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STONEHENGE, AMESBURY, WILTSHIRE
CHRONOLOGICAL MODELLING

SCIENTIFIC DATING REPORT

Peter Marshall, Timothy Darvill, Mike Parker Pearson, and Geoffrey Wainwright

INTERVENTION
AND ANALYSIS

ENGLISH HERITAGE

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SUMMARY

This report contains details of all the radiocarbon determinations obtained on samples dated from Stonehenge up to the end of 2011. A series of chronological models based on different readings of the archaeology are presented for the monument as a way of exploring how these interpretations influence our understanding of its chronology.

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CONTENTS

INTRODUCTION

This document is a technical archive report on the dating of Stonehenge and has been produced as part of a programme of research on the World Heritage Site. It is beyond the brief of this document to describe the archaeology of the site in detail – recent published accounts can be found in Darvill (2006), Field and Pearson (2010), Lawson (2007), and Parker Pearson (2012). The definitive volume on the twentieth-century excavations (Cleal *et al* 1995), together with the interim report on the small trench excavated in 2008 (Darvill and Wainwright 2009) should be consulted for more detailed information on the stratigraphy of the monument.

This report contains details of all the radiocarbon determinations obtained on samples dated from Stonehenge up to the end of 2011. A series of chronological models based on different readings of the archaeology are presented for the monument as a way of exploring how these interpretations influence our understanding of its chronology.

Stonehenge (SU 1224 4219) is located on Salisbury Plain about 12km north of Salisbury in the parish of Amesbury, Wiltshire (Scheduled Monument number 10390 and National Monuments Record number SU 14 SW 1). Its is the world's most famous stone circle and sits within one of the densest concentrations of Neolithic long barrows, cursus, henges, and early Bronze Age round barrows within northern Europe. It forms part of the Stonehenge, Avebury and Associated Sites World Heritage Site (Darvill 2005).

THE RADIOCARBON DETERMINATIONS

Details of all the radiocarbon determinations obtained on samples from Stonehenge, the Stonehenge Avenue, and Stonehenge Palisade up to the end of 2011 are presented in Tables 1–3. These tables include the results previously published in Cleal *et al* (1995), Bronk Ramsey and Bayliss (2000), and Parker Pearson *et al* (2009), together with a number cited in advance of full publication - Parker Pearson *et al* (forthcoming (a) and (b)).

Assessment of the interpretative value of the radiocarbon determinations

In order to identify the accurate measurements (ie where the radiocarbon concentration in the sample has been accurately measured) and the accurate dates (ie those accurate measurements from samples with good taphonomic provenance) an assessment of the existing radiocarbon determinations from the site was undertaken. This built on the extensive exercise undertaken by Allen and Bayliss (1995) using the following three basic criteria for assessing a sample:

Firstly, was the carbon from the sample in equilibrium with the carbon in the atmosphere when the sample died? The most widespread example of samples that are not in equilibrium are determinations obtained from long lived charcoal – the 'old-wood effect'

(Bowman 1990, 51). Other potential sources of error are reservoir effects (Bowman 1990, 24–7) and isotopic fractionation (Bowman 1990, 20–1), however, no samples from marine or freshwater reservoirs have been dated. The majority of the dates are conventional radiocarbon ages that have been corrected for isotopic fractionation using measured $\delta^{13}C$ values. The only exceptions are some of the early radiocarbon measurements where details of how exactly corrections for fractionation (using measured or global average values) were made has not been determined.

Secondly, has the sample been contaminated by a carbon containing material? Aside from the removal of contamination by the burial environment for which chemical pre-treatment protocols have been adopted by radiocarbon laboratories since the very first applications of the method, material from Stonehenge is fortunate in that very little conservation has been required with no evidence of Polyvinyl Acetate (PVA) having been applied to any samples. The assessment undertaken in Cleal *et al* (1995) of new and existing dates contained details of all the pre-treatment and measurement protocols employed; similar details for those measurements obtained since 1995 are listed in Appendix 1.

Thirdly, is the sample securely associated with the archaeological activity that is of interest? The fundamental importance of this relationship, when the dating of the sample is not of intrinsic interest in its own right, was first outlined in Waterbolk (1971) with more recent calls for a grater emphasis on sample taphonomy to be found in Van Strydonck *et al* (1999) and Bayliss (2009).

The interpretation of the taphonomy of the dated material from Stonehenge has been assessed as follows, in an approximately descending order of reliability based on that outlined in Bayliss *et al* (2011):

1) Bones found in articulation and recorded in the ground as such. These samples would have still been connected by soft tissue/tendons when buried and are therefore from people/animals which were not long dead (Mant 1987).

2) Bones identified as articulating during faunal analysis. These samples may have been articulated when deposited, although not recorded as such during excavation or have been slightly disturbed before final deposition. The presence of more than one bone from the same individual provides evidence that such samples are close in age to their contexts. The security of such an inference increases with the number of articulating bones that are recorded.

3) Cremations which appear, on the basis of the expected amount of bone to be produced (McKinley 1993), to represent complete *in situ* disposals.

4) Antler tools discarded on the base of the ditch and other negative features (stone holes) thought to be functionally related to the digging of the feature. This inference is

most secure when the tine is embedded in the base of the cut or striations from the picks are visible in the substrate.

5) Well-preserved disarticulated animal bones are interpreted on the basis that the latest date from a group of measurements should provide a *terminus post quem* which is earlier, but close in date to the actual date of interest.

6) Bulk samples of unidentified charcoal (eg C-602), even if functionally related to the feature, are treated as providing a *termini post quos* because of the potential for an unknown age-at-death offset (Bowman 1990).

7) Finally come samples which may well be residual or intrusive such as single bones from the fills of features (eg animal bone from the unidentified Q Hole, material in the fills of the ditch); carbonised plant material from small assemblages sieved from litres of sediment, and single fragments of bone (cremated or unburnt). Although these have often been dated because of intrinsic interest in the age of the material rather than to date their context.

THE RELIABLE AND REJECTED RADIOCARBON DATES

Tables 1 and 4 include all those determinations that we accept as being reliable for the purposes of understanding the chronology of the monument and its associated features. Tables 2 and 5 details those that have been 'rejected' on archaeological and taphonomic grounds and Tables 3 and 6 those 'rejected' as being unreliable for technical reasons.

Re-assessment of determinations obtained before 1995

For the majority of the dates obtained before 1995 our assessment has followed that outlined in Allen and Bayliss (1995), although below we summarise our reasoning for the re-interpretation of four dates 'rejected' by Allen and Bayliss (1995, 518–521) together with an assessment of the reliability of those determinations obtained since 1995.

Q Hole (OxA-4901)

The belief in a direct stratigraphic relationship between the Q and R Holes and the Sarsen Circle (Atkinson 1979, 61; Cleal *et al* 1995, 182–3) resulted in the interpretation that the feature from which the dated pig humerus (OxA-4901; 3800±45 BP) derived was a Q Hole being rejected, as this date had poor agreement when constrained to be earlier than those from the Sarsen Circle (Allen and Bayliss 1995, 521).

Atkinson (1979, 61) interpreted the fill of Q Hole 4 as being cut by the socket for Stone 3 in the Sarsen Circle, but his plan and photograph (Cleal *et al* 1995, figs. 278 and 92) illustrate that the cut for Stone 3 is much wider than almost all the others for sockets in the Sarsen Circle (cf. Case 1997, 164–5). Given that the 2008 excavations have clearly demonstrated that later episodes of digging adjacent to extant stones has resulted in recutting of their upper fills (Darvill and Wainwright 2009, 16) thus obscuring the original stratigraphic relationships between features, Atkinson's interpretation can no longer be upheld.

Additional support for reinterpreting the relationships between the Q and R Holes and the Sarsen Circle is provided by the fact that Stone 7 in the Sarsen Circle appears to have been recut on the inside (Cleal *et al* 1995, fig. 97) to produce its apparent relationship with Q Hole 9. Furthermore, WA 3433, a feature cut by the socket for Stone 60, part of the Trilithon Horseshoe, cannot be considered a Q or R Hole on the basis of its spatial position (Cleal *et al* 1995, figs. 96, 145 and plan 2).

Given the revised reading of the primary records and the fact that the Q and R Holes are not necessarily earlier than the Sarsen Circle, the measurement (OxA-4901) from the fill near the top of Q Hole does provide a date for the feature. However, as a single fragment of bone which has no functional relationship to the infilling event, we suggest this sample provides a *terminus post quem* for the Q Hole's infilling after the removal of its stone.

Secondary Ditch fill (OxA-4844, OxA-4879, and OxA-4903)

Two samples (OxA-4844 and OxA-4903) from the secondary fill of the ditch in C41 and C42 were 'rejected' when information came to light following Atkinson's death that suggested these samples may have been intrusive as a result of animal burrowing or mixing. While the sample from C41, OxA-4879, was 'rejected' due to uncertainty about which context the sample originated from (Allen and Bayliss 1995, 520–1).

Although we accept the possibility that these samples may be disturbed, we do not believe they can have been moved far from their original place of deposition given their size (OxA-4844 is a 'large *Bos*, axis vertebra'), and therefore they provide reliable *termini post quos* for the secondary infilling of the ditch.

Determinations obtained since 1995

Since 1995, 29 radiocarbon measurements have been produced on samples from Stonehenge, three from the Avenue (from a single sample), and two from the Palisade. The following section provides summary details of the dating programmes that produced these results and what additional information about the chronology of Stonehenge they provide. Details of the laboratory procedures used on these samples are given in Appendix 1.

Skeleton 4.10.4

Following the rediscovery in 1999 of skeleton 4.10.4, originally excavated by Hawley in 1926 inside the stone circle, two new samples were dated (Pitts *et al* 2002). Given that only three more or less complete skeletons have been found at Stonehenge, it was imperative to determine what age it was given suggested dates had ranged from Neolithic to Roman. The two original measurements (OxA-9921 and 9931) were withdrawn following the discovery of a contamination problem in the ultrafilitration protocol used for the processing of bone at Oxford in 2002 (Bronk Ramsey *et al* 2000), which resulted in some bone samples giving ages which were about 100–300 radiocarbon years (BP) too old (Bronk Ramsey *et al* 2004a), and replaced by a new determination (OxA-13193; 1258±34 BP). OxA-13193 is statistically consistent (T'=0.6, T'(5%)=3.6, ν=1; Ward & Wilson 1978) with an all but undocumented result on leg bone shafts from the same skeleton obtained from AERE Harwell in 1976 (1190±80 BP; Pitts 2001, 318; Pitts *et al* 2002, 134).

SPACES

Fourteen samples were submitted to the Oxford Radiocarbon Accelerator Unit in 2008 following excavations at Stonehenge earlier that year which aimed to date the construction of the Double Bluestone Circle (Q and R Holes; Darvill and Wainwright 2009). The material submitted was "charcoal recovered from the flotation of the environmental samples and bone from secure contexts" (Darvill and Wainwright 2009, 10). Where possible the selection of samples followed standard procedures (M Allen pers comm.); with single entity (Ashmore 1999) short-lived carbonised samples from the fills of features thought to be associated with stone sockets, which were duplicated if possible, and large unweathered bones preferred.

The samples

Excavation of the socket for Stone 10 (F10), part of the Sarsen Circle, ceased halfway down due to the restrictions of the trench (Darvill and Wainwright 2009, 13). Three charcoal samples (OxA-18653–18655; Table 2) from context [37] produced two post-medieval and a Mesolithic date. The two latest measurements (OxA-18653 and OxA-18654) are not statistically consistent (T'=37.6; ν=1; T'(5%)=3.8; Ward and Wilson 1978) and the context clearly contains material of very different ages. As the socket is cut by F5, a possible Roman grave from which a coin of Valens on its base provides a *terminus post quem* of AD 348. Explaining how the post-medieval dated material found its way into the fill is difficult.

The earliest features in the trench were four small circular pits and stake holes F11, F13, F15, and F16. As the small circular pits have no evidence for a post-pipe then interpreting them as post-holes is problematic, although it could be that the post-pipe does not survive at the base (Darvill and Wainwright 2009, 12). A single fragment of charcoal (OxA-18662) from F11, one of the small circular pits has been dated to 2920–2620 cal BC (95% confidence).

F11 is stratigraphically cut by the original part of F12 (Darvill and Wainwright 2009, 11) that would have been the hole for Q Hole 13 (ibid, 12). A single carbonised cereal grain (OxA-18660) from context [32], a fill at the base of the Q Hole, is the stratigraphically earliest fill of F12 that has been dated (cal AD 720–950; 95% confidence). An unfused pig phalanx from the later context [31] dates to cal AD 1440–1620 (95% confidence; OxA-18661). Three samples (OxA-18657–18659) from the stratigraphically later context [32] produced dates of cal AD 870–985 (95% confidence; OxA-18657), 2470–2200 cal BC (95% confidence; OxA-18658), and 3370–3090 cal BC (95% confidence; OxA-18658).

Context [28] is the bottom fill of a pit that cuts through the earlier fills of F11 from which a single fragment of oak sapwood dates to cal AD 1465–1645 (95% confidence; OxA-18656). The base of the re-cut contained a number of amphibian bones, suggesting the pit may have been open for some time, and it is therefore plausible that material migrated downwards into the underlying contexts through animal activity and bioturbation during this period (Darvill and Wainwright 2009, 11).

F12 (Q Hole 13) is cut by F6, which may originally have been the socket for Bluestone 35a, although pits and hollows dug against the stone have partly destroyed its original edges (Darvill and Wainwright 2009, 15). Three samples from context [23], part of the fill of F6 were dated; a single fragment of oak sapwood charcoal (OxA-18651; 3090–2900 cal BC), a carbonised cereal grain (OxA-18650; cal AD 1660–1955*), and piece of holly charcoal (OxA-18652; cal AD 1680–1955*). The two latest measurements are statistically inconsistent at 95% confidence (T'=4.3; ν=1; T'(5%)=3.8; Ward and Wilson 1978), but pass at 99% confidence.

A single human tooth (OxA-18649) from immediately below the turf (context [1]), although prehistoric in date may not even be from Stonehenge, as the turf was put down some 20–25 years ago, possibly incorporating topsoil from nearby (Darvill and Wainwright 2009, 7)

Assessment

For the purposes of modelling the chronology of Stonehenge, we have chosen to not use any measurements obtained from samples dated from the 2008 excavations, given the uncertainty about their taphonomy.

Discounting the tooth (OxA-18649) that might have been imported to the site the other 13 measurements do, however, provide a variety of important information about Stonehenge.

- The Mesolithic pine charcoal is further evidence that this species of tree was growing in the area in the early Holocene.
- Holly, which is not a common taxa of open woodland, hedgerow, and scrub (Barnett 2008), is represented in the dated charcoal assemblage from the Neolithic to post-medieval periods.
- The stratigraphic sequence is much more complex than commonly believed, with the re-cutting of features due to stone robbing and possibly antiquarian investigations (Darvill and Wainwright 2009, 11) being much more prevalent than previously thought.

Stonehenge Riverside Project

The Stonehenge Riverside Project started in 2003 with the overall aim of better understanding Stonehenge within its changing monumental and landscape context (Parker Pearson *et al* 2004). As part of this extensive project (for example see Parker Pearson *et al* 2006, 2008a; Thomas *et al* 2009) small-scale excavations have targeted the Stonehenge Avenue and Stonehenge Palisade.

The Avenue

In 2008, Richard Atkinson's 1956 trench, C48 (Montague 1995a, fig 178) was re-opened and extended (Parker Pearson and Pullen 2008). A single antler pick [1027] from layer [045] in pit 056, one of a pair (the other being 055), dug within the east side of the Avenue, was laid on the base of the pit prior to its backfilling. Three radiocarbon measurements on samples from the antler (OxA-20011, OxA-20350, and SUERC-23205; Table 1) are statistically consistent (T'=5.8; ν=2; T'(5%)=6.0; Ward and Wilson 1978) and allow a weighted mean to be calculated (SAV 1027; 3827±17 BP). The antler is interpreted as deriving from the digging of the pit and therefore provides a date for this activity.

The Palisade

Four trenches, also excavated in 2008, aimed to help better understand the date of construction of the Palisade Ditch and determine the extent of the original palisade line (Garwood *et al* 2008). A femur (UB-3820; Table 1) from the crouched burial (skeleton 9470) placed in a pit cutting the Palisade Ditch (C81), dated at the Queen's University Belfast in 1994 (Allen and Bayliss 1995), had previously provided an Iron Age *terminus ante quem* for the construction and infilling of the ditch.

Two samples; from an articulated sheep/goat (1018) deposited on the base of pit [1024] cut into the east terminal of the main ditch close to its intersection with the Palisade Ditch (SUERC-32160), and an infant buried at the base of pit [556] cut into the upper fills of the ditch (SUERC-32164; Table 1), were dated and provide mid to late Bronze Age *terminus ante quos* for the construction of the ditch.

Stonehenge Riverside and Beaker People Projects

A joint radiocarbon dating programme by the Stonehenge Riverside Project and Beaker People Project started in 2007 to determine when Stonehenge was used as a burial space (Parker Pearson *et al* 2009, 24). Given the aim of the programme was to date the age of individuals buried at the site, and not to contribute to the overall chronology, the majority of these samples only provide at best *termini post quos* for their contexts.

Aubrey Holes and an associated cremation

Since the 1995 radiocarbon dating programme, the ability to date cremated bone (Lanting and Brindley 1998, Lanting *et al* 2001, Van Strydonck *et al* 2005) has allowed for the first time the direct dating of human cremation burials found at Stonehenge, and in particular those associated with the Aubrey Holes and Ditch.

At present only a single sample (OxA-18036) from the cremation burial found within Aubrey Hole 32 (Parker Pearson *et al* 2009, 26) has been dated. The additional importance of this sample is due to the fact that it "is possibly from a primary context" (Walker 1995a, 101). Aubrey Hole 32 is different to other excavated examples "being deeper and larger, with more brown earthy fill cut through a thick layer of the chalk rubble" (Walker 1995a, 98; figs 49, 55). Thus the cremation in this Aubrey Hole seems to be the exception to the normal practice of insertion "some time after the hole had been dug and the primary silt formed" (Walker 1995b, 152).

The 150.7g of cremated bone in context [3008] (AH 32) probably represents only part of the whole cremation burial (maximum 15% expected body weight; McKinley 1993; 1995, 458). A few scattered fragments of cremated bone from the disturbed main fill were recovered (Atkinson *et al* 1952), however, this material does not survive and therefore it is not possible to determine whether it represented the same burial (McKinley 1995, 458).

Re-excavation of Aubrey Hole 7 (AH 7) in 2008 to recover the cremations from the Aubrey Holes and Ditch excavated by Hawley (Parker Pearson *et al* 2009, 21), and interred here in 1935, also revealed a bowl-shaped pit containing an untouched cremation burial (weight 689.5g – maximum 66% body weight, McKinley 1993). Unfortunately, its relationship with AH7 could not be established because of truncation by previous excavations, although it is possible that the cremation is later than the Aubrey Hole (Parker Pearson *et al* 2008b, 15).

Ongoing analysis of the cremated bones from Aubrey Hole 7 to identify a minimum number of individual (MNI) and duplicated bones suitable for radiocarbon dating (to ensure that the same individual is not dated more than once) is ongoing (C Wills pers comm). The results from the dating of this material will provide important information about the currency of cremation activity at Stonehenge, but unfortunately, as the context of the cremations cannot be determined, they cannot be used to model the overall chronology of the site.

Ditch fills

Seven samples of human bone were dated from the fills of the Ditch, two from cremations and five from unburnt bone fragments.

Cutting 42, west of the north-east entrance was excavated by Atkinson in 1954 and contained the cremation burial (54/821) of a young adult female in context 3898 (McKinley 1995, 458). The large amount of bone that had been collected for burial, 1546.6g, represents a minimum of 45% of the expected bone weight and possibly most of the recoverable bone (McKinley, 1995, 458, 1993). Two other small amounts of cremated bone from context 3898 (54/820, 54/841, with unburnt bones 54/843 and 54/848) were scattered in the ditch fragment and may have derived from the same cremation – there is no osteological evidence to suggest they did not (J McKinley pers comm). As the dated bone fragment 54/841 (OxA-17957; Parker Pearson *et al* 2009, 26) does not derive from the single discrete deposit (54/821), clearly representing an *in situ* burial, it does not provide a constraint for the construction of the ditch, but simply a *terminus post quem* for its secondary infilling.

Atkinson also recovered 78.9g of cremated human bone (McKinley 1995, table 58) from within Cutting 41 (context 3893). This cremated material was collected from the upper Ditch silt, Ditch fill, and upper Ditch fill suggesting that the burial had been disturbed. Given that the burial is clearly not *in situ*, and the uncertainty about the exact location of the sample (54/36), the determination (OxA-17958) provides a *terminus post quem* for the end of secondary infilling of the Ditch.

The five unburnt fragments of human bone from the ditch fills were selected “to establish whether any of them were contemporary with Stonehenge’s three principal stages of use within the third millennium cal BC” (Parker Pearson *et al* 2009, 27), not to explicitly contribute to understanding the chronology of the Ditch. The results have been assessed as follows:

OxA-V-2232-46, one of four fragments from the same parietal found in the upper filling of the Ditch (C25) excavated by Hawley in 1922 (Cleal *et al* 1995, 125–6) provides a *terminus post quem* for the end of its secondary infilling.

OxA-V-2232-47 a single fragment of human skull from the fill of the Ditch in C28 (eastern section) excavated in 1925 provides as *terminus post quem* for the end of secondary infilling.

OxA-V-2232-48, one of two conjoining skull fragments from the secondary ditch fill (C19) excavated in 1920–1, is significantly later than the Beaker-age burial that provides a *terminus ante quem* for the secondary infilling of the Ditch, and the sample must therefore be intrusive. It has therefore been excluded from the modelling, although it provides a date for the death of the individual.

OxA-2232-49, a single fragment of skull from the 'topsoil' (McKinley, table 59) of the fill of Ditch cutting C42 provides a *terminus post quem* for the deposit but does not provide a constraint for the infilling of the Ditch as it could be residual. Given the uncertainty as to the actual position of the sample due to the paucity of the records (Cleal *et al* 1995, 72), we have excluded the measurement from the modelling.

OxA-2232-50, a single adult ulna from ditch fill (1384, C21) cannot be assigned to any of the ditch fills because the entries for this section of the ditch in Hawley's diary are missing (Cleal *et al* 1995, 84). We have therefore decided to exclude the determination from the modelling.

Sarsen Circle - Stone 27

OxA-2232-34, the dentine from the root of the lower left 2nd premolar, provides a *terminus post quem* (cal AD 770–950) for the upper fill (WA 3543; Stonehenge layer) of Stonehole 27 excavated by Atkinson in 1964 (Cleal *et al* 1995, 188–91). We have therefore decided to exclude the determination from the modelling as it clearly does not relate to the third millennium cal BC activity on the site.

Postholes

The pig rib fragment (OxA-V-2232-51), dated from the fill [1885] of posthole ([1884] in Cutting 8) between Stones 8 and 9 (Cleal *et al* 1995, 541; figs 69 and 274), was dated as the human rib from this context (McKinley 1995, table 59) could not be located in the archives (Parker Pearson *et al* 2009, 29). The result provides a *terminus post quem* for the infilling of the posthole as the single fragment of animal bone could be residual.

The human dentine from the root of the upper left 1st premolar (OxA-V-2232-35), recovered from a possible posthole ([1815] in Cutting 7; McKinley 1995, table 59) in the eastern area, has been excluded from the modelling due to uncertainty about its context and because it is early medieval in date.

The reliable radiocarbon dated samples

The reassessment has identified a total of 68 radiocarbon determinations which can contribute to our understanding the chronology of Stonehenge, this total includes:

- Fifty-three for the monument and associated features.

- Three from the Palisade Ditch.
- Seven from the Avenue.
- Five from the Mesolithic postholes.

The reliable series (Table 1) also contains results that although not of direct relevance for understanding the third millennium cal BC chronology of the monument, do provide important information on later use of the site (inhumation 4.10.4) and cultural artefacts (OxA-4855).

ANALYSIS OF THE RADIOCARBON DATES

Results

The radiocarbon results given in Tables 1–3, and are quoted in accordance with the international standard known as the Trondheim convention (Stuiver and Kra 1986). They are conventional radiocarbon ages (Stuiver and Polach 1977).

Calibration

The calibrations of the results, relating the radiocarbon measurements directly to calendar dates, are given in Tables 1–3 and in Figures 1–4. All have been calculated using the calibration curve of Reimer *et al* (2009) and the computer program OxCal (v4.1) (Bronk Ramsey 1995; 1998; 2001; 2009). The calibrated date ranges cited in the text are those for 95% confidence. They are quoted in the form recommended by Mook (1986), with the end points rounded outwards to 10 years. The ranges quoted in italics are posterior density estimates derived from mathematical modelling of archaeological problems (see below). The ranges in Tables 1–3 have been calculated according to the maximum intercept method (Stuiver and Reimer 1986). All other ranges are derived from the probability method (Stuiver and Reimer 1993).

Methodological approach

A Bayesian approach has been adopted for the interpretation of the chronology from this site (Buck *et al* 1996; Bayliss *et al* 2007a; 2011). Although the simple calibrated dates are accurate estimates of the dates of the samples, this is usually not what archaeologists really wish to know. It is the dates of the archaeological events, which are represented by those samples, which are of interest. In the case of Stonehenge, it is the chronology of the monument that is under consideration, not the dates of individual samples. The dates of this activity can be estimated not only using the scientific dating information from the radiocarbon measurements, but also by using the stratigraphic relationships between samples.

Fortunately, methodology is now available which allows the combination of these different types of information explicitly, to produce realistic estimates of the dates of interest. It should be emphasised that the posterior density estimates produced by this modelling are not absolute. They are interpretative estimates, which can and will change as further data become available and as other researchers choose to model the existing data from different perspectives.

The technique used is a form of Markov Chain Monte Carlo sampling, and has been applied using the program OxCal v4.1 (http://c14.arch.ox.ac.uk/). Details of the algorithms employed by this program are available from the on-line manual or in Bronk Ramsey (1995; 1998; 2001; 2009). The algorithm used in the models described below can be derived from the structures shown in Figures 5–8, 13–14, 16, 18, 20, and 22.

For features with more than one dated item we have followed Bayliss *et al* (1997, 56) in calculating the last dated event as the best estimate of construction. This is based on the principle that the last dated material in a context should provide the most accurate date for its formation. Although such an approach does not counteract the inherent statistical scatter of radiocarbon measurements (Bayliss *et al* 2011), the small number of measurements from features associated with the stone settings should counteract this problem.

Mesolithic activity

The model for Mesolithic activity (Bronk Ramsey and Allen 1995, fig. 267; Bronk Ramsey and Bayliss 2000; fig 5.2) that includes the prior information that the five dates are randomly selected from a uniform phase of activity (Buck *et al* 1992) has been re-run. The model (Fig 5) has good overall agreement (Amodel=85%) between the radiocarbon dates and prior information, and provides an estimate for the span of dated events of between *305–1595 years* (*94% probability*) with these events taking place between *8580–7645 cal BC* (*95% probability; first_mesolithic*) and *7520–6820 cal BC* (*95% probability; last_mesolithic*). Due to the fact that the prior information about the phase of activity weighs a short phase more strongly, the small number of measurements does not provide useful estimates for the start and end of the phase of activity. It should also be borne in mind that the pine trees used for the posts may themselves have been up to 200 years in age (Bronk Ramsey and Allen 1995, 528), so the samples may have a considerable age-at-death offsets (Bowman 1990).

The Ditch and Aubrey Holes

The early phase of activity and initial construction of the monument comprised the digging of a segmented ditch with a bank and counterscarp, the use of the Aubrey holes (for either posts or standing stones), and the interment of cremation burials (Cleal *et al* 1995).

The Ditch

Two models are presented below for the chronology of the Ditch; the first of these is based on a re-running of the original model (Bronk Ramsey and Bayliss 2000), with the inclusion of the additional measurements obtained as part of the Stonehenge Riverside and Beaker People Projects, and re-assessment of the taphomony of sample (OxA-5982). The second is based on a revised interpretation of the ditch sequence (Parker Pearson *et al* 2009, 29–31).

Since the last two samples (OxA-5981 and OxA-5982) from the fill of the ditch were measured in October 1995 (Bronk Ramsey and Bayliss 2000), a further seven samples (OxA-V-2232-46–2232-50, and OxA-17957–8; Parker Pearson *et al* 2009; see above) have been dated, although only four of these, (OxA-17957–8, and OxA-V-2232-47–48), have been assessed as contributing usefully to the chronology of the monument (see above).

Re-analysis of the Ditch sequence (Parker Pearson *et al* 2009) and interrogation of the primary records relating to the two samples dated in 1995 (OxA-5981 and OxA-5982; Bronk Ramsey and Bayliss 2000; table 5.2) showed that the cattle vertebra (OxA-5982) from cutting C42 was not from three articulating vertebra (S54.862, 863, 864) but a single vertebra, with the other two being from different individuals (Serjeantson pers comm.). Hence this sample does not provide a constraint for the digging of the Ditch (contra Bronk Ramsey and Bayliss 2000) as it could be residual and therefore only provides a *terminus post quem* for the secondary Ditch fill.

The original Ditch model

The following minor changes to the Bronk Ramsey and Bayliss (2000, fig 5.2) model for the Ditch included in our re-running are as follows:

- OxA-5982 does not provide a constraint on the digging of the Ditch (see above).
- OxA-5982 and all the other samples from the secondary fill (including OxA-17957–58 and OxA-V-2232-47–48) of the Ditch that could be residual (Table 1) are included as providing *termini post quos* for the accumulation of the Ditch's secondary fill.
- The articulated piglet (OxA-5981) must be later than the construction of the ditch and the material used to excavate it and therefore provides a constraint for this event.

The updated version of the Bronk Ramsey and Bayliss (2000, fig 5.2) model (Figs 6–8) shows good agreement between the radiocarbon dates and prior information (Amodel=82%). This produces an estimate for the digging of the ditch of *2990–2755 cal BC* (*95% probability*, *ditch_constructed*, Fig 6) and probably *2955–2830 cal BC* (*68% probability*).

The curated animal bones deposited on the base of the Ditch terminals either side of the southern entrance were collected between *3640–3085 cal BC* (*95% probability*, *start structured deposit*, Fig 6) or *3400–3165 cal BC* (*68% probability*) and *3315–2910 cal BC (95% probability*, *end structured deposit*, Fig 6) or *3245–3015 cal BC* (*68% probability*). By taking the difference between *end structured deposit* and *ditch_constructed* (Fig 6) we can therefore estimate the latest of these deposits was *5–435 years* old (*95% probability*, Fig 9) or *110–360 years* old (*68% probability*) before being placed on the base of the Ditch.

The difference between *start_ditch_antlers* and *end_ditch_antlers* (Fig 6) allows us to estimate that the antlers used for the digging of the Ditch represent material collected over a period of *1–125 years* (*95% probability*, Fig 10) and probably *1–55 years* (*68% probability*).

Following the completion of the Ditch and the placing of the curated animal bone on its bottom, the primary fill of the Ditch started to accumulate. Although no samples from the primary fill have been dated we can estimate how long the primary phase of sediment accumulation was (ie the difference between the first dated event in secondary fill (*first_secondary_fill;* Fig 6) and the estimate for construction of the Ditch (*ditch_constructed;* Fig 6). The primary infilling of the ditch with chalk rubble (Cleal *et al* 1995, 71) and the overlying dark chalky loam (Evans 1984, 10) occurred over a period (this is a maximum given the one constraining sample does not come from the base of the secondary fill) of *10–255 years* (*95% probability*, Fig 11) and probably *50–190 years* (*68% probability*). This should be compared with the estimate for the initial rapid silting of the primary fill of the ditches of 20 years (Allen 1995a, 5).

The secondary fill of the ditch clearly contains some residual material, with a cumulative probability of 69% that four samples (UB-3791, OxA-4904, OxA-4843, and OxA-5982; Table 7) are older than the digging of the ditch.

As the secondary filling of the ditch seems to have ceased by the time the Beaker-age grave was dug (Walker and Montague 1995, 162), in *2345–2195 cal BC* (*95% probability*, *Beaker_burial*, Fig 8) or *2295–2200 cal BC* (*68% probability*), the time taken for the infilling of the ditches primary and secondary fills can be estimated as between *455–770 years* (*95% probability*, Fig 13) and probably *550–710 years* (*68% probability*).

The Ditch - re-cut

A re-examination of the records relating to the ditch fills has revealed the presence of what appears to be a clear stratigraphic break that has been interpreted as a re-cut of the upper fills of the ditch that took place before the insertion of the Beaker burial (Parker Pearson *et al* 2009, 29–31). This has resulted in the following changes to the interpretation of the stratigraphy of the dated samples from the ditch's secondary fill and re-cut in our alternative model.

OxA-5981 provides a date for the secondary infilling of the ditch and the following; OxA-4883, 4904, 5982, UB-3791, OxA-17957–58, OxA-V-2232-46–47, and OxA-V-2232-51 provide *termini post quos* for this period of deposition.

The following samples can be located within the fill of the re-cut of the ditches secondary fill and therefore provide *termini post quos* for the infilling of the re-cut; OxA-4841, 4843, 4844, 4879, 4880, 4881, 4882, and 4903.

A model (Fig 13) including this revised interpretation of the stratigraphy of the ditch and the inclusion of the three dates (OxA-4844, 4879, and 4903) rejected by Bayliss *et al* (1995, 520–21; see above) does not change the estimate for the digging of the Ditch. This is because the one sample from the ditch fill that can be demonstrated to not be residual (OxA-5981) cannot be precisely located to either the secondary fill or the re-cut, and is therefore included as being later than the digging of the Ditch. The only new estimate to be derived from the revised model for the Ditch is the production of an estimate for the date after which the re-cut must have happened of *2450–2230 cal BC* (*95% probability*; *Last re-cut*; Fig 13) and probably *2400–2280 cal BC* (*95% probability*). The other estimates given above remain unchanged.

Alternative 'uninformative priors'

The models (Figs 6–8 and 13) for the two groups of material from the base of the ditch – the animal bone deposits and antlers – both assume that the dated material represents a random sample of a material that was gathered at a fairly constant rate over the period of collection (Bayliss *et at* 1997, 50). This 'uniformative prior' has been found to be fairly robust (Bayliss *et al* 2007a), however, in order to evaluate what differences (cf sensitivity analyses Buck *et al* 1996) the different assumptions made we constructed an alternative model. This is based on the suggestion that it is actually most likely that the antlers found in the base of the ditch come from the last stage of construction, with a few older antlers being mixed in the same deposit (Bronk Ramsey 2009). An exponential distribution rising to the greatest numbers of samples found from the end of the phase construction (Bronk Ramsey 2009) provides the best way of mathematically implementing such a scenario.

A model incorporating an exponential distribution for the antlers deposited on the base of the ditch (Fig 14) has good overall agreement (Amodel=92%). It provides a slightly longer estimate for the period over which the antlers were collected - *1–150 years* (*95% probability*; Fig 15) or *1–80 years* (*68% probability*) as against *1–125* (*95% probability*) or *1-55 years* (*68% probability*) derived from the original ditch model (see above), however, the estimate for the date of construction of the ditch is identical in both.

Aubrey Holes

The two measurements from the dated cremations, from Aubrey Hole 32 (AH 32) and the pit adjacent to Aubrey Hole 7 (AH 7), are statistically consistent (T'=3.2; ν=1; T'(5%)=3.8; Ward and Wilson 1978) and could therefore be of the same actual age. Given that only two independently events associated with the Aubrey Holes have been dated we have not modelled this phase of activity. Figure 6 therefore shows the chronological relationship between the digging of the Ditch (see above), and the dated cremations from Aubrey Hole 32 and the pit adjacent to Aubrey Hole 7.

On the basis of the very limited evidence presently available there is a *86% probability* that the cremation in AH 32 pre-dates the Ditch and a *98% probability* that the cremation from next to AH 7 is earlier. Hence there is an *84% probability* that both the dated cremations associated with the Aubrey Holes are earlier than the construction of the Ditch.

The possibility that the Aubrey Holes are part of activity that pre-dated construction of the Bank and Ditch has been suggested on the basis that the spacing in the circle takes no account of the north-east entrance, although the correspondence between AH 23 and AH 22 and the southern entrance is suggested to be a coincidence Walker (1995a, 107).

Radiocarbon dating of the cremated remains interred in AH 7 will not conclusively identify the Aubrey Holes as pre-dating the construction of the enclosure because AH 7 is known to contain all the cremated material that Hawley excavated from the Aubrey Holes, the Ditch and the back of the Bank. This unfortunately means the context of the cremations has been lost so the results, although of undoubted importance for understanding the currency of cremation burials at Stonehenge, will not contribute to a better understanding of the overall chronology.

The Avenue and stone settings

The results of the radiocarbon dating programme published in Cleal *et al* (1995) acknowledged the very limited number of samples available for dating from the phases of activity associated with the stone setting, their possible timber pre-cursor, and the Avenue. Since 1995, small-scale excavations of the Avenue (Parker Pearson *et al* 2008b) and the interior of Stonehenge (Darvill and Wainwright 2009) have taken place with the aim of addressing this issue. However, the number of reliable radiocarbon measurements available for modelling the third millennium cal BC chronology of the Avenue and stone settings/timber phase of the monument is still only 22 and this includes seven from the Avenue!

The Avenue

The model for the dating of the Avenue (Fig 16) is derived from Parker Pearson *et al* (forthcoming (a)) and shows good agreement between the radiocarbon dates and stratigraphy (Amodel=67%). In this model pit 056 is interpreted as post-dating the initial Avenue ditch but pre-dating the re-cutting. The best estimate for the date of its construction is *2430–2200 cal BC* (*95% probability*; *Last construction*; Fig 10) and probably *2370–2275 cal BC* (*68% probability*).

Interpretations of the stratigraphic and structural sequence of the stone settings

A number of alternative chronological models for the 'timber' and stone phases of activity at Stonehenge are discussed below. The differences in these models relate to different archaeological interpretations of the stratigraphic and structural sequence.

Model 1

The first Bayesian model for the dating of Stonehenge (Bronk Ramsey and Allen 1995; Bayliss *et al* 1997; Bronk Ramsey and Bayliss 2000, and Bayliss *et al* 2007b, fig 8) has been re-run using the current internationally agreed calibration data (Reimer *et al* 2009). The model is based on the assumption that each of the major settings is a unitary construction and hence stratigraphic relationships between one element is representative of the overall picture (Bayliss *et al* 2007b, 46). In this reading of the sequence the Sarsen Trilithons must be earlier than the Bluestones settings and the Sarsen Circle must be earlier than the Z Holes (Fig 17). The model (Fig 18) shows good overall agreement (Amodel=84%) and the revised estimates for the dates of construction of the stone settings are shown in Table 8.

Model 2

The alternative model published by Bayliss *et al* (2007b; fig 9), incorporating the sequence (Fig 19) proposed by Case (1997) with the antler (UB-3821) from the Sarsen Circle excluded as being residual, has also been re-run. This is based on the simple architectural logic that the Sarsen Trilithons must have been erected before the Sarsen Circle (Case 1997). The model (Fig 20) also shows good overall agreement (Amodel=80%) and the revised estimates for the construction of the stone settings from this model are given in Table 9.

Model 3

Many of the relationships between architectural elements are based on single intersections; recent re-evaluation of excavation archives (Parker Pearson *et al* 2007) and the 2008 excavations (Darvill and Wainwright 2009) have resulted in a different reading of some of the relationships described in Cleal *et al* (1995).

A third model based on this revised sequence (Darvill *et al* 2012) is summarised in Figure 21 and incorporates the following revision to that described in Cleal *et al* (1995).

Trilithon Horseshoe

The stratigraphy around the western upright of the Great Trilithon (Stone 56) has been re-evaluated from the primary excavation records (Parker Pearson *et al* 2007, 619–26). The construction ramp for Stone 56 (WA 2448/3773; Cleal *et al* 1995, fig. 100) has been re-interpreted as a large pit dug against the northwest side of the stone, after the construction of the Trilithon Horseshoe, and prior to construction of the Bluestone Horseshoe. Thus the latest of the two samples (BM-46 and OxA-4839) provides the best estimate for digging pit (WA 2448).

Bluestone Circle and Q and R Holes

As the Bluestone Circle is later than the Q and R Holes (Cleal *et al* 1995, 330, table 68) this stratigraphic relationship has been included in the model, given that OxA-4901 is interpreted as being from the backfill of a Q Hole.

New samples

The model incorporates a single *terminus post quem* for the timber settings on the eastern side (OxA-V-2232-51).

The model (Fig 22) based on this new reading of the sequence shows good overall agreement (Amodel=88%) and the estimates for the construction of the stone settings are given in Table 10.

Order of construction

The radiocarbon evidence from the models for the stone settings provides a most likely order for the all of the dated constructional events of:

Model 1 Sarsen Circle>Stonehole E>Sarsen Trilithons>Beaker burial>Bluestone Circle>Bluestone Horseshoe>Z Holes>Y Holes.

The probability of this is though only 27%.

Model 2 Stonehole E>Sarsen Trilithons>Beaker burial>Bluestone Circle>Bluestone Horseshoe>Z Holes>Y Holes.

The probability of this is only 31%.

Model 3 Sarsen Circle>Stonehole E>Sarsen Trilithons>Beaker burial>pit_WA_2448>Bluestone Circle>Bluestone Horseshoe>Z Holes>Y Holes.

The probability of this is though only 13%.

Tables 11-13 provide order probabilities for individual constructional elements derived from Models 1-3 (Figs 18, 20, and 22).

Constructional elements

If the sequence is analysed using groups of constructional elements that are believed archaeologically to belong together, for example the Stages proposed by Darvill *et al* (2012; Table 14) then the probability of the order being correct increases to 97.9% for Model 3. This offers a more robust indication of the sequence because it is not reliant on single dates from structural elements. Similarly for Models 1 and 2 with the following constructional groups as defined in Cleal *et al* (1995); Sarsen settings (Sarsen Circle and Trilithons), Bluestone settings (Bluestone Circle and Horseshoe), and the Y and Z Holes, the probability is >99%.

Models, data, and statistics

The models that have been produced for the stone settings are attempts to produce a description of the processes that generate the data which has been obtained (Scott 2011). Given that "all models are wrong" (Box 1979) due to the fact that they are a simplification of reality we need to decide whether anything is importantly wrong with them. The statistical techniques employed in this analysis provide quantitative estimates of model outputs, but these models need to be scrutinised with the same degree of critical archaeological judgement as would the output of any other model.

The prior beliefs incorporated into the chronological models derive from a number of archaeological sources. In some cases strong archaeological evidence exists for the relative chronology of samples, but stratigraphy is not the only archaeological evidence which can provide information on relative chronology – at Stonehenge the practical limitations of raising stones, eg the Sarsen Trilithons (Case 1997) gives evidence for how various phases of the monument must have been constructed.

In considering the evidence for these alternative models we have in effect undertaken a 'sensitivity analyses' – that is to explore how the results are affected by changes in the model or in the data (Scott 2011, 561). If the outputs from the models are very similar the model can be regarded as insensitive to the components that have been changed. While conversely if the model outputs vary significantly then the model is sensitive to that component.

All three models show good agreement between the radiocarbon dates and prior information (Amodel>60%; Bronk Ramsey 1995, 2009). The overall index of agreement is calculated for a model from the individual agreement indices (Bronk Ramsey 2009) and provides a measure of the consistency between the prior beliefs included in a model and the calibrated radiocarbon dates. The individual index of agreement (A: Bronk Ramsey 1995) is derived from the overlap between the calibrated date included in the model and the posterior probability distribution for that sample. Only a single sample BM-46 has a value <60% (Models 1 and 2), indicating a potential variance between the prior information and the radiocarbon date, however, in this case it is probably a reflection of the radiocarbon result being a simple statistical outlier.

They also have convergence values (>95%) indicating that the MCMC sampling has reached a representative solution (Bronk Ramsey 1995). As such, all three models are equally plausible with the estimated date for the beginning of the stone settings phase almost identical in all the models (Tables 8–10; Figs 18, 20, and 22; *start_stone_settings*).

The sensitivity analysis undertaken as part of this exercise has demonstrated that the following archaeological interpretations are at present of primary importance to the chronology of the monument:

1) The Sarsen Circle seems likely to be the first dated event, but this is reliant on a single sample that could be residual (Case 1997). The interpretation of this sample therefore has important consequences for how the chronology of the Sarsen Circle and Sarsen Trilithons are perceived; was it a sequential unitary programme, or did it take place over a longer period of piecemeal construction (Bayliss *et al* 2007b, 46)?
2) The stratigraphy around the western upright of the Great Trilithon (Stone 56). Either this is interpreted as the construction ramp for Stone 56 (WA 2448/3773; Cleal *et al* 1995, fig. 100) or as a large pit dug against the north-west side of the stone after the construction of the Trilithon Horseshoe, and prior to construction of the Inner Bluestone Circle. (Parker Pearson *et al* 2007, 619–26).

DISCUSSION

"*As to when Stonehenge was built, it must be frankly admitted that any definitive date is at present beyond our knowledge*" (Newell 1929, 88).

Undoubtedly the most important conclusion from the modelling is that some of the Aubrey Holes probably pre-date the construction of the Ditch and Bank at Stonehenge. The dating of cremated bones deposited in AH 32 and in a pit associated with AH 7 has for the first time allowed these features to be independently dated and placed with the Stonehenge sequence. Before the advent of radiocarbon dating of cremated bone (Lanting *et al* 2001), these features had simply been assigned to the first phase of activity on the basis that their accurate layout could not have been achieved with the stone settings in place (Walker 1995a, 96).

In order to provide a more robust estimate for the date of the Aubrey Holes the submission of further samples for radiocarbon analysis is required. This material could potentially come from some of the skewer pins (bone) in the archive (Montague 1995b, 409-14), if these can be demonstrated to be fully cremated, (heated to >600°) rather than just burnt. Alternatively, excavation of a number of the 22 un-excavated Aubrey Holes is likely to have a high probability of providing samples for dating given that only 24% of the 34 excavated examples have so far failed to yield cremated bones. Excavation would also allow the somewhat vexed question of what the original purpose of the Aubrey Holes was to be more fully explored. A full discussion of the alternative hypotheses is beyond the brief of this report but they can be found in Atkinson (1979); Burl (2006), Cleal *et al* (1995), Hawley (1921), and Parker Pearson *et al* (2009).

All three chronological models for the stone settings at Stonehenge presented above have produced stable model outputs with the prior beliefs they contain being compatible with the available radiocarbon dates. Thus, although the statistical models have allowed us to combine different types of information, we ultimately still need to use archaeological judgement to decide between them.

The models are all based on the belief that the major settings are the product of single (relatively quick) unitary episode of activity rather than the result of longer and more piecemeal episodes of construction (Bayliss *et al* 2007b, 46). Given the limited number of samples available at present such an assumption remains the only pragmatic way of modelling the chronology. Sensitivity analyses have highlighted the key component of these models that determines the differences in the monuments chronology is the relationship between the Sarsen Circle and Trilithons. The choice of a preferred model is therefore at present a simple matter of archaeological interpretation, and without further excavation to provide more samples associated with the major constructional events (for example the Sarsen Circle), reaching agreement is likely to be some way off. Model 3 is our preference for the chronology of the monument because it incorporates what we believe to be the most reliable reading of the stratigraphy of the stone settings (Darvill and Wainwright 2009, Darvill *et al* 2012; Parker Pearson *et al* 2007, 2009).

TABLES

Table 1: Radiocarbon determinations accepted for the purposes of modelling the chronology of the monument Stonehenge

Lab Number	Material	Context	Radiocarbon Age (BP)	$\delta^{13}C$ (‰)	$\delta^{13}C$ (‰) diet	$\delta^{15}N$ (‰)	C:N	Calibrated date range (95% confidence)	Reference
Aubrey Holes and associated features									
OxA-18036	Cremated human longbone fragment	Aubrey Hole 32, [3898].	4332±35					3080–2890 cal BC	Parker Pearson *et al* 2009
C-602	Charcoal, unidentified	Aubrey Hole 32,	3798±275					3010–1520 cal BC	Atkinson *et al* 1952
SUERC-30410	Cremated human bone, femur fragment	Cremation adjacent to Aubrey Hole 7	4420±35	-22.7				3330–2910 cal BC	Parker Pearson and Cox Wills 2010
Ditch – antlers									
UB-3788	Antler, *Cervus elaphus*, pick	Ditch primary fill, [2804], (C20)	4381±18	-22.5				3090–2915 cal BC	Allen and Bayliss 1995
UB-3787	Antler, *Cervus elaphus*,	Ditch primary fill, [2801], (C22)	4375±19	-23.1				3085–2910 cal BC	Allen and Bayliss 1995
UB-3789	Antler, *Cervus elaphus*, pick	Ditch primary fill, [2800], (C22)	4430±18	-23.1				3010–2895 cal BC	Allen and Bayliss 1995
UB-3790	Antler, *Cervus elaphus*,	Ditch primary fill, [2799], (C22)	4367±18	-23				3080–2910 cal BC	Allen and Bayliss 1995
UB-3792	Antler, *Cervus elaphus*	Ditch primary fill, [2935], (C25.2)	4365±18	-22.9				3080–2910 cal BC	Allen and Bayliss 1995
UB-3793	Antler, *Cervus elaphus*	Ditch primary fill, [2934], (C25.4)	4393±18	-23.4				3095–2915 cal BC	Allen and Bayliss 1995
UB-3794	Antler, *Cervus elaphus*, ?rake	Ditch primary fill, [2934], (C25.4)	4432±22	-23.7				3310–2940 cal BC	Allen and Bayliss 1995
BM-1583	Antler	Ditch primary fill near west terminal, [3895/3900], (C41/2)	4410±60	-22.7				3350–2900 cal BC	Burleigh *et al* 1982
BM-1617	Antler	Ditch primary fill near west	4390±60	-22.7				3340–2890 cal BC	Burleigh *et al* 1982

		terminal, [3895/3900], (C41/2)							
Ditch – structured deposits									
OxA-4833	Animal bone, *Cervus elaphus*, right tibia	Ditch south entrance near terminal, [3928], (C26.2)	4550±60	-22.5				3500–3020 cal BC	Allen and Bayliss 1995
OxA-4835	Animal bone, *Bos* right jaw, with three teeth	Ditch south entrance near terminal, [2480], (C26.2)	4455±40	-22.4				3350–2920 cal BC	Allen and Bayliss 1995
OxA-4834	Animal bone, *Bos* right jaw with four teeth	Ditch south entrance near terminal, [3929], (C26.6)	4460±45	-23.1				3360–2920 cal BC	Allen and Bayliss 1995
OxA-4842	Animal bone, *Bos primigentus*, skull	Ditch south entrance near terminal, [3930], (C29.4)	4520±100	-23.8				3620–2910 cal BC	Allen and Bayliss 1995
Ditch – secondary infilling									
UB-3791	Antler, *Cervus elaphus*, pick	Ditch secondary fill near ENE causeway, [1552], (C25.2),	4397±18	-21.5				3095–2920 cal BC	Allen and Bayliss 1995
OxA-4904	Antler, *Cervus elaphus*, tine	Ditch base of secondary fill, [3893], (C41)	4365±55	-22.4				3310–2880 cal BC	Allen and Bayliss 1995
OxA-4881	Red deer, meta tarsal	Ditch upper secondary fill, [3899], (C41)	4300±60	-21.6				3090–2770 cal BC	Allen and Bayliss 1995
OxA-4841	Animal bone, ox ulna, right hand side	Ditch upper secondary fill, [3899], (C41)	4295±60	-19.6				3090–2760 cal BC	Allen and Bayliss 1995
OxA-4882	Animal bone, ox femur	Ditch upper secondary fill, [3899], (C41)	4270±65	-23.2				3080–2670 cal BC	Allen and Bayliss 1995
OxA-4880	Animal bone, pig radius and ulna	Ditch upper secondary fill, [3899], (C41)	3875±55	-20.7				2490–2140 cal BC	Allen and Bayliss 1995
OxA-4843	Animal bone, ox pelvis, left hand side	[3893] Ditch fill C41, cut within secondary fill	4315±60	-22.3				3100–2870 cal BC	Allen and Bayliss 1995
OxA-4883	Animal bone, *Bos*, chisel	?cut within secondary fill of ditch, [2475], (C26.5)	4300±70	-21.4				3100–2700 cal BC	Allen and Bayliss 1995
OxA-V-2232-46	Human skull, sub-adult or adult	Ditch fill, [1560], C25	4169±31	-21.8	-21.8	9.9	3.4	2890–2620 cal BC	Parker Pearson *et al* 2009
OxA-V-2232-47	Human skull, older mature adult or older	Ditch fill, [2589], C28	4127±31	-21.9	-21.9	10.4	3.4	2880–2570 cal BC	Parker Pearson *et al* 2009

	adult								
OxA-17957	Cremated human bone, humerus, young/mature adult	Ditch fill, [3893], C41, 54/36	4271±29					2920–2870 cal BC	Parker Pearson *et al* 2009
OxA-17958	Cremated human bone, radius, young/mature adult	Ditch fill, [3898], C42, 54/841	3961±29					2570–2360 cal BC	Parker Pearson *et al* 2009
OxA-5981	Animal bone, articulated piglet	AB49, AB50 from secondary fill of ditch, [1291], (C20)	4220±35	-21.2				2910–2690 cal BC	Bronk Ramsey and Bayliss 2000
OxA-5982	Animal bone cattle vertebrae	S54: 862, 834, 854 from secondary fill of ditch, [3898], (C42)	4405±30	-23.0				3270–2910 cal BC	Bronk Ramsey and Bayliss 2000
OxA-4903	Animal bone, ox scapula	Ditch upper secondary fill, [3899], C42, section LQ,	3980±45	-23.2				2620–2340 cal BC	Allen and Bayliss 1995
OxA-4879	Pig tibia, fused, left hand side	Ditch upper secondary fill, [3893], C41, section A-E,	3885±55	-20.4				2450–2150 cal BC	Allen and Bayliss 1995
OxA-4844	Large ox axis vertebra	Ditch upper secondary fill, [3898] C42, section LQ	4220±60	-22.1				2920–2620 cal BC	Allen and Bayliss 1995
Timber phase									
OxA-V-2232-51	Pig rib fragment	Posthole 1884 filled by [1885]. Hawley no 9, between Stones 8 & 9, C8	3977±31	-20.5	-20.5	6.4	3.3	2580–2460 cal BC	Parker Pearson *et al* 2009
Stone settings									
UB-3821	Antler, red deer	Sarsen Circle, stonehole 1 from the 4th layer at base, [1093], (C2.1)	4023±21	-22.9				2620–2470 cal BC	Allen and Bayliss 1995
OxA-4840	Antler, red deer, tine tip	Sarsen Trilithon, stonehole 53/54 from pit WA 2448/3773, [3516], (C56)	3895±45	-23.4				2620–2340 cal BC	Allen and Bayliss 1995
OxA-4838	Antler, red deer, pick	Stonehole E, on causeway from primary packing, [1131], (C3)	3885±40	-23.9				2480–2200 cal BC	Allen and Bayliss 1995

OxA-4837	Antler, red deer, pick	[Stonehole E, on causeway from primary packing, [1131], (C3)	3995±60	-21.2				2840–2340 cal BC	Allen and Bayliss 1995
OxA-4839	Antler, red deer, crown	Sarsen Trilithon stonehole 57 from pit WA 2448/3773, [2452], (C17)	3860±40	-21.3				2470–2200 cal BC	Allen and Bayliss 1995
BM-46	Antler	Sarsen Trilithon, stonehole 56 chalk rubble, erection ramp, [2449], (C17)	3670±150	-				2480–1680 cal BC	Piggott 1959; Barker and Mackey 1960
OxA-4900	Antler, red deer, tine	Bluestone Circle, stonehole 40c, [2427], (C17)	3865±50	-23.1				2480–2140 cal BC	Allen and Bayliss 1995
OxA-4878	Animal bone, canid, ulna	Bluestone Circle, stonehole 40c, [2427], (C17)	3740±40	-21.8				2290–2020 cal BC	Allen and Bayliss 1995
OxA-4877	Antler fragment	Bluestone Horseshoe, stonehole 63a, [3511], (C56)	3695±55	-21.3				2280–1930 cal BC	Allen and Bayliss 1995
OxA-4901	Animal bone, pig humerus	Q hole, in fill near top of hole, [3813]	3800±45	-20.7				2460–2050 cal BC	Allen and Bayliss 1995
UB-3822	Antler, red deer	Y Hole 30, stacked on base [3927], [1655] (C34.30)	3341±22	-22.3				1690–1530 cal BC	Allen and Bayliss 1995
UB-3823	Antler, red deer	Y Hole 30, stacked on base [3927], [1655] (C34.30)	3300±19	-22.5				1630–1515 cal BC	Allen and Bayliss 1995
UB-3824	Antler, red deer	Y Hole 30, stacked on base [3927], [1655] (C34.30)	3449±24	-22.6				1880–1685 cal BC	Allen and Bayliss 1995
OxA-4836	Antler, red deer	Z Hole 29, [3774], C33.29	3540±45	-21.2				2020–1740 cal BC	Allen and Bayliss 1995
Beaker-age burial									
OxA-4886	Human bone, right femur	Burial cut into secondary ditch fill, [4028], (C61.1)	3960±60	-21.2					Allen and Bayliss 1995
OxA-5044	As OxA-4886	As OxA-4886	3785±70	-20.7					Allen and Bayliss 1995
OxA-5045	As OxA-4886	As OxA-4886	3825±60	-20.6					Allen and Bayliss 1995
OxA-5046	As OxA-4886	As OxA-4886	3775±55	-20.6					Allen and Bayliss 1995
BM-1582	As OxA-4886	As OxA-4886	3715±70	-21.8					Burleigh *et al* 1982
		Weighted mean	3819±28					2400–2140 cal BC	

The Avenue									
OxA-20011	Antler, *Cervus elaphus*	Base of pit [056] within the fill (045)	3868±28						Parker Pearson *et al* forthcoming (a)
OxA-20350	As OxA-20011	As OxA-20011	3836±29	-23.5					Parker Pearson *et al* forthcoming (a)
SUERC-23205	As OxA-20011	As OxA-20011	3770±30	-23.3					Parker Pearson *et al* forthcoming (a)
	Weighted mean SAV 045 (1027)		3827±17					2345–2200 cal BC	Parker Pearson *et al* forthcoming (a)
BM-1164	Antler, *Cervus elaphus,*	Avenue Northern ditch, Stonehenge terminal primary silt, (C6)	3678±68	-23.7				2290–1880 cal BC	Burleigh and Hewson 1979
HAR-2013	Antler pick	Avenue Southern ditch, north side of A344 primary fill near bottom, (C83)	3720±70	-23.6				2340–1920 cal BC	Pitts 1982
OxA-4884	Antler, red deer (shed tine)	Northern Ditch, Stonehenge terminal on bottom, [1912], (C6)	3935±50	-20.4				2580–2280 cal BC	Allen and Bayliss 1995
OxA-4905	Animal bone	Southern Ditch 0.9km from Avon terminal on bottom, (C86)	3865±40	-22.1				2470–2200 cal BC	Allen and Bayliss 1995
Stonehenge Palisade									
SUERC-32164	Animal bone, from complete articulated sheep/goat skeleton	Base of the easternmost pit [1024] cut into the east terminal of the Main Ditch close to its intersection with the Palisade ditch [Trench 54]	3155±30	-21.3		4.9	3.2	1500–1380 cal BC	Parker Pearson *et al* forthcoming (b)
SUERC-32160	Human bone	Pit [556] one of a series of four features cut into the upper fills of the ditch. On the bottom of pit [556]	2995±30	-20.2		10.7	3.3	1300–1050 cal BC	Parker Pearson *et al* forthcoming (b)

		was the crouched burial of a neonatal infant.							
UB-3820	Human bone, femur	Burial cut into ditch (C81)	2468±27	-21				770–410 cal BC	Allen and Bayliss 1995
Mesolithic									
OxA-4920	Charcoal, *Pinus*	[9582] tertiary fill of postpit 9580	8400±100	-25.1				7590–7170 cal BC	Allen and Bayliss 1995
OxA-4919	Charcoal, *Pinus*	[9585] secondary fill of postpit 9580	8520±80	-25.4				7660–7470 cal BC	Allen and Bayliss 1995
GU-5109	Charcoal, *Pinus*	[9585] secondary fill of postpit 9580	8880±120	-24.5				8300–7600 cal BC	Allen and Bayliss 1995
HAR-455	Charcoal, *Pinus*	Postpit A. Posthole A, 0.76m deep in post circle, halfway between the top (natural chalk) and the base, at the edge of the hole	9130±180	-24.2				8800–7790 cal BC	Vatcher and Vatcher 1973; Walker *et al* 1976
HAR-456	Charcoal, *Pinus*	Postpit B Posthole B, 0.31m from base, from the surface of the natural chalk	8090±140	-25.4				7490–6640 cal BC	Vatcher and Vatcher 1973; Walker *et al* 1976
Miscellaneous									
OxA-13193	Human bone	Skeleton 4.10.4 from grave inside the stone circles on the central axis, close to Y Hole 7	1258±34	-19.5		8.6	3.3	cal AD 660–880	Pitts *et al* 2007
OxA-4885	Animal bone, *Bos*?, longbone manufactured into a perforated bone point	Sarsen circle, stonehole 8 disturbed upper fill, [2315], (C13)	2840±60	-21.1				1210–840 cal BC	Allen and Bayliss 1995

Table 2: Radiocarbon determinations rejected for the purposes of modelling the chronology of the monument

Lab Number	Material	Context	Radiocarbon Age (BP)	$\delta^{13}C$ (‰)	$\delta^{13}C$ (‰) diet	$\delta^{15}N$ (‰)	C:N	Calibrated date range (95% confidence)	Reference
OxA-V-2232-34	Human tooth dentine from root of lower 2nd premolar	[3543] Stonehole 27 upper fill C 58	1181±25	-18.6	-19.1	9.3	3.2	cal AD 770–950	Parker Pearson *et al* 2009
OxA-V-2232-35	Human tooth dentine from root of upper left 1st premolar	[1815] eastern area C7	1236±25	-19.3	-19.5	11	3.2	cal AD 680–890	Parker Pearson *et al* 2009
OxA-4902	Animal bone, cow-sized long bone fragment	[3547] Sarsen Circle, Stonehole 27 amongst packing stones	5350±80	-21.7				4350–3970 cal BC	Allen and Bayliss 1995
OxA-V-2232-48	Human skull	(1282) Ditch fill C19. 1 of 2 conjoining fragments	1646±27	-20.3	-20.2	10.9	3.3	cal AD 340–530	Parker Pearson *et al* 2009
OxA-V-2232-49	Human skull	[3896] Ditch fill C42	2379±28	-20.3	-20.5	8.9	3.3	520–390 cal BC	Parker Pearson *et al* 2009
OxA-V-2232-50	Human adult ulna	[1384] Ditch fill C21	3436±30	-20.5	-20.8	10.5	3.3	1880–1680 cal BC	Parker Pearson *et al* 2009
OxA-18649	Human tooth M2	From immediately below the turf [STH08 1 16]	3883±31	-20.8				2470–2210 cal BC	Darvill and Wainwright 2009
OxA-18650	Carbonised cereal grain (indet.)	Socket for Stone 35a Bluestone Circle [STH08 F6 23 84]	178±22	-21.1				cal AD 1660–1955*	Darvill and Wainwright 2009, 10
OxA-18652	Charcoal, *Ilex* sp.	Socket for Stone 35a Bluestone Circle [STH08 F6 23 89b]	112±23	-27.5				cal AD 1680–1955*	Darvill and Wainwright 2009, 10
OxA-18653	Charcoal, *Quercus* sp. sapwood	Socket for Stone 10 in the Sarsen Circle [STH08 F10 37a]	321±23	-25.7				cal AD 1475–1650	Darvill and Wainwright 2009, 10
OxA-18654	Charcoal, *Ilex* sp.	Socket for Stone 10 in the	126±22	-26.7				cal AD 1675–	Darvill and Wainwright

		Sarsen Circle [STH08 F10 37b]						1955*	2009, 10
OxA-18655	Charcoal, *Pinus* sp.	Socket for Stone 10 in the Sarsen Circle [STH08 F10 37c]	8183±36	-25.8				7330–7060 cal BC	Darvill and Wainwright 2009, 10
OxA-18656	Charcoal, *Quercus* sp. sapwood	Q Hole (F12) [STH08 F12 28 90]	336±23	-25.3				cal AD 1465–1645	Darvill and Wainwright 2009, 11
OxA-18657	Carbonised cereal grain (indet.)	Q Hole (F12) [STH08 F12 30a]	1134±24	-26.2				cal AD 870–985	Darvill and Wainwright 2009, 11
OxA-18658	Charcoal, *Quercus*. sp sapwood	Q Hole (F12) [STH08 F12 30b]	3847±27	-25.9				2470–2200 cal BC	Darvill and Wainwright 2009
OxA-18659	Charcoal, *Ilex* sp.	Q Hole (F12) STH08 F12 30c	4534±35	-24.1				3370–3090 cal BC	Darvill and Wainwright 2009
OxA-18660	Carbonised cereal grain (indet.)	Q Hole (F12) [STH08 F12 32 106]	1187±32	-24.0				cal AD 720–950	Darvill and Wainwright 2009
OxA-18661	Animal bone, pig, 1st phalanx unfused	Q Hole (F12) STH08 F12 31 295	402±24	-19.9				cal AD 1440–1620	Darvill and Wainwright 2009
OxA-18651	Charcoal, *Quercus* sp. sapwood	Socket for Stone 35a Bluestone Circle [STH08 F6 23 89]	4360±29	-24.4				3090–2900 cal BC	Darvill and Wainwright 2009
OxA-18662	Charcoal, *Ilex* sp.	F11, cut by Q Hole (F12) [STH08 F11 29 95]	4164±28	-24.2				2890–2620 cal BC	Darvill and Wainwright 2009

Table 3: Radiocarbon determinations from Stonehenge rejected for technical reasons

Lab Number	Material	Context	Radiocarbon Age (BP)	$\delta^{13}C$ (‰)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	C:N	Calibrated date range (95% confidence)	Reference
I-2328	Antler	Ditch near west terminal	4130±105					2920–2460 cal BC	Atkinson *et al* 1976
	Too young as a result of chemical processing failing to remove humic acid contamination (Bayliss *et al* 1995, 518)								
I-2445	Antler	Y Hole 30	3190±105					1740–1210 cal BC	Atkinson 1967
	As I-2328								
I-2384	Antler	R Hole	3570±110					2270–1630 cal BC	Atkinson 1967
	As I-2328								
I-3216	Ox scaula and ox scapula & antler tine	Ox scaula from Avenue Northern ditch near Avon terminal + ox scapula & antler tine from the Southern ditch (C86)	2750±100					1200–770 cal BC	Atkinson *et al* 1976
	As I-2328								
HAR-4878	Charcoal, Pomoideae, *Prunus* sp., *Rhamnus catharticus* and charred *Prunus* sp. stone	Stone floor, near heelstone. A small quantity of charcoal obtained from a hearth in the centre of the floor	3400±150					2140–1400 cal BC	Allen and Bayliss 1995; Pitts 1982
	Preliminary result only from AERE Harwell mini-counter system, no evidence of a final result (Bayliss *et al* 1995, 519). Phone call 16/7/82 – "error pure guess, RLO"								
BM-1079	Antler, *Cervus elaphus*	From Avenue Northern ditch near Avon terminal (C87)	3020±180	-24.8				1690–810 cal BC	Burleigh and Hewson 1979
	Small collagen yield and probable humic acid contamination (Bayliss *et al* 1995, 518)								
OxA-9361	Human bone	As OxA-13193	1359±58	-19.7		7.6	3.2		Pitts *et al* 2002
	Result withdrawn following the identification of a problem with the ultrafiltration procedures (Bronk Ramsey *et al* 2004a)								
OxA-9921	Human bone	As OxA-13193	1490±60	-19.5		8.1	3.1		Pitts *et al* 2002
	Result withdrawn following the identification of a problem with the ultrafiltration procedures (Bronk Ramsey *et al* 2004a)								

Table 4: Interpretation of the radiocarbon determinations accepted for the purposes of modelling the chronology of the monument

Lab Number	Interpretation
	Aubrey Holes and associated features
OxA-18036	A date for the cremation of the individual and infilling of Aubrey Hole 32, context [3898]. The relatively small amount of bone (150.7g) probably represents only part of the whole cremation burial (McKinley 1995, 458), however, it is one instance in which human remains are likely to be primary depositions within these pits (Parker Pearson *et al* 2009, 25)
C-602	Unidentified bulked charcoal associated with a cremation which could have an unknown age-at-death offset (Bowman 1990) and therefore provides a *terminus post quem* for the cremation and its deposition in Aubrey Hole 32
SUERC-30410	A date for the cremation of the single adult female interred adjacent to Aubrey Hole 7.
	Ditch – antlers
UB-3788	A date for the acquisition of the antler pick used to dig the ditch and thus a *terminus post quem* for its digging. As the antler will not have been kept for long prior to its use (Serjeanston and Gardiner 1995, 429–30) the latest antler should be very close in date to the construction of the ditch.
UB-3787	As UB-3788
UB-3789	As UB-3788
UB-3790	As UB-3788
UB-3792	As UB-3788
UB-3793	As UB-3788
UB-3794	As UB-3788
BM-1583	As UB-3788
BM-1617	As UB-3788
Ditch – structured deposits	
OxA-4833	The sample, interpreted as a structured deposit, was placed in the ditch soon after its digging as there was no primary silt beneath it (Bronk Ramsey and Allen 1995, 529–30). The sample provides a *terminus post quem* for the digging of the ditch.
OxA-4835	As OxA-4833
OxA-4834	As OxA-4833
OxA-4842	As OxA-4833
Ditch – secondary infilling	
UB-3791	The sample could be residual from activity associated with the digging of the ditch as there is no evidence it is functionally related to the secondary infilling of the ditch. It provides a *terminus post quem* for the secondary fill.
OxA-4904	The sample could be residual and therefore represent a tine broken from one of the antlers at the bottom of the ditch (Bronk Ramsey and Allen 1995, 531). It therefore provides a *terminus post quem* for the secondary fill of the ditch (Parker Pearson *et al* 2009, 29–31)

OxA-4881	The sample could be residual as it represents a single bone and there is no evidence it is functionally related to the secondary infilling of the ditch. It provides a *terminus post quem* for the secondary fill.
OxA-4841	As OxA-4881
OxA-4882	As OxA-4881
OxA-4880	As OxA-4881
OxA-4843	As OxA-4881
OxA-4883	As OxA-4881
OxA-V-2232-46	A date for the death of the individual and *terminus post quem* for context [1560] as the sample could be residual.
OxA-V-2232-47	A date for the death of the individual and *terminus post quem* for context [2589] as the sample could be residual.
OxA-17957	A date for the cremation of the individual and *terminus post quem* for context [3898]. The sample (54/841) was not from the 1546.6g of well-cremated bone clearly represent a single burial (McKinley 1995, 458) that been deposited while the secondary fill of the ditch was accumulating.
OxA-17958	A date for the cremation of the individual and a *terminus post quem* for the formation of context [3893]. The scattered bone from Ditch cutting C41 is interpreted as representing a disturbed cremation burial.
OxA-5981	A date for the lowest secondary fills of the ditch (Parker Person *et al* 2009, 29). The sample comes from an articulated animal disposal and is therefore unlikely to be residual.
OxA-5982	One of three vertebrae from different animal (Parker Pearson *et al* 2009). A *terminus post quem* for the secondary fills of the Ditch as the sample could be residual.
OxA-4903	Sample thought possibly to be intrusive as a result of animal burrowing or mixing (Bayliss *et al* 1995, 520–1), but as it cannot have moved far given its size it provides a *terminus post quem* for the secondary infilling of the Ditch
OxA-4879	Uncertain as to which of two contexts it originated from (Bayliss *et al* 1995, 521), but it provides a *terminus post quem* for the secondary infilling of the Ditch
OxA-4844	As OxA-4903
Timber phase	
OxA-V-2232-51	A *terminus post quem* for the infilling of posthole 1884
Stone settings	
UB-3821	A date for the construction of the Sarsen Circle
OxA-4840	A date for the construction of the Sarsen Trilithons
OxA-4838	A date for the construction of Stonehole E
OxA-4837	As OxA-4838
OxA-4839	A date for the infilling of pit WA 2448/3773 dug after the erection of the Sarsen Trilithons but before construction of the Bluestone oval (Parker Person *et al* 2007, 619–26)
BM-46	As OxA-4839

OxA-4900	A date for the Bluestone Circle
OxA-4878	A large animal bone that is unlikely to be intrusive and therefore provides a date for the Bluestone Circle
OxA-4877	A date for the Bluestone Horseshoe
OxA-4901	As the Q holes are not early than the Sarsen Circle (contra Bayliss *et al* 1995, 521) the sample provides a *terminus post quem* for the infilling of the Q hole after the removal of the Bluestone
UB-3822	The three dated antlers from the five deliberately placed on the bottom of the pit are not statistically consistent (T'=24.2; T' (5%)=6.0; ν=2). As the material represents fresh and curated tools the last dated event provides the best estimate for the digging of the feature (Walker 1995c, 260–4)
UB-3823	As UB-3822
UB-3824	As UB-3822
OxA-4836	A date for the digging of the Z Hole, although the antler may be curated as it is older than those obtained from the Y Hole (Walker 1995c, 264)
Beaker-age burial	
OxA-4886	A date for the burial. The five measurements are statistically consistent (T'=8.7; T' (5%)=9.5; ν=4) and so a weighted mean has been calculated
OxA-5044	As OxA-4886
OxA-5045	As OxA-4886
OxA-5046	As OxA-4886
BM-1582	As OxA-4886
The Avenue	
OxA-20011	A date for the digging of pit [056] that post-dates the initial Avenue ditch but pre-dates the re-cutting. The three measurements on sample SAV 045 (1027) are statistically consistent (T'=5.8; T' (5%)=6.0; ν=2; Ward and Wilson 1978) so a weighted mean has been calculated, 3827±17 BP (Parker Pearson *et al* forthcoming (a))
OxA-20350	As OxA-20011
SUERC-23205	As OxA-20011
BM-1164	About 0.5m above the ditch bottom (presumably in re-cut)
HAR-2013	Below/within junction of primary fill and re-cut
OxA-4884	A date for the digging of the ditch
OxA-4905	*Terminus post quem* for the infilling of the ditch
Stonehenge Palisade	
SUERC-32164	A *terminus ante quem* for the Palisade ditch
SUERC-32160	Death of the individual and *terminus ante quem* for the Palisade ditch
UB-3820	Death of the individual and *terminus ante quem* for the Palisade ditch
Mesolithic	
OxA-4920	Small fragment from tree up to 200 years old, all three samples from 9580 could be from a single post. Dates Mesolithic clearance and human

	activity in the area (Allen 1995b, 47)
OxA-4919	As OxA-4920
GU-5109	As OxA-4920
HAR-455	Small fragment from tree up to 200 years old. Dates Mesolithic clearance and human activity in the area (Allen 1995b, 47)
HAR-456	As HAR-455
OxA-13193	A date for the death of the individual (Pitts *et al* 2002)
OxA-4885	A date for the bone point. Dated for intrinsic interest as not from a securely stratified context (Montague 1995b, 412)

Table 5: Interpretation of radiocarbon determinations rejected for the purposes of modelling the chronology of the monument

Lab Number	Interpretation
OxA-V-2232-34	Intrusive single bone from disturbed context no contemporary with 3rd millennium cal BC activity.
OxA-V-2232-35	Intrusive single bone from disturbed context not contemporary with 3rd millennium cal BC activity.
OxA-4902	The result is much earlier than the digging of the ditch and as a single bone must be residual.
OxA-V-2232-48	Intrusive single bone from disturbed context not contemporary with 3rd millennium cal BC activity.
OxA-V-2232-49	Intrusive single bone from disturbed context not contemporary with 3rd millennium cal BC activity.
OxA-V-2232-50	Intrusive single bone from disturbed context not contemporary with 3rd millennium cal BC activity.
OxA-18649	A date for the death of the individual. The tooth may have come to the site in topsoil associated with re-turfing 20–25 years ago.
OxA-18650	Intrusive post-medieval cereal grain in the socket for bluestone 35a (Darvill and Wainwright 2009, 10)
OxA-18652	Intrusive post-medieval charcoal in the socket for bluestone 35a (Darvill and Wainwright 2009, 10)
OxA-18653	Intrusive post -medieval charcoal in the socket for Stone 10 (Darvill and Wainwright 2009, 11)
OxA-18654	Intrusive post-medieval charcoal in the socket for Stone 10 (Darvill and Wainwright 2009, 11)
OxA-18655	Residual pine charcoal in the socket for Stone 10 (Darvill and Wainwright 2009, 11)
OxA-18656	Post-medieval charcoal in the upper fill of Q Hole (F12) Darvill and Wainwright 2009, 11)
OxA-18657	Intrusive medieval charcoal in Q Hole (F12)
OxA-18658	Charcoal of unknown provenance in feature containing medieval and post-medieval material from Q hole (F12)
OxA-18659	Charcoal of unknown provenance in feature containing medieval and post-medieval material from Q hole (F12)
OxA-18660	Intrusive medieval charcoal in Q Hole (F12)
OxA-18661	Intrusive post-medieval animal bone in Q Hole (F12)
OxA-18651	Residual charcoal in the socket for Bluestone 35a (Darvill and Wainwright 2009, 10)
OxA-18662	Charcoal of unknown provenance in the infilling of pit F11

Table 6: Interpretation of radiocarbon determinations from Stonehenge rejected for technical reasons

Lab Number	Interpretation
I-2328	Too young as a result of chemical processing failing to remove humic acid contamination (Bayliss *et al* 1995, 518)
I-2445	As I-2328
I-2384	As I-2328
I-3216	As I-2328
HAR-4878	Preliminary result only from AERE Harwell mini-counter system, no evidence of a final result (Bayliss *et al* 1995, 519). Phone call 16/7/82 – "error pure guess, RLO"
BM-1079	Small collagen yield and probable humic acid contamination (Bayliss *et al* 1995, 518)
OxA-9361	Result withdrawn following the identification of a problem with the ultrafiltration procedures (Bronk Ramsey *et al* 2004a)
OxA-9921	Result withdrawn following the identification of a problem with the ultrafiltration procedures (Bronk Ramsey *et al* 2004a)

Table 7: Percentage probabilities for the relative order of samples from the secondary fill of the ditch and the estimated date for its construction. The cells show the probability of the distribution in the left-hand column being earlier than the distribution in the top row. For example, the probability that UB-3791 is earlier than the digging of the ditch is 95.8%

	UB-3791	*OxA-4904*	*OxA-4881*	*OxA-4841*	*OxA-4882*	*OxA-4843*	*OxA-4883*	*OxA-4880*	*OxA-5982*	*OxA-17957*	*OxA-17958*	*OxA-V-2232-46*	*OxA-V-2232-47*	*ditch_constructed*
UB-3791		51.7	77	79.3	88.2	70.2	73.6	100	41.7	99.4	100	100	100	95.8
OxA-4904	48.3		74.0	76.4	86.3	67.2	71.4	100	41.6	97.4	100	99.9	100	92.6
OxA-4881	23	26		53.1	68.6	42	49.7	100	19.1	74.5	100	94.1	95.9	72.3
OxA-4841	20.8	23.6	46.9		65.9	39	47	100	17.2	70.3	100	92.8	94.8	69
OxA-4882	11.8	13.7	31.4	34.1		24.9	33	100	9.8	45.5	100	80.7	86	49.2
OxA-4843	29.8	32.8	58	61	75.1		56.8	100	25	84.2	100	97.1	98	80.2
OxA-4883	26.4	28.6	50.3	53.0	67	43.2		100	22.4	70.8	100	91	93.5	69.8
OxA-4880	0	0	0	0	0	0	0		0	0	9.8	0	0	0
OxA-5982	58.3	58.4	80.9	82.8	90.2	75.0	77.7	100		99.5	100	100	100	96.6
OxA-17957	0.6	2.6	25.5	29.7	54.5	15.8	29.3	100	0.5		100	98.5	99.0	56.1
OxA-17958	0	0	0	0	0	0	0	90.2	0	0		0	0.1	0
OxA-V-2232-46	0	0.1	5.9	7.2	19.3	2.9	9.0	100	0	1.5	100		64	10.5
OxA-V-2232-47	0	0.1	4.1	5.2	14.0	2	6.5	100	0	1	99.9	36		7.3
ditch_constructed	4.2	7.4	27.7	31	50.8	19.8	30.2	100	3.4	43.9	100	89.5	92.7	

Table 8: Estimates for the construction of the stone settings (derived from Model 1; Fig 18)

parameter	*95% probability*	*68% probability*
start_stone_settings	*2780–2485 cal BC*	*2650–2520 cal BC*
Sarsen Circle	*2580–2475 cal BC*	*2575–2560 (7%) or 2595–2485 (61%) cal BC*
Sarsen Trilithons	*2455–2215 cal BC*	*2410–2265 cal BC*
Stonehole E	*2470–2275 (90%) or 2255–2210 (5%) cal BC*	*2440–*2295 cal BC
Bluestone Circle	*2275–2030 cal BC*	*2205–2120 (46%) or 2090–2045 (22%) cal BC*
Bluestone Horseshoe	*2275–2255 (2%) or 2210-1930 (93%) cal BC*	*2195–2175 (6%) or 2145–2020 (58%) or 1995–1980 (4%) cal BC*
Z Holes	*2020–1995 (2%) or 1980–1745 (93%) cal BC*	*1945–1870 (39%) or 1850–1775 (29%) cal BC*
Y Holes	*1630–1525 cal BC*	*1620–1555 cal BC*
end_stone_settings	*1630–1340 cal BC*	*1610–1485 cal BC*

Table 9: Estimates for the construction of the stone settings (derived from Model 2; Fig 20)

parameter	*95% probability*	*68% probability*
start_stone_settings	*2815–2405 cal BC*	*2650–2485 cal BC*
Sarsen Circle	*-*	*-*
Sarsen Trilithons	*2450–2215 cal BC*	*2405–2270 cal BC*
Stonehole E	*2470–2275 (90%) or 2255–2210 (5%) cal BC*	*2425–*2295 cal BC
Bluestone Circle	*2275–2250 (3%) or 2240-2030 (92%) cal BC*	*2205–2125 (46%) or 2090–2045 (22%) cal BC*
Bluestone Horseshoe	*2275–2255 (2%) or 2210-1930 (93%) cal BC*	*2195–2175 (6%) or 2145–2020 (58%) or 1995–1980 (4%) cal BC*
Z Holes	*2020–1995 (2%) or 1985-1745 (93%) cal BC*	*1945–1870 (38%) or 1850–1775 (30%) cal BC*
Y Holes	*1630–1525 cal BC*	*1620–1550 cal BC*
end_stone_settings	*1630–1305 cal BC*	*1605–1475 cal BC*

Table 10: Estimates for the construction of the stone settings (derived from Model 3; Fig 22)

parameter	*95% probability*	*68% probability*
start_stone_settings	*2790–2490 cal BC*	*2645–2520 cal BC*
Sarsen Circle	*2580–2475 cal BC*	*2575–2560 (6%) or 2540–2485 (62%) cal BC*
Sarsen Trilithons	*2585–2400 (93%) or 2380–2350 (2%) cal BC*	*2565–2515 (35%) or 2505–2465 (33%) cal BC*
Stonehole E	*2470–2275 (90%) or 2255–2210 (5%) cal BC*	*2435–*2295 cal BC
pit WA 2448	*2410–2005 cal BC*	*2315–2095 cal BC*
Bluestone Circle	*2275–2030 cal BC*	*2205–2125 (46%) or 2090–2045*

		(22%) cal BC
Bluestone Horseshoe	*2205–1920 cal BC*	*2140–2010 (59%) or 2000–1920 (9%) cal BC*
Z Holes	*2020–1995 (2%) or 1985–1745 (93%) cal BC*	*1945–1870 (39%) or 1850–1775 (29%) cal BC*
Y Holes	*1630–1525 cal BC*	*1620–1555 cal BC*
end_stone_settings	*1630–1340 cal BC*	*1605–1485 cal BC*

Table 11: Percentage probabilities for the relative order of construction derived from Model 1 (Fig 18). The cells show the probability of the distribution in the left-hand column being earlier than the distribution in the top row. For example, the probability that Sarsen Circle is earlier than Stonehole E is 99.8%

	Sarsen Trilithons	*Sarsen Circle*	*Stonehole E*	*Beaker_burial*	*Bluestone Circle*	*Bluestone Horseshoe*	*Y Holes*	*Z Holes*
Sarsen Trilithons	0	0	36.8	84.4	100	100	100	100
Sarsen Circle	100	0	99.8	100	100	100	100	100
Stonehole E	63.2	0.2	0	90.8	99.3	99.6	100	100
Beaker_burial	15.6	0	9.2	0	93.2	96.5	100	100
Bluestone Circle	0	0	0.7	6.8	0	69.3	100	99.8
Bluestone Horseshoe	0	0	0.4	3.5	30.7	0	100	98.3
Y Holes	0	0	0	0	0	0	0	0
Z Holes	0	0	0.	0	0.2	1.7	100	0

Table 12: Percentage probabilities for the relative order of construction derived from Model 2 (Fig 20). The cells show the probability of the distribution in the left-hand column being earlier than the distribution in the top row. For example, the probability that Sarsen Circle is earlier than Stonehole E is 99.8%

	Sarsen Trilithons	*Stonehole E*	*Beaker_burial*	*Bluestone Circle*	*Bluestone Horseshoe*	*Y Holes*	*Z Holes*
Sarsen Trilithons		36.8	83.8	100	100	100	100
Stonehole E	63.2		90.4	99.3	99.6	100	100
Beaker_burial	16.2	9.6		93	96.5	100	100
Bluestone Circle	0.	0.7	7		69.4	100	99.8
Bluestone Horseshoe	0	0.4	3.5	30.6		100	98.2
Y Holes	0	0	0	0	0		0
Z Holes	0	0	0	0	1.8	100	

Table 13: Percentage probabilities for the relative order of construction derived from Model 3 (Fig 22). The cells show the probability of the distribution in the left-hand column being earlier than the distribution in the top row. For example, the probability that Sarsen Circle is earlier than the Sarsen Trilithons is 62.8%

	Sarsen Trilithons	*Sarsen Circle*	*Stonehole E*	*pit WA 2448*	*Beaker_burial*	*Bluestone Circle*	*Bluestone Horseshoe*	*Z Holes*	*Y Holes*
Sarsen Trilithons		37.2	96.6	100	100	100	100	100	100
Sarsen Circle	62.8		99.8	100	100	100	100	100	100
Stonehole E	3.5	0.2		89.7	92	99.4	99.9	100	100
pit WA 2448	0	0	10.3		37.2	71.4	100	99.8	100
Beaker_burial	0.1	0	7.6	62.8		92.5	98.4	100	100
Bluestone Circle	0	0	0.7	28.6	7.5		77.8	99.8	100
Bluestone Horseshoe	0	0	0.1	0	1.6	22.2		97.3	100
Z Holes	0	0	0.	0	0	0.2	2.7		100
Y Holes	0	0	0	0	0	0	0	0	

Table 14: Simplified five stage model (Darvill et al *2012)*

Stage	Events
1	Aubrey Holes
	Ditch and Bank
	Postholes and stakeholes
2	Sarsen Trilithons
	Sarsen Circle
	Double Bluestone Circle (Q and R Holes)
	Station Stones
	Heel Stone
	Stones D, E, and 95 (Slaughter Stone)
3	Pit WA 2448
	Avenue
	Beaker-age burial
4	Bluestone Oval
	Outer Bluestone Circle
5	Y and Z Holes

FIGURES

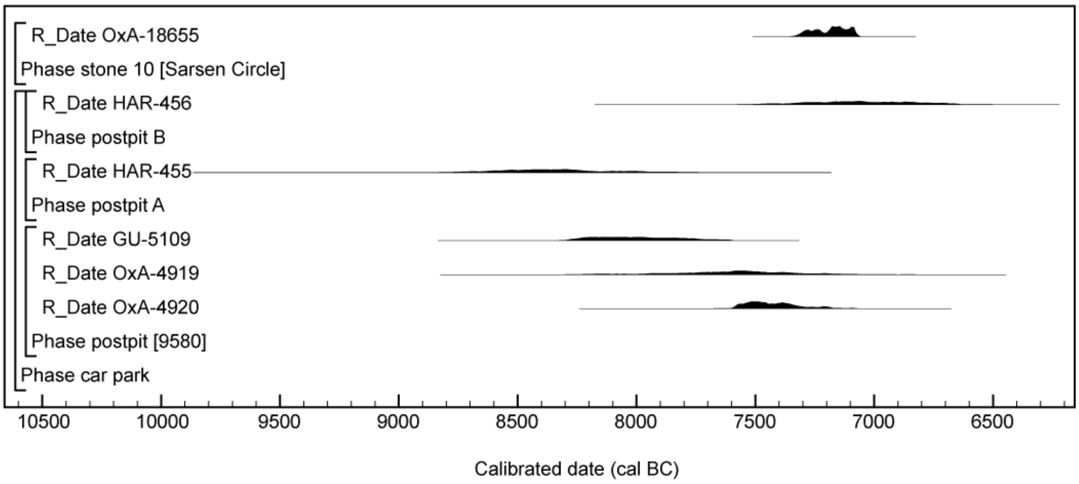

Figure 1: Probability distributions of Mesolithic dates from Stonehenge. Each distribution represents the relative probability that an event occurred at a particular time. These distributions are the result of simple radiocarbon calibration (Stuiver and Reimer 1993)

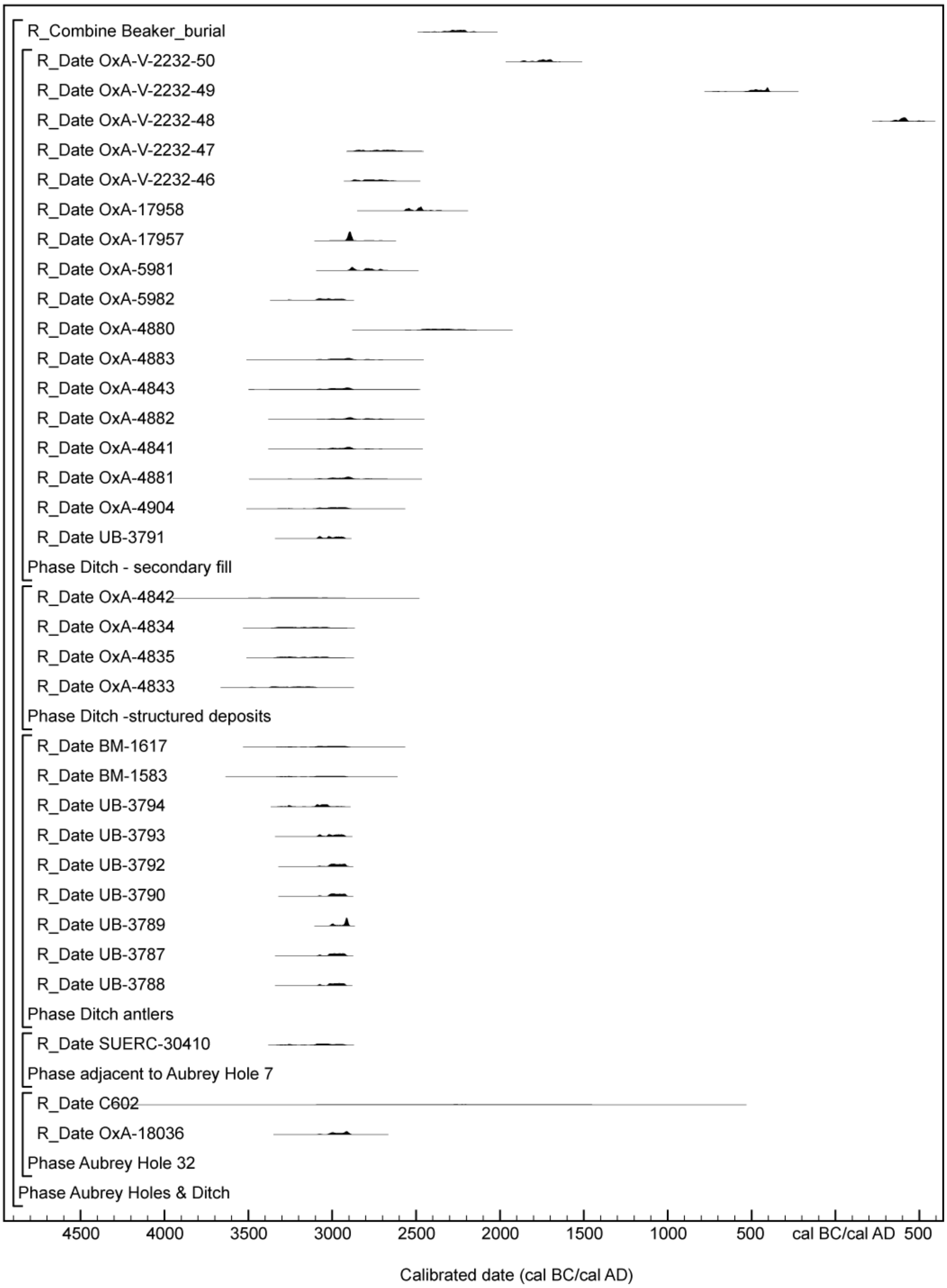

Figure 2: Probability distributions of dates from Aubrey Holes and Ditch. The format is identical to Figure 1

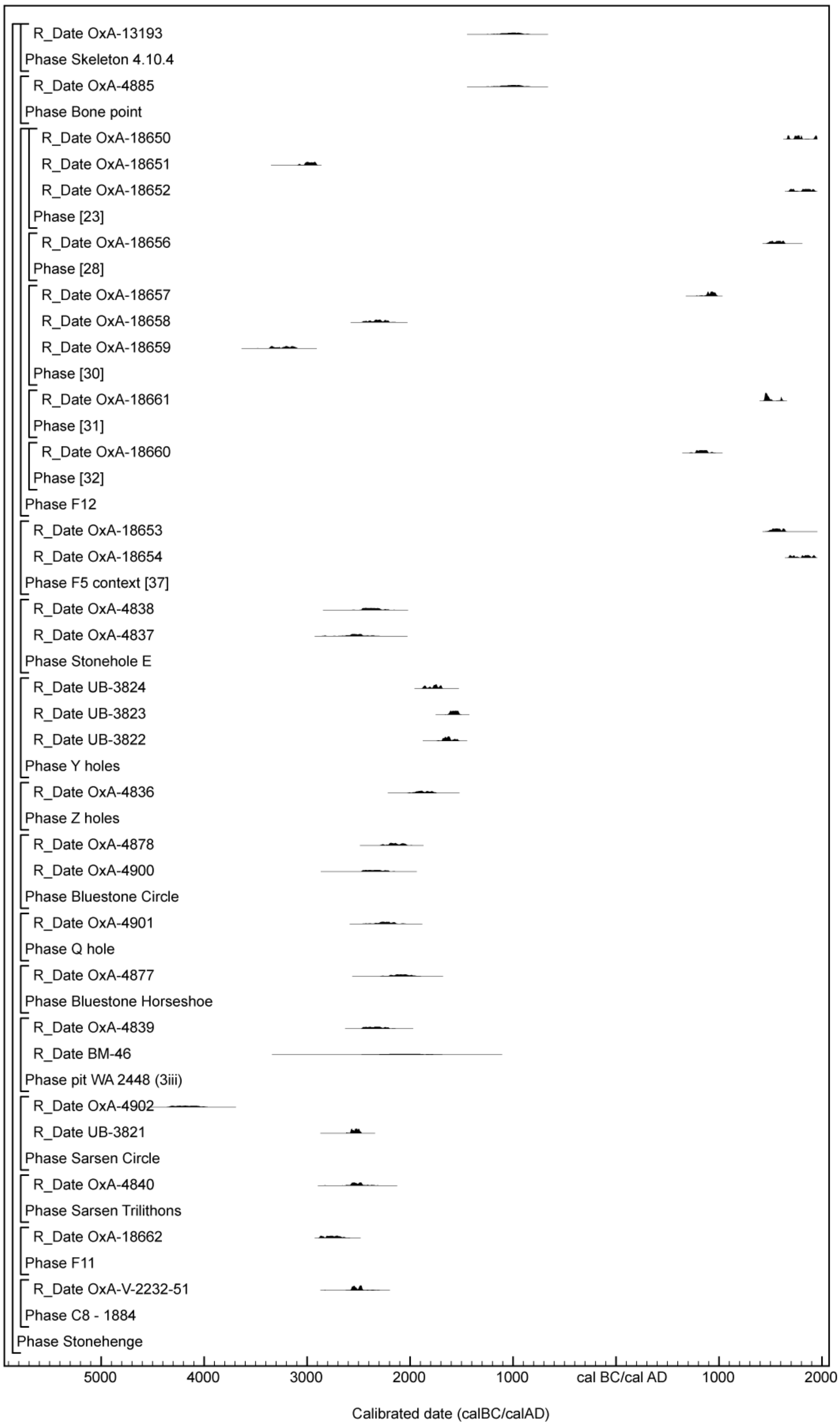

Figure 3: Probability distributions of dates from Stonehenge. The format is identical to Figure 1

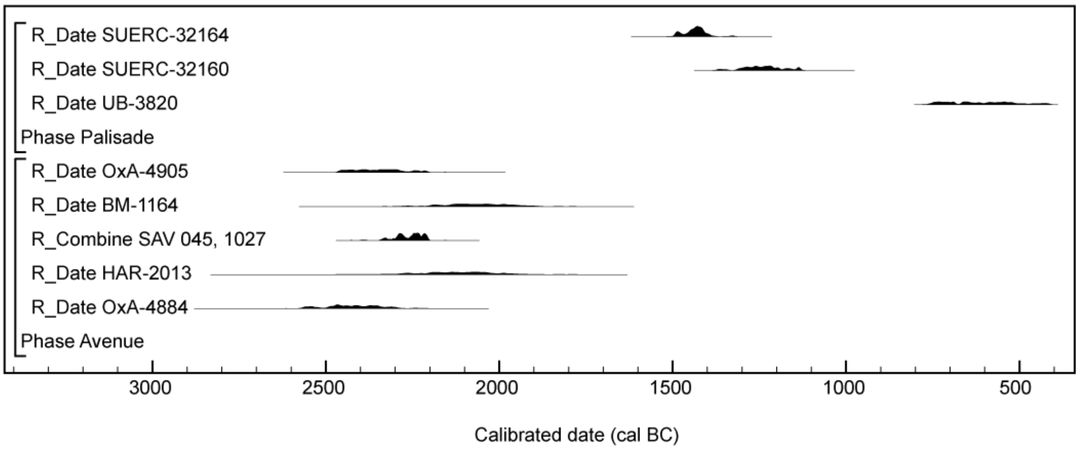

Figure 4: Probability distributions of dates from the Stonehenge Avenue and Palisade. The format is identical to Figure 1

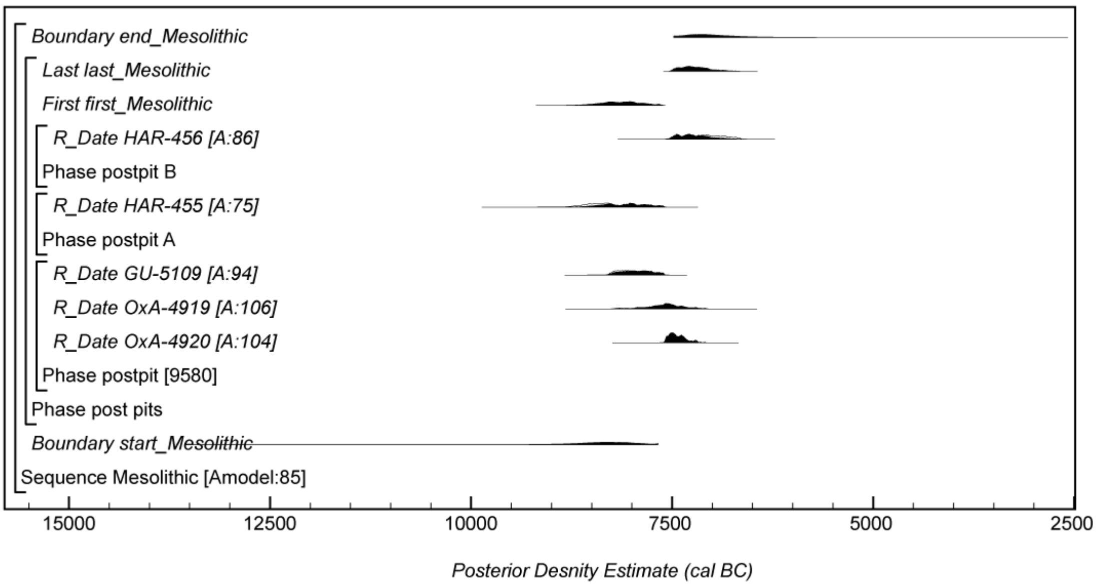

Figure 5: Probability distributions of dates from the Stonehenge car park Mesolithic postholes: each distribution represents the relative probability that an event occurs at a particular time. For each of the radiocarbon dates two distributions have been plotted, one in outline, which is the result of simple calibration, and a solid one, which is based on the chronological model used. Figures in brackets after the laboratory numbers are the individual indices of agreement which provide an indication of the consistency of the radiocarbon dates with the prior information included in the model (Bronk Ramsey 1995). The large square brackets down the left hand side along with the OxCal keywords define the model exactly.

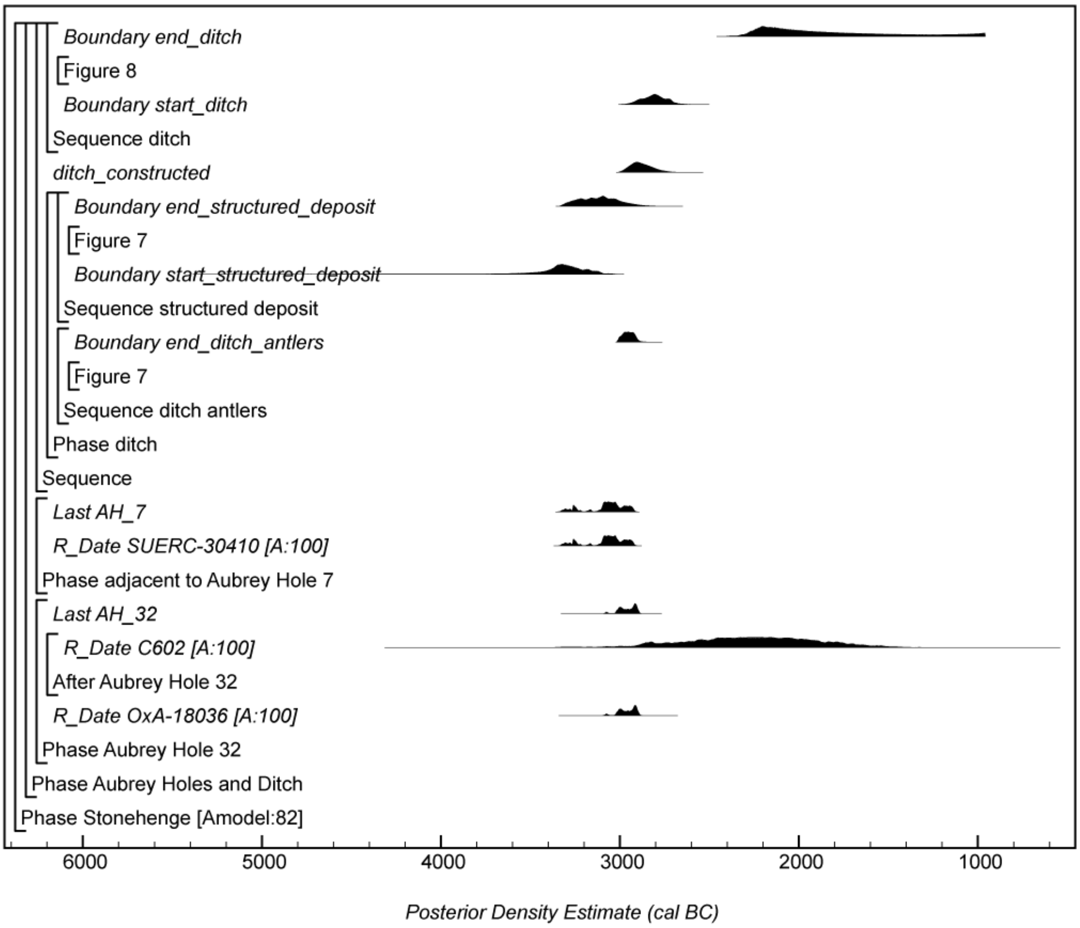

Figure 6: Overall structure for the chronology of the Ditch and Aubrey Holes. The component sections of this model are shown in Figures 7–8. The large square brackets down the left-hand side of the figure, along with the OxCal keywords define the overall model exactly.

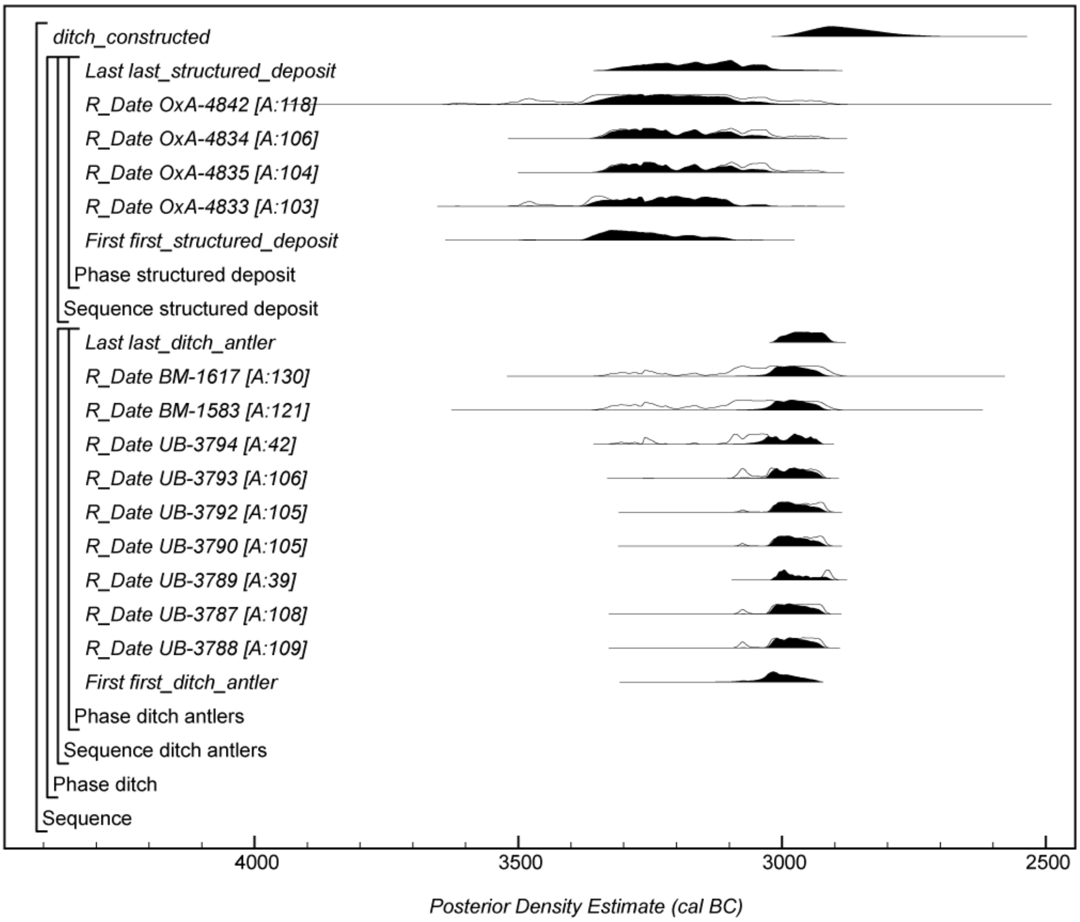

Figure 7: Probability distributions of dates from the Ditch (original model) – antlers and structured deposits

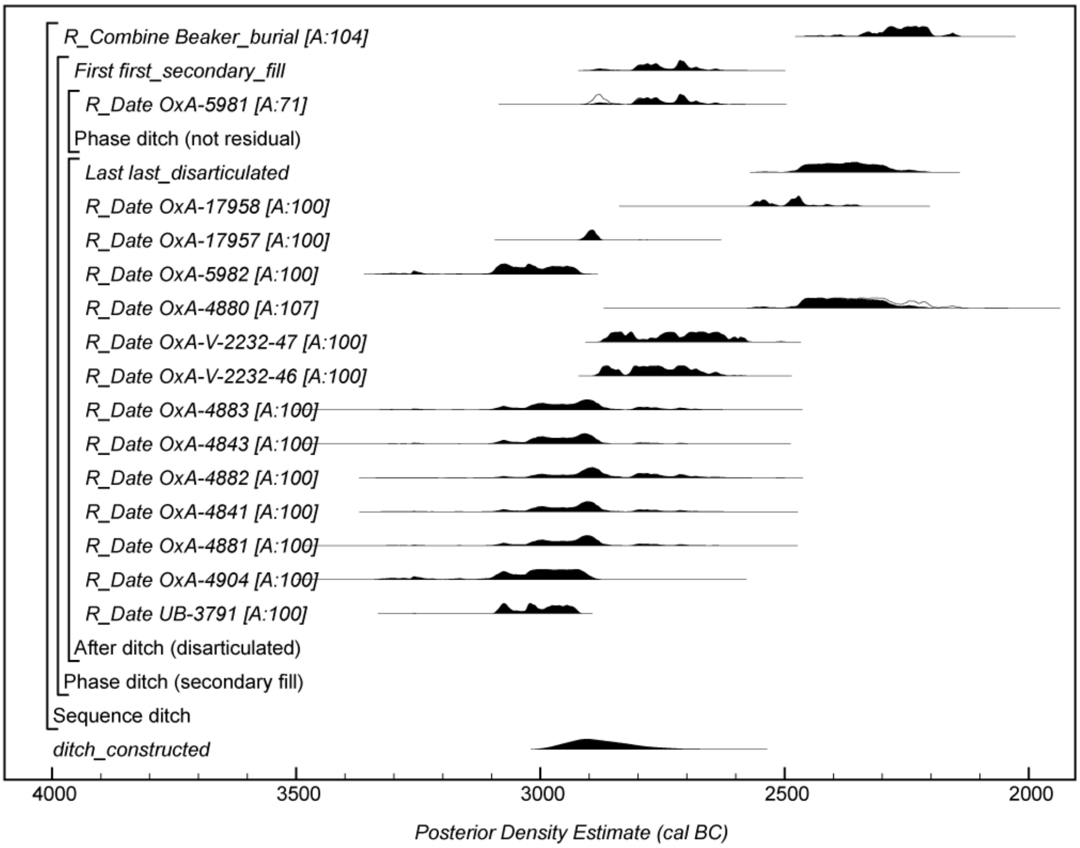

Figure 8: Probability distributions of dates from the Ditch (original model) – secondary fill and Beaker-age burial

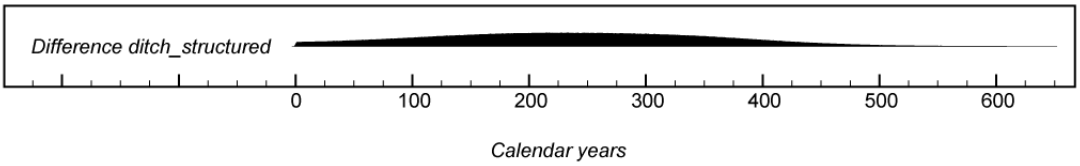

Figure 9: Estimated difference between the date of the latest structured deposit (end_structured_deposit; Figure 6) and the date when construction of the ditch was completed (ditch_constructed; Figure 6)

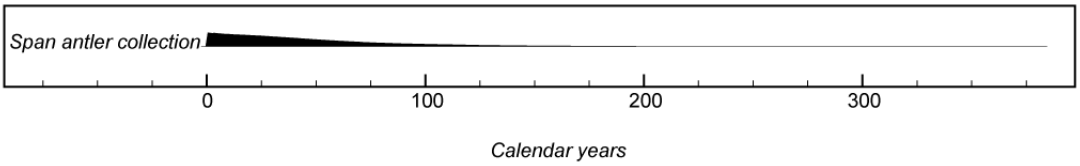

Figure 10: Probability distribution showing the number of calendar years over which antlers used for construction of the ditch were used. This distribution is derived from the model shown in Figures 6–8

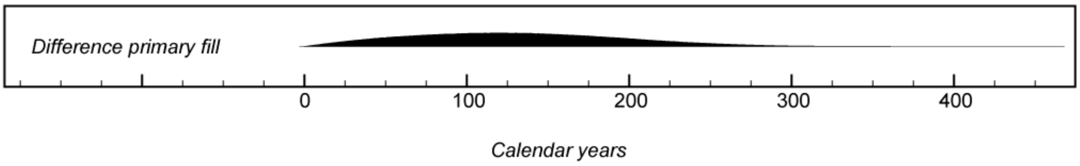

Figure 11: Estimated difference between the date when construction of the ditch was completed (ditch_constructed; Figure 6) and the start of accumulation of its secondary fill (first_secondary_fill; Figure 8)

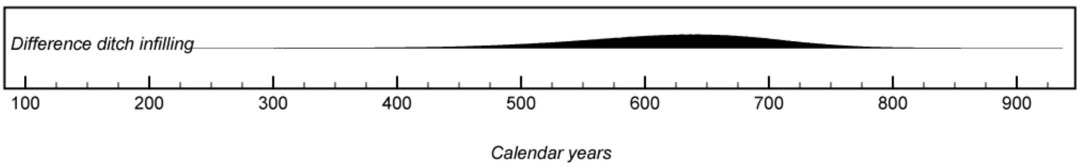

Figure 12: Estimated difference between the date when construction of the ditch was completed (ditch_constructed; Figure 6) and the insertion of the Beaker-age burial into the top of the secondary fill (Beaker_burial; Figure 8)

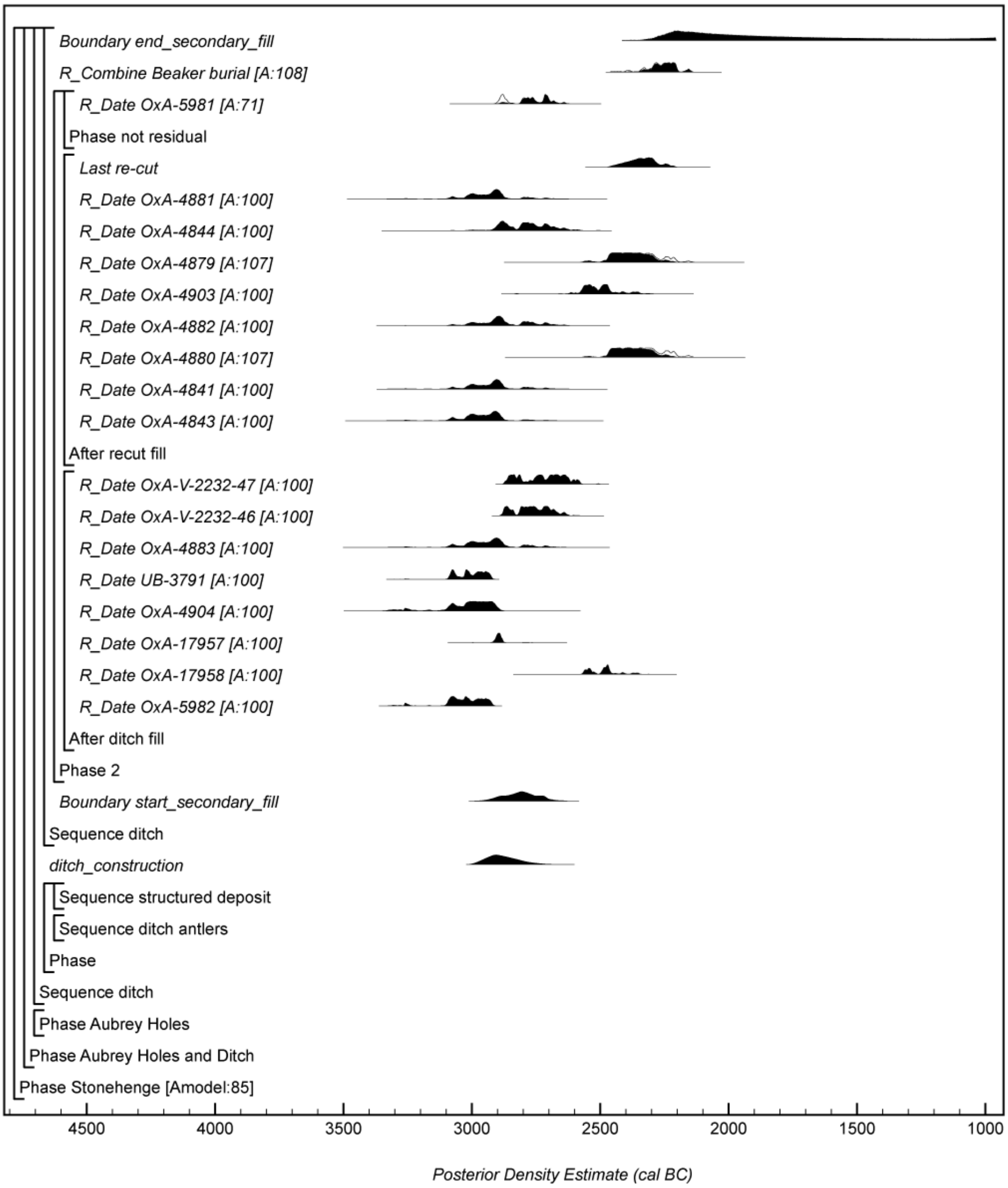

Figure 13: Probability distributions of dates from the Ditch (revised model). The format is identical to Figure 6

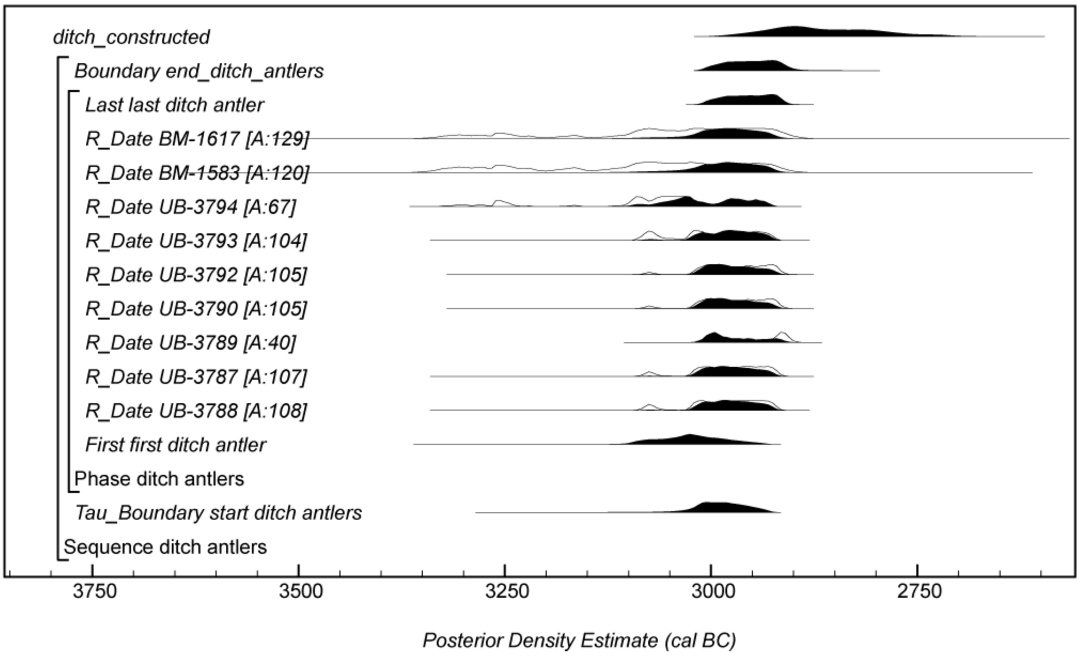

Figure 14: Probability distributions of antler dates from the Ditch. The extract is derived from a revised version of the model shown in Figure 7 that uses an exponential distribution for the collection of the antlers

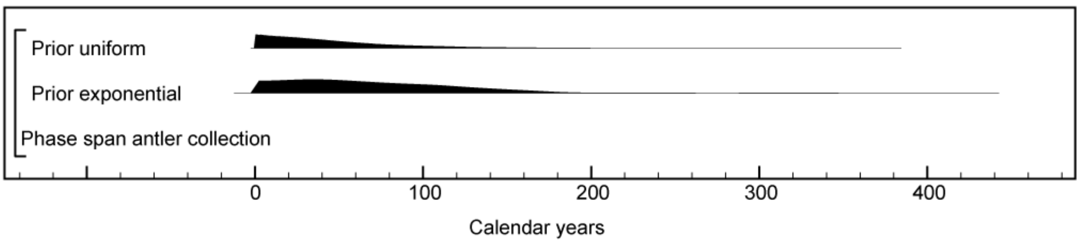

Figure 15: Probability distributions showing the number of calendar years over which antlers used for construction of the ditch were used. These distributions are derived from the models shown in Figures 6–8 (uniform) and Figure 14 (exponential)

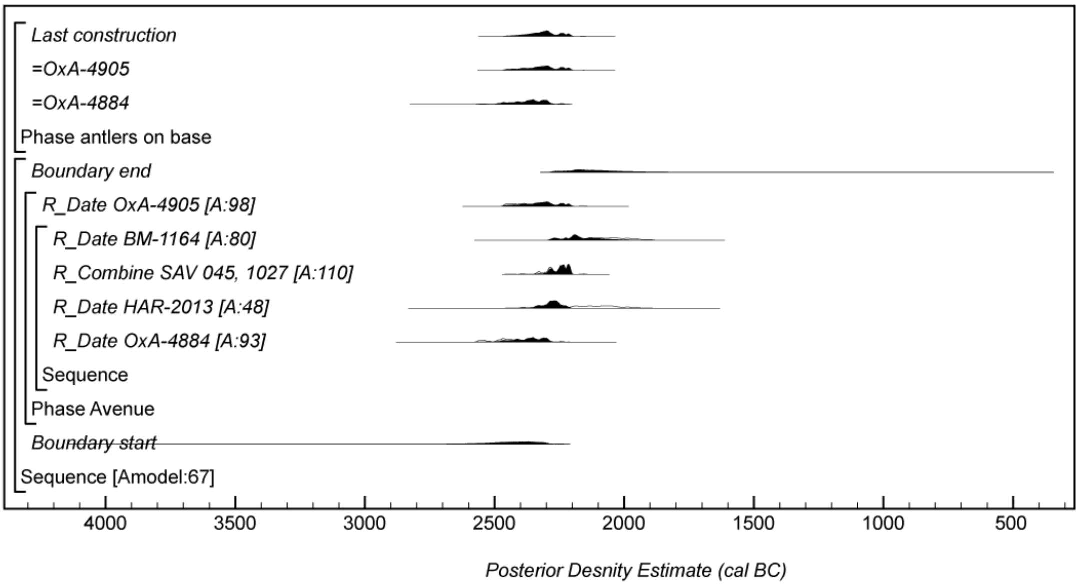

Figure 16: Probability distributions of dates from the Avenue. The format is identical to Figure 5

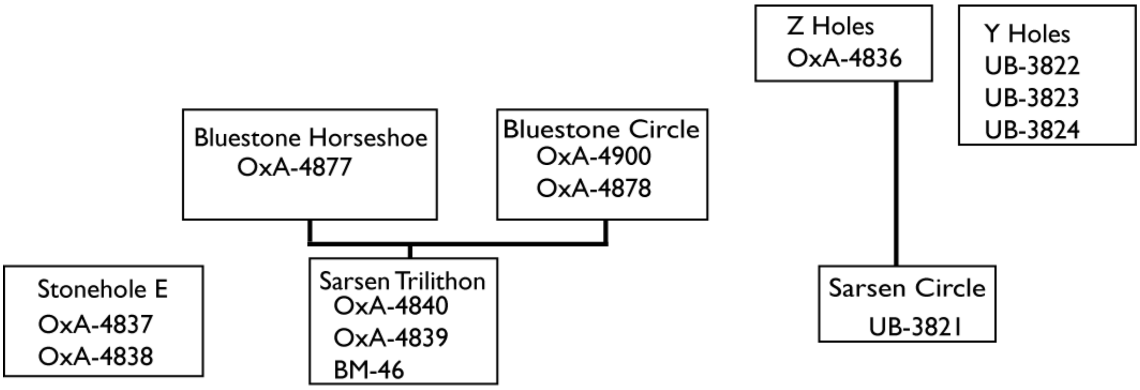

Figure 17: Summary of the prior information incorporated into the chronological model shown in Figure 18 – model 1 (from Cleal et al *1995)*

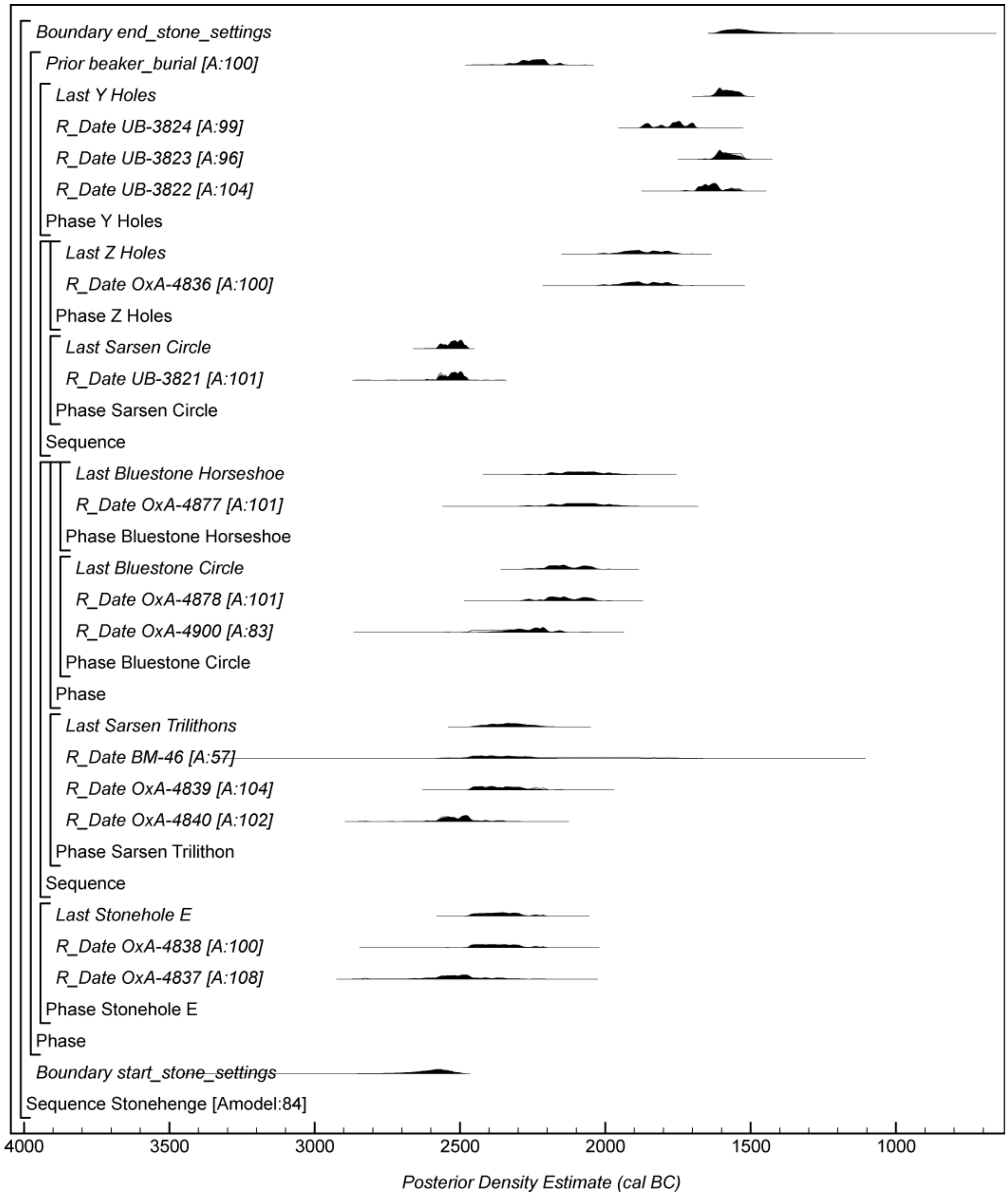

Figure 18: Probability distributions of dates from the stone settings (model 1). The format is identical to Figure 5

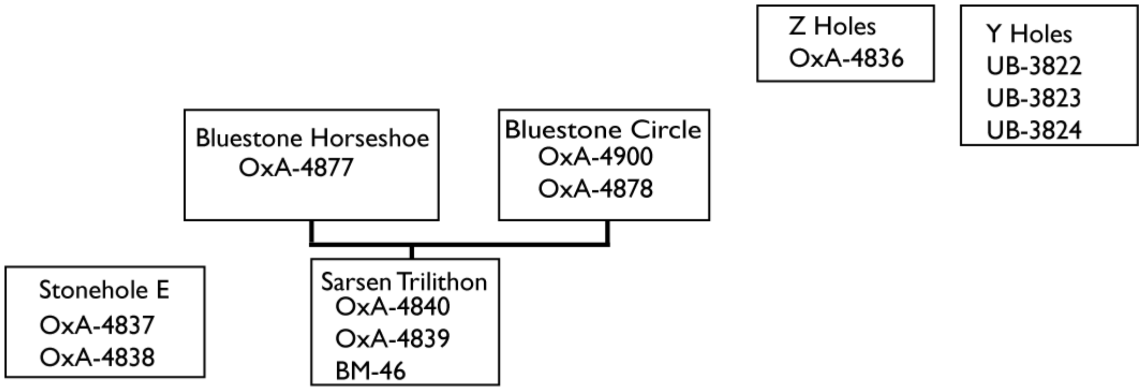

Figure 19: Summary of the prior information incorporated into the chronological model shown in Figure 20 – model 2 (from Bayliss et al *2007b incorporating suggestions by Case 1997)*

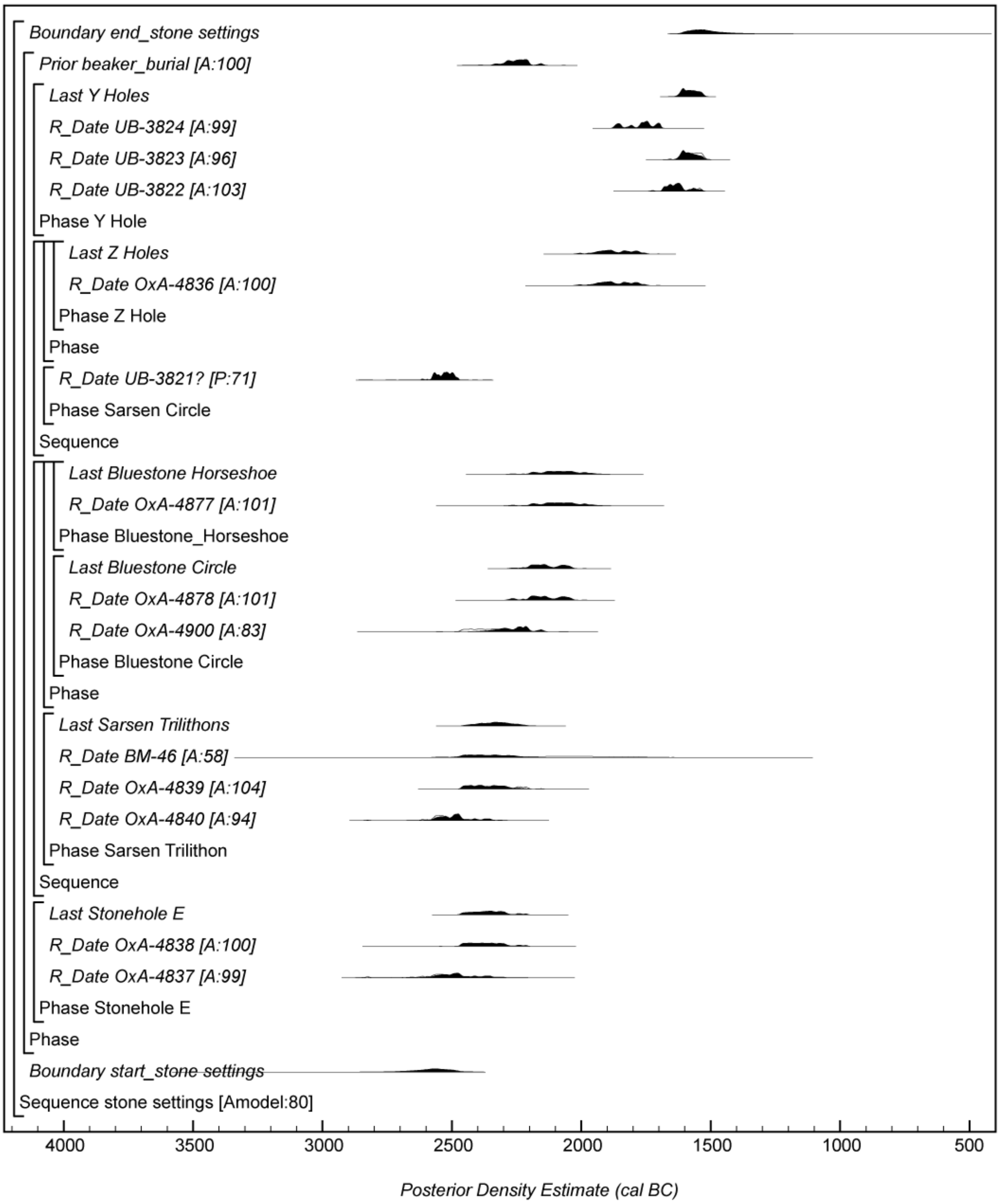

Figure 20: Probability distributions of dates from the stone settings (model 2). The format is identical to Figure 5

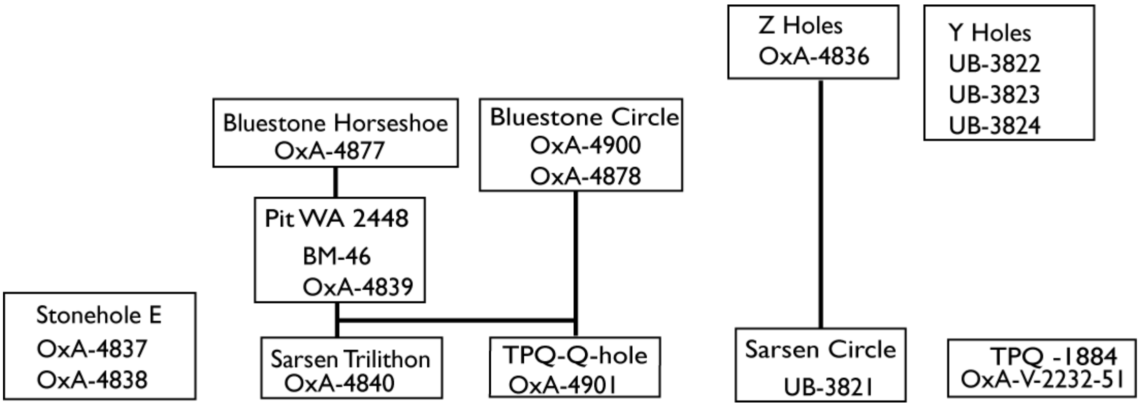

Figure 21: Summary of the prior information incorporated into the chronological model shown in Figure 22 – model 3 (from Darvill et al *2012)*

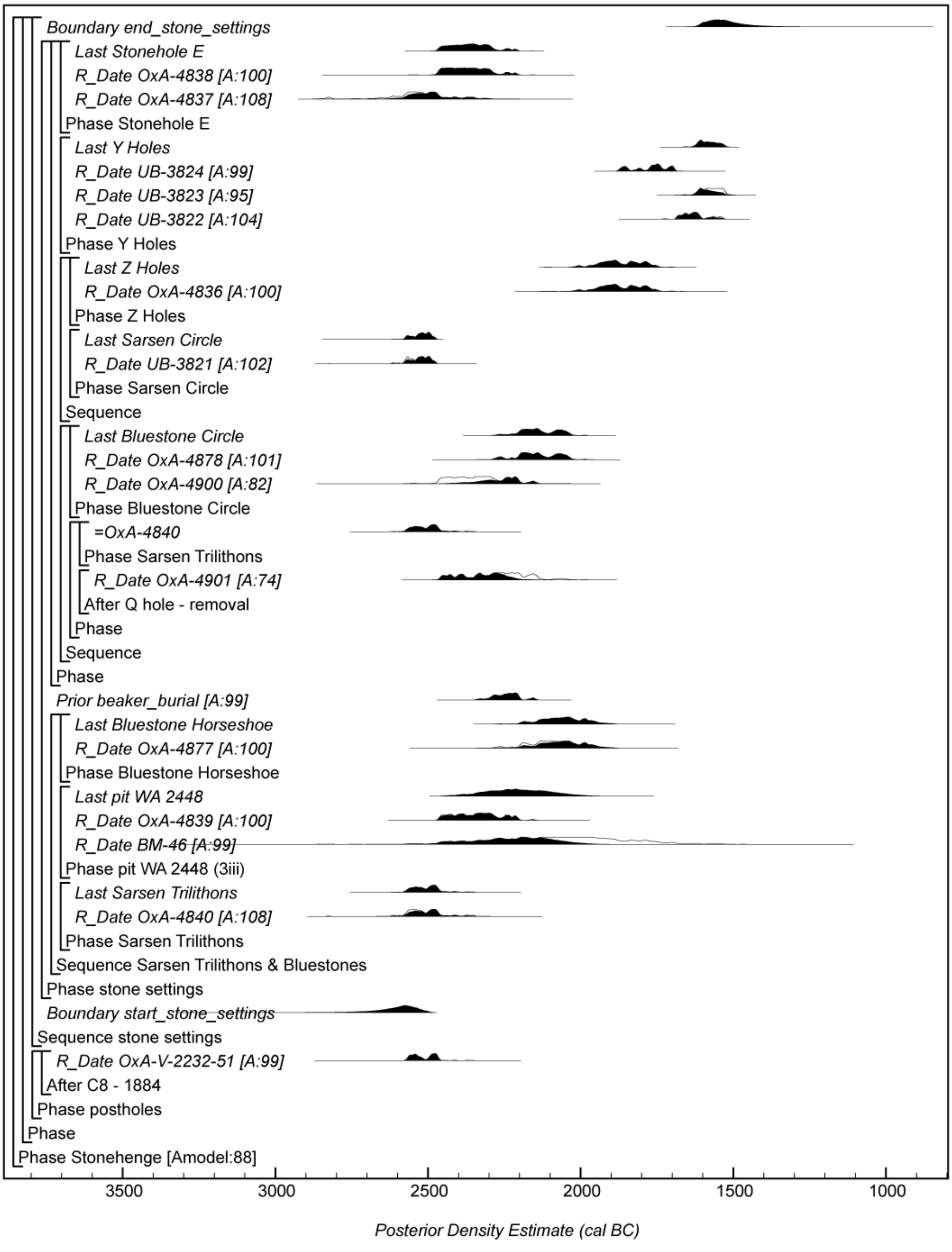

Figure 22: Probability distributions of dates from the stone settings (model 3). The format is identical to Figure 5

APPENDIX 1

Radiocarbon methods for samples dated since 1995

Scottish Universities Environmental Research Centre (SUERC)

The two bone samples were pre-treated following a modified version of Longin (1971) and the single cremated bone sample following Lanting *et al* (2001). CO_2 was obtained from the samples by combustion in pre-cleaned sealed quartz tubes as described by Vandeputte *et al* (1996), the purified CO_2 was converted to graphite (Slota *et al* 1987), and dated by AMS (Xu *et al* 2004; Freeman *et al* 2007).

Oxford Radiocarbon Accelerator Unit

The charred plant material was pretreated are described in Brock *et al* (2010) and the cremated bone following Lanting *et al* (2001). Bone samples were prepared following the revised ultrafiltration protocol described by Bronk Ramsey *et al* (2004a) (also see Brock *et al* 2007; 2010).

The human bone, teeth, and single animal bone with laboratory code OxA-V were combusted and dated at ORAU as detailed above on ultrafiltered collagen samples prepared at the Max Planck Institute for Evolutionary Anthropology, Leipzig, following the methods described in Richards and Hedges (1999) and Brown *et al* (1988). These measurements also include the number of the AMS wheel (wwww) that the sample was measured in and its position with in (pp) (Brock *et al* 2010).

All samples were dated using the current AMS machine at Oxford (Bronk Ramsey *et al* 2004b).

Quality assurance

Both laboratories maintain a continual programme of quality assurance procedures, in addition to participation in international inter-comparison exercises during the period when the measurements were made (Scott 2003; Scott *et al* 2010). These tests identified a problem with ultrafiltration protocol used for the processing of bone at Oxford in 2000–2002 (Bronk Ramsey *et al* 2000) which resulted in some bone samples giving ages which were about 100–300 radiocarbon years (BP) too old (Bronk Ramsey *et al* 2004a).

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