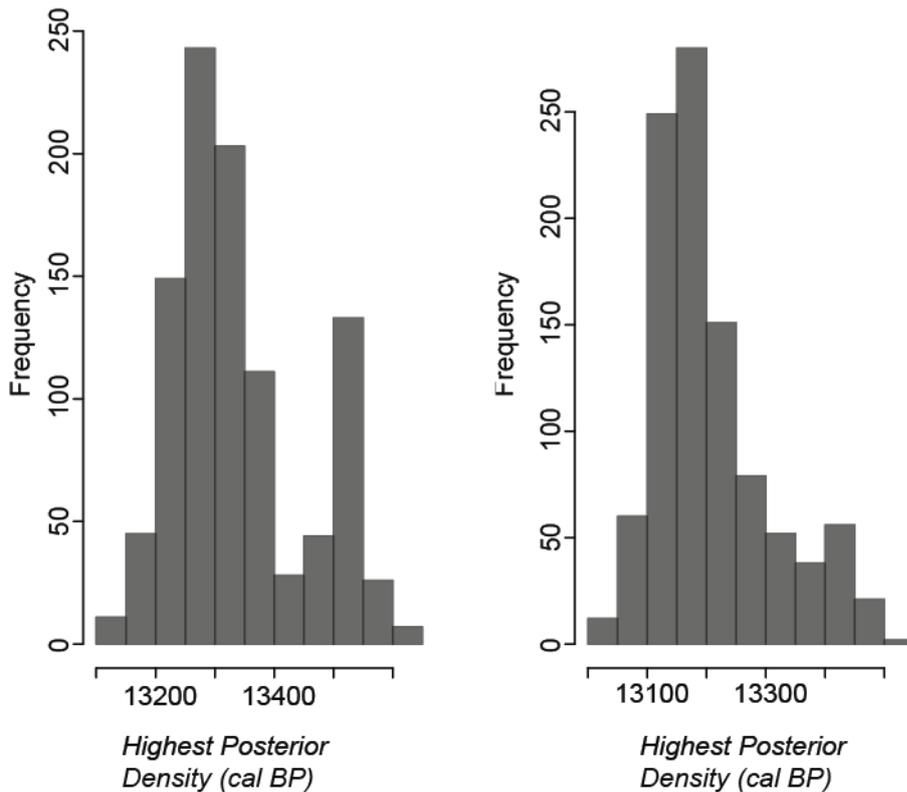
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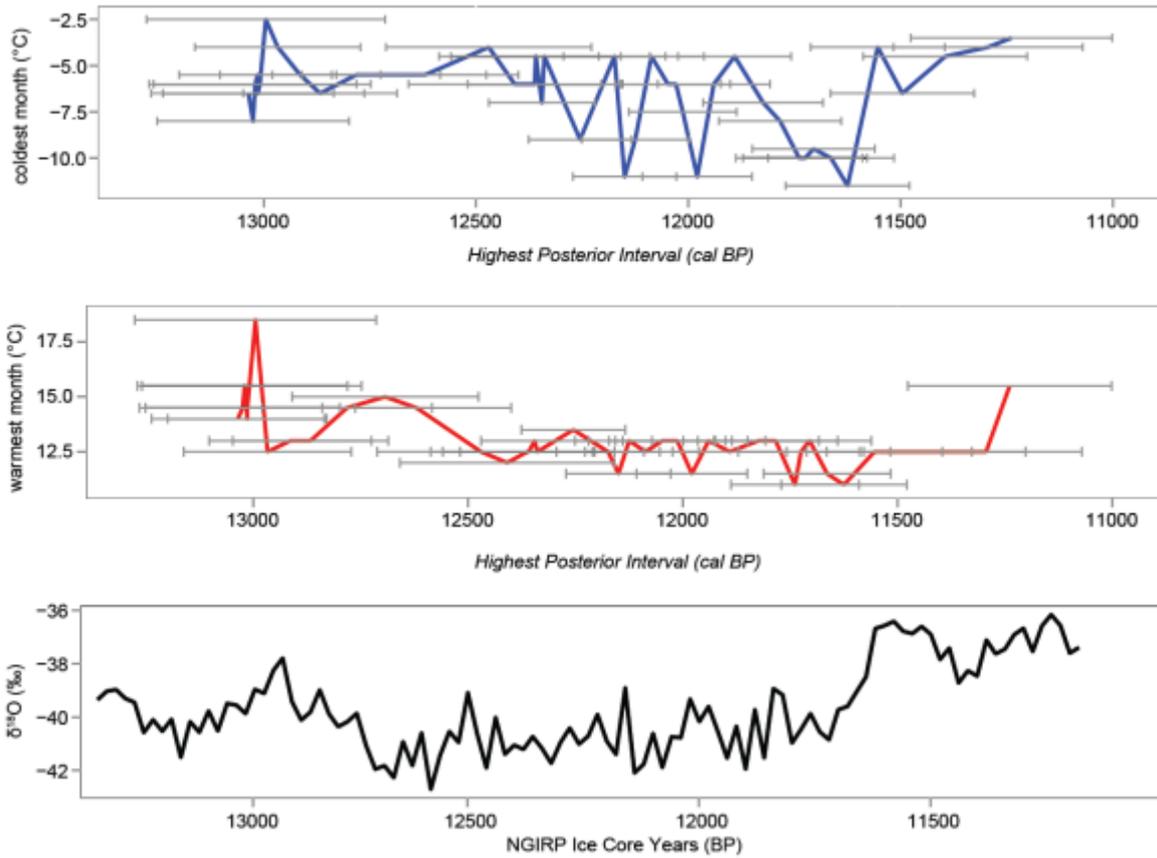
2568 **Fig 40** Gransmoor age-depth model constructed using Bchron. The 95% highest posterior density
 2569 regions (HDR) indicate the uncertainty of the ages assigned to the samples between the dated
 2570 depths. The probability distributions in grey represent the calibrated radiocarbon dates



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2572 **Fig 41** Histogram for the start (2.0m) and end (1.9m) of the *Betula sp.* decline, derived from the
 2573 model shown in Figure 40

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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 $\delta^{18}\text{O}$ record (NGRIP 2004). The chronology for late-glacial temperatures is derived from the model shown in Fig 40