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Ring-width Dendrochronology and Radiocarbon Wiggle-matching of additional Oak Timbers

Martin Bridge, Cathy Tyers, Alex Bayliss, Silvia Bollhalder, and Lukas Wacker

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SUMMARY
An original set of samples taken in 2004 were re-assessed, and an additional 21 timbers were sampled, along with one measured by digital photography. Some timbers are thought to have been derived from the same parent trees, and a new site master made from the ring-width series of 17 trees was made. One later timber was dated individually. Radiocarbon wiggle-matching was undertaken on the main post, which could not be dated by ring-width dendrochronology.

The main post was found to have come from a tree felled after *cal AD 1574–1620 (95% probability)*, but probably after *cal AD 1584–1605 (68% probability)*. Spring vessels for AD 1774 were found on four timbers, pushing the construction date for the majority of the mill a year later than previously found. Some elements of the cross tree appear to have come from trees felled in AD 1791–1824, which may suggest that the trestle has been replaced. A packing piece under a cross tree dates to after AD 1845.

CONTRIBUTORS
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INTRODUCTION

The post mill is a Scheduled Monument (List Entry Number 1005061 here) and a Grade II* Listed (List Entry Number 1360710 here) structure on the east side of the village of Kibworth Harcourt, which lies on the A6, approximately halfway between Leicester to the north-west, and Market Harborough to the south-east (Fig 1). It has long been thought to date to AD 1711, based on a carved date on the main post, but earlier dendrochronological studies (Arnold *et al* 2004a) concluded that the timbers used had been felled in a single phase in AD 1773, although no date could be obtained for the main post, an element which has been shown often to be re-used from previous structures (Bridge 2006).

It is the only remaining post mill in Leicestershire and has its internal machinery intact. It is owned by the Society for the Protection of Ancient Buildings (SPAB) who have undertaken several restorations of the mill over the latter half of the last century, but a recent survey by Cambridge Mills Consultancy (Pearce and Davies 2019) revealed that extensive work was necessary to sustain the structure. In order to inform this new programme of repair and gain further insights into its history, further sampling of the mill was requested by Nick Carter, Inspector of Ancient Monuments and Amanda White, Heritage at Risk Surveyor, for the Midlands Region of Historic England in tandem with SPAB.

Further dendrochronological investigations, including trying to establish a date for the main post and other timbers not sampled in the previous study, would also contribute to a wider study of post mills, including those of Drinkstone (Suffolk), Herstmonceux (East Sussex), and the Cambridgeshire mills of Little (Great) Chishill, Great Gransden, and Bourn (funded by Historic England), and others undertaken by various teams over the last two decades. A mill is noted in Kibworth in the records of Merton College, Oxford, who used to own the mill in AD 1635, but is not shown on an estate map of AD 1609. The main post has been re-used from an earlier structure. The lower section of the post is weathered and retains evidence of having been painted white, suggesting that it was exposed prior to the building of the brick roundhouse.

RING-WIDTH DENDROCHRONOLOGY

Sampling

An assessment of the potential of surviving timbers in the trestle and buck for dendrochronology and radiocarbon wiggle-matching was undertaken in September 2021. Sampling was undertaken on two occasions in October 2021. Details of the 14 samples taken in the previous study, and the 24 samples obtained for this study are given in Table 1. Two core samples were taken from the LHS top plate (kibw03a and kibw03b) and from the crown-tree (kibw08a and kibw08b) in order to maximise the length of the ring series obtained, as well as getting as much sapwood information as possible. Figures 2–5 show the positions of most of the timbers sampled for scientific dating. The windshaft (kibw17) and the main post (kibw04) are not shown in the diagrams, and the cross-trees (kibw19, kibw20, and kibw22) are incorrectly shown, so Figures 6, 7, and 8a are photographs of these elements.

Figure 9 shows the lower part of the main post. The *ex situ* packing piece from under the cross-trees (kibw21) is also shown in Figure 8a, and part of the sequence from kibw22 in Figure 8b.

Methodology

Cores were extracted using a 16mm diameter drill bit and an electric drill, with each core hole being ringed in chalk, numbered, and recorded photographically, at the request of SPAB. These photographs are lodged with Historic England. Some slices of *ex situ* timbers removed as part of the ongoing repairs were also taken, and/or recorded using digital photography.

The cores were polished on a belt sander using 80 to 400 grit abrasive paper to allow the ring boundaries to be clearly distinguished. The samples had their tree-ring sequences measured to an accuracy of 0.01mm, using a specially constructed system utilising a binocular microscope with the sample mounted on a travelling stage with a linear transducer linked to a PC, which recorded the ring widths into a dataset. The software used in measuring and subsequent analysis was written by Ian Tyers (2004). Cross-matching was attempted by a process of qualified statistical comparison by computer combined with visual matching. The ring-width series were compared for statistical cross-matching, using a variant of the Belfast CROS program (Baillie and Pilcher 1973). Ring-width series were plotted on the computer monitor to allow visual comparisons to be made between sequences. This method provides a measure of quality control in identifying any potential errors in the measurements when the samples cross-match.

In comparing one sample or site master against other samples or chronologies, *t*-values over 3.5 are considered significant, although in reality it is common to find demonstrably spurious *t*-values of 4 and 5 because more than one matching position is indicated. For this reason, dendrochronologists prefer to see some *t*-value ranges of 5, 6, and higher, and for these to be well replicated from different, independent chronologies with both local and regional chronologies well represented, except where imported timbers are identified. Where two individual samples match together with a *t*-value of 10 or above, and visually exhibit exceptionally similar ring patterns, they may have originated from the same parent tree. Same-tree matches can also be identified through the external characteristics of the timber itself, such as knots and shake patterns. Lower *t*-values however do not preclude same-tree derivation.

Once a tree-ring sequence has been firmly dated in time, a felling date, or felling date range, is ascribed where possible. With samples which have sapwood complete to the underside of, or including bark, this process is relatively straightforward. Depending on the completeness of the final ring (ie if it has only the spring vessels or early wood formed, or the latewood or summer growth) a precise felling date and season can be given. If the sapwood is partially missing, or if only a heartwood/sapwood transition boundary survives, then an estimated felling date range can be given for each sample. The number of sapwood rings can be estimated by using an empirically derived sapwood estimate. If no sapwood or heartwood/sapwood boundary survives then the appropriate sapwood estimate is added to the last measured ring to give a *terminus post quem* (*tpq*) or felled-after date.

The sapwood estimate for oaks in this area is that for the North and Midlands provided by Miles (1997, fig 5).

Results and Interpretation

Details of the samples from the previous study are presented, along with the new samples in Table 1. Three of the newly obtained samples, kibw03b, kibw10, and kibw13, were not measured as they contained less than 20 rings. The two samples obtained from the crown-tree, kibw08a and kibw08b, cross-matched (t =10.5 with 45 years overlap) and were combined to produce a single timber series kibw08. Details of the cross-matching between the ring-width series are given in Table 2.

Some discrepancies have been noted, namely that kib-a11 from the 2004 study was recorded as from the rear corner post in the possible extension, but this timber was re-examined and did not match the number of rings quoted. A clear sampling hole was noted in the crown-tree, but this is not listed in the original report, and it is possible that kib-a11 was in fact from the crown-tree with this series and kibw08 matching (t = 8.3 with 111 years overlap), although the series actually gave stronger matches with kibw02 the RHS top plate (t = 9.0 with 94 years overlap) and kibw15, the LHS front corner post (t = 8.1 with 61 years overlap), and kibw08 gives stronger matches with kib-a13 (t = 18.4 with 55 years overlap), kib-a12 (t = 14.4 with 70 years overlap), and kib-a06 (t =9.5 with 99 years overlap).

A number of timbers appear to have been potentially derived from the same parent tree, and these are highlighted in Table 2. Mean series were therefore made for kib-a02, kib-a08, and kib-a09 (two sheer spacers and a quarter bar); kib-a03 and kib-a04 (two quarter bars); kib-a07, kib-a12, kib-a13, kibw02, kibw07, and kibw08 (breast beam, a corner post, stud, a top plate, a mid-rail, and crown-tree). Two other samples, kib-a06 and kibw16 (a sheer and a side girt) also matched well and were considered as a possible same-tree pair, but since they were felled in different years, they were treated as individual timbers in the subsequent analysis.

These three mean ring-width series, representing individual trees, were then combined with the series of the other 14 cross-matching samples included in Table 2 at their relative offset positions to produce site-master chronology, KIBWRTHt17, which is dated as spanning AD 1582–1786 (Table 3a). The other ring-width series were then compared with the database of master chronologies for oak, and sample kibw21 was found to cross-match when spanning AD 1714–1833 (Table 3b). It also produces a t = 3.2 with 73 years overlap against KIBWRTHt17 at this date.

Of twenty-two timbers sampled in the present study, two had insufficient rings for measurement and seven failed to date, one of which was the main post, with 63 rings recovered, but a band of narrow rings within that. This was selected for radiocarbon wiggle-matching, discussed below. The other six all had fewer than 42 rings, and could not be cross-matched with any certainty, either with other timbers in the assemblage, or with the database of dated oak. One of these undated timbers was the windshaft (kibw17), thought to be an early example of the type.

One of the significant findings from the present study is that two timbers, a mid-rail (kibw07) and the crown-tree (kibw08), derived from the same tree, retained the spring vessels formed in AD 1774. A re-assessment of the 2004 samples taken by the Nottingham Tree Ring Dating Laboratory resulted in three timbers having their felling dates altered: kib-a07 to winter AD 1773/4, and kib-a12 and kib-a06 to spring AD 1774.

The left-hand side girt that extends the full length of the buck (kibw16) has a precise felling date of spring AD 1773, and the rear top-plate (kibw01) and side top plates (kibw02 and kibw03) that extend over what is sometimes regarded as a rear extension, have a felled after date and likely felling dates that suggest they are of the same phase, suggesting that this rear part is not a later extension, but part of the main build.

Although the quarter bars were sampled previously, none gave a precise felling date. In this study two timbers from the cross-tree were dated from sections removed during repairs (kibw19 and kibw20), both being later than the AD 1774 date for most of the timbers, with a felling date range for one of AD 1791–1824. It seems possible that the whole trestle assembly was replaced in this period, although the packing piece (kibw21) has a later date still. It is unclear whether this was introduced later, or when the cross trees were installed. The brick piers on which the cross-trees sit are not bonded with the roundhouse walls, indicating that they are not contemporaneous, and this along with the white paint on the lowest part of the buck, indicates that the mill had an open trestle for much of its life (Bonwick, pers comm), so it is not unlikely that the timbers would have needed replacement at some stage.

The ring-width data for the measured samples are given in Appendix 1.

RADIOCARBON DATING

It has been postulated that the main post of this mill is older than most of the other timbers, as witnessed by the carved date of AD 1711, and it was thought possible that it may have come from the mill recorded in AD 1635. The dendrochronological sample from the main post (kibw04) had 63 rings, with suppressed growth in the early decades, and so the ring-width series did not date. Although no sapwood was present, the post was sampled just above the weathered and knotty wood that looked as if it was the outside of the tree. Any date obtained for the outer rings would not give a precise felling date, but should give a good indication of the likely date range of the tree used, and distinguish between an early seventeenth-century timber and an eighteenth-century timber.

Radiocarbon dating is based on the radioactive decay of ^{14}C, which trees absorb from the atmosphere during photosynthesis and store in their growth-rings. The radiocarbon from each year is stored in a separate annual ring. Once a ring has formed, no more ^{14}C is added to it, and so the proportion of ^{14}C versus other carbon isotopes reduces in the ring through time as the radiocarbon decays. Radiocarbon ages, like those in Table 4, measure the proportion of ^{14}C in a sample and are expressed in radiocarbon years BP (before present, 'present' being a constant, conventional date of AD 1950).

Six radiocarbon measurements have been obtained from single annual tree-rings from kibw04 (Table 4; Fig 10). Dissection was undertaken by Alison Arnold and Robert Howard at the Nottingham Tree-Ring Dating Laboratory. Prior to sub-sampling, the core was checked against the tree-ring width data. Then each annual growth ring was split from the rest of the tree-ring sample using a chisel or scalpel blade. Each radiocarbon sample consisted of a complete annual growth ring, including both earlywood and latewood. Each annual ring was then weighed and placed in a labelled bag. Rings not selected for radiocarbon dating as part of this study have been archived by Historic England.

Radiocarbon dating was undertaken by the Laboratory of Ion Beam Physics, ETH Zürich, Switzerland in 2022. Cellulose was extracted from each ring using the base-acid-base-acid-bleaching (BABAB) method described by Němec *et al* (2010), combusted and graphitised as outlined in Wacker *et al* (2010a), and dated by Accelerator Mass Spectrometry (AMS) (Synal *et al* 2007; Wacker *et al* 2010b). Data reduction was undertaken as described by Wacker *et al* (2010c). The facility maintains a continual programme of quality assurance procedures (Sookdeo *et al* 2020), in addition to participation in international inter-comparison exercises (Scott *et al* 2017; Wacker *et al* 2020). These tests demonstrate the reproducibility and accuracy of these measurements.

The results are conventional radiocarbon ages, corrected for fractionation using $\delta^{13}C$ values measured by AMS (Stuiver and Polach 1977; Table 4). These $\delta^{13}C$ values may deviate from the natural $\delta^{13}C$ of the sample by a few per mille, because sample preparation and the ion source of the AMS may lead to fractionation during the dating process, but this value is most appropriate for correcting for $^{14}C/^{12}C$ fractionation in dating.

WIGGLE-MATCHING

Radiocarbon ages are not the same as calendar dates because the concentration of ^{14}C in the atmosphere has fluctuated over time. A radiocarbon measurement has thus to be calibrated against an independent scale to arrive at the corresponding calendar date. That independent scale is the IntCal20 calibration curve (Reimer *et al* 2020). For the period covered by this study, this is constructed from radiocarbon measurements on tree-ring samples dated absolutely by dendrochronology. The probability distributions of the calibrated radiocarbon dates from kibw04 derived from the probability method (Stuiver and Reimer 1993), are shown in outline in Figure 11.

Wiggle-matching is the process of matching a series of calibrated radiocarbon dates which are separated by a known number of years to the shape of the radiocarbon calibration curve. At its simplest, this can be done visually, although statistical methods are usually employed. Floating tree-ring sequences are particularly suited to this approach as the calendar age separation of tree-rings submitted for dating is known precisely by counting the rings in the timber. A review of the method is presented by Galimberti *et al* (2004).

The approach to wiggle-matching adopted here employs Bayesian chronological modelling to combine the relative dating information provided by the tree-ring analysis with the calibrated radiocarbon dates (Christen and Litton 1995). It has been implemented using the program OxCal v4.4 (http://c14.arch.ox.ac.uk/oxcal.html; Bronk Ramsey *et al* 2001; Bronk Ramsey 2009). The modelled dates are shown in black in Figure 11, and quoted in italics in the text. The Acomb statistic shows how closely the assemblage of calibrated radiocarbon dates as a whole agree with the relative dating provided by the tree-ring analysis that has been incorporated in the model; an acceptable threshold is reached when it is equal to or greater than An (a value based on the number of dates in the model). The A statistic shows how closely an individual calibrated radiocarbon date agrees its position in the sequence (most values in a model should be equal to or greater than 60).

Figure 11 illustrates the chronological model for kibw04, the main post. This model incorporates the gaps between each dated annual ring (eg that the carbon in ring 10 of kibw04 (ETH-120579) was laid down ten years before the carbon in ring 20 (ETH-120580); Fig 10). It also incorporates the radiocarbon measurements from the core (Table 4) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer *et al* 2020).

The model has good overall agreement (Acomb: 115.6, An: 28.9, n: 6), and all the dates on the single rings have good individual agreement (A > 60) with their positions in the sequence. It suggests that the final surviving ring of kibw04 formed in *cal AD 1554–1584 (95% probability; kibw04 last ring*; Fig 11*)*, probably in *cal AD 1568–1579 (68% probability)*.

A *terminus post quem* for the felling of kibw04 is provided by adding the probability distribution of sapwood rings observed on historic oak timbers in the North and Midlands of England (Miles 1997, fig 5) to the estimated date of the last surviving ring (*kibw04 last ring*; Fig 11). This is after *cal AD 1574–1620 (95% probability; kibw04 tpq*; Fig 11*)*, probably after *cal AD 1584–1605 (68% probability)*.

DISCUSSION

The present study builds on the 2004 investigation by showing that further timbers from the late eighteenth-century phase of construction survive, but pushes the likely construction date one year later, as spring vessels formed in AD 1774 were identified on the samples from several timbers (Fig 12). The other main finding is the date for the main post. This has often been assumed to date from AD 1711 because of the carved name and date it bears, but this study shows that it is likely to be of even earlier origin. It is assumed that a post mill stood nearby on Carlton Hill in AD 1515 (Holmes, pers comm) and the date for the main post fits between this and the confirmed map evidence of the mill on its present site in AD 1636. The new results also support the idea that the 'extension' at the rear of the mill is actually a part of the main construction phase.

The cross-matching for the site chronology and individually dated timber (Table 3) suggests that the timber is of local origin.

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TABLES

Table 1: Details of samples taken from Kibworth Harcourt Mill for scientific dating

Sample No	Location	No rings		Date of measured sequence AD	Sapwood	Mean ring width (mm)	Mean sensitivity	Felling date range (AD/*cal AD*)
	2004 samples (Arnold et al 2004) –renamed as appropriate to conform to the element naming convention applied to post mills and current sapwood estimates applied							
kib-a01	NE quarter bar	87		1677–1763	6	2.08	0.21	1769–1802
kib-a02	SW quarter bar	93		1643–1735	-	1.98	0.25	after 1747
kib-a03	SE quarter bar	120		1582–1701	-	2.26	0.22	after 1713
kib-a04	NW quarter bar	110		1583–1692	-	2.09	0.21	after 1704
kib-a05	RH sheer	102		1656–1757	h/s	2.15	0.20	1769–1802
kib-a06	LH sheer	99		1675–1773	14¼C	2.02	0.20	spring 1774
kib-a07	Front sill (breast beam)	129		1645–1773	18C	2.12	0.25	winter 1773/4
kib-a08	Front sheer spacer	71		1660–1730	-	1.53	0.21	after 1742
kib-a09	Rear sheer spacer	82		1660–1741	-	1.74	0.29	after 1753
kib-a10	Main post	<		-	-	NM	-	-
kib-a11	Rear LH 'extension' corner post	111		1648–1758	7	2.15	0.28	1763–96
kib-a12	Rear LH 'true' corner post	70		1704–1773	27¼C	1.28	0.24	spring 1774
kib-a13	Stud 6 above lower side girt RHS	55		1664–1718	-	1.65	0.30	after 1730
kib-a14	Stud 7 below lower side girt RHS	61		1691–1751	h/s	2.13	0.17	1763–96
	2021 samples							
kibw01	Rear top-plate over extension	42		1679–1720	-	2.14	0.26	after 1732
kibw02i	RHS top plate (inner rings)	49		1657–1705	-	1.75	0.35	
kibw02ii	ditto (outer rings)	45		1706–50	h/s	1.56	0.24	
kibw02	02i + 02ii	94		1657–1750	h/s	1.66	0.30	1762–95
kibw03a	LHS top plate	42		1709–50	?h/s	2.65	0.24	?1762–95
kibw03b	ditto	<20		-	-	NM	-	
kibw04	Main post	63				4.00	0.19	after

								cal AD 1574–1620 (95% probability)
kibw05	RHS rear extension lower central stud	31		-	-	2.04	0.20	-
kibw06	Rear threshold to main part of buck	34		-	-	4.39	0.15	-
kibw07	LHS mid-rail	73		1701–73	24¼C	1.42	0.24	spring 1774
kibw08a	Crown-tree	65		1709–73	27¼C	1.32	0.22	
kibw08b	ditto	129		1625–1753	h/s	1.86	0.29	
kibw08	Mean of 08a and 08b	149		1625–1773	27¼C	1.78	0.27	spring 1774
kibw09	LHS front jowl post	41		-	?h/s	3.30	0.16	-
kibw10	RHS front jowl post	<20		-	-	NM	-	
kibw11	Rear lintel to main part of buck	40		1722–61	6	2.80	0.26	1767–1800
kibw12	LHS corner post to main part of buck	46		1709–54	h/s	2.45	0.23	1766–99
kibw13	RHS rear corner post to main part of buck	<20		-	-	NM	-	
kibw14	RHS rear corner post in extension	25		-	h/s	3.21	0.17	-
kibw15	LHS front corner post	61		1668–1728	-	1.59	0.25	after 1740
kibw16	LHS side girt	104		1669–1772	17¼C	1.84	0.26	spring 1773
kibw17	Windshaft	37		-	-	3.57	0.27	-
kibw18	RHS front corner post	88		1671–1758	16	3.10	0.21	1758–87
kibw19	*Ex situ* slice cross-tree D	77		1710–86	7 (+1NM)	1.85	0.21	1791–1824
kibw20	*Ex situ* slice cross-tree B	51		1725–75	-	2.77	0.22	after 1787
kibw21	*Ex situ* slice packing piece under cross-tree D	120		1714–1833	-	1.36	0.18	after 1845
kibw22	Photo-sequence cross-section cross-tree C	73		-	-	5.25	0.16	-

Key: RH (RHS) = right hand side; LH (LHS) = left hand side; ¼C = complete sapwood, felled the following spring; C = complete sapwood, felled the following winter; h/s = heartwood/sapwood boundary; NM = not measured; ranges *in italics* derive from radiocarbon wiggle-matching alone. Note re-interpretation of some felling dates for 2004 samples after re-assessment of the cores

Table 2: Cross-matching between the dated timbers from both investigations (t-values over 3.5 are statistically significant)

Sample	kiba02	kiba03	kiba04	kiba05	kiba06	kiba07	kiba08	kiba09	kiba11	kiba12	kiba13	kiba14	kibw01	kibw02	kibw03a	kibw07	kibw08	kibw11	kibw12	kibw15	kibw16	kibw18	kibw19	kibw20	kibw21
kiba01	4.4	1.4	\	3.5	5.4	5.2	4.0	3.6	4.2	4.4	1.9	3.0	3.5	6.0	3.1	4.2	3.6	2.8	2.7	3.8	5.8	3.3	3.4	1.7	1.7
kiba02		4.1	3.9	3.8	8.0	7.6	12.3	10.6	6.9	4.6	8.0	3.2	2.6	8.4	6.6	9.9	8.0	\	1.7	5.3	8.1	6.9	4.3	\	\
kiba03			17.2	2.1	3.6	3.5	5.2	5.3	4.4	\	4.3	\	\	4.0	\	\	4.5	\	\	4.0	5.2	7.0	\	\	\
kiba04				1.7	\	2.8	4.0	4.6	3.9	\	4.3	\	\	2.8	\	\	4.5	\	\	3.2	4.3	4.7	\	\	\
kiba05					4.4	5.5	3.6	4.0	5.7	4.6	3.2	7.0	4.3	5.1	3.0	4.7	4.6	3.1	3.5	5.9	4.8	5.6	2.2	2.8	2.5
kiba06						8.2	7.4	7.5	6.3	3.8	7.0	3.4	2.8	9.2	3.7	6.8	9.5	3.4	2.1	6.4	13.4	8.9	3.8	3.9	3.5
kiba07							6.7	6.1	8.8	7.4	7.4	4.4	3.0	11.0	5.5	7.7	8.1	2.6	2.8	7.2	8.6	7.3	5.0	4.4	3.3
kiba08								9.8	6.2	3.6	6.7	3.1	3.3	7.4	6.1	8.1	7.7	\	\	6.1	7.1	6.3	3.5	\	\
kiba09									5.9	5.3	6.1	3.6	2.7	7.4	4.8	8.0	7.1	\	2.1	5.6	6.8	7.8	3.3	\	1.3
kiba11										5.5	7.2	3.3	2.7	9.0	3.4	5.6	8.3	3.1	8.0	8.1	7.2	7.5	1.8	2.6	1.2
kiba12											\	4.2	\	6.9	4.6	8.6	14.4	2.8	4.6	\	4.9	4.0	3.2	4.3	2.7
kiba13												2.6	2.4	7.3	\	\	18.4	\	\	4.5	5.3	7.3	\	\	\
kiba14													1.8	3.1	2.6	4.5	4.5	3.8	3.1	2.6	3.6	4.8	2.2	1.7	1.5
kibw01														4.7	\	5.8	3.0	\	\	5.0	2.6	3.1	\	\	\
kibw02															7.0	12.1	9.6	4.7	4.7	6.7	9.1	8.3	4.4	4.4	1.9
kibw03a																9.6	4.0	3.0	2.5	4.7	3.9	3.8	4.8	5.4	1.8
kibw07																	10.1	3.3	4.4	4.0	6.8	6.3	4.3	6.2	3.2
kibw08																		3.0	4.0	5.1	7.7	8.7	3.5	4.1	2.7
kibw11																			3.3	\	3.6	3.2	1.3	1.5	1.0
kibw12																				\	3.1	4.5	1.5	2.1	1.4
kibw15																					5.3	8.4	\	\	\
kibw16																						8.2	3.3	3.5	3.1
kibw18																							2.2	2.0	2.7
kibw19																								7.5	2.5
kibw20																									3.1

Key: \ represents overlaps of 20 years or less (no figure calculated) and highlighted cells are potentially samples derived from the same tree

Table 3a: Dating evidence for the site chronology KBWRTHt17, AD 1582–1786

Source region:	Chronology name:	Publication reference:	File name:	Span of chronology (AD)	Overlap (years)	*t*-value
Northamptonshire	Kirby Hall	Arnold *et al* forthcoming	KRBHSQ01	1378–1795	205	11.7
Worcestershire	Croome Court	Arnold *et al* 2004b	CRMASQ01	1639–1753	115	11.3
Leicestershire	Church Farm, Bringhurst	Groves *et al* 2004	BRNGHST1	1664–1781	118	10.8
Rutland	Oakham Castle	Arnold and Howard 2013	OKMCSQ03	1598–1737	140	10.2
Lincolnshire	St Firmin's, Thurlby	Arnold and Howard 2010	THUBSQ01	1599–1792	188	10.0
Warwickshire	Stoneleigh Abbey	Howard *et al* 2000	STOISQ04	1646–1813	141	9.7
Northamptonshire	Apethorpe Hall	Arnold *et al* 2008	APTASQ02	1574–1749	168	9.6
Buckinghamshire	Home FarmBarn, Stowe	Miles *et al* 2003	STOWE7	1652–1781	130	9.3
Oxfordshire	Chazey Court	Miles et al 2004	CHAZEY2	1674–1737	64	9.2
Lincolnshire	Old Barholm Hall Barn	Arnold *et al* 2019	BARDSQ04	1610–1730	121	9.2

Table 3b: Dating evidence for the kibw21, AD 1714–1833

Source region:	Chronology name:	Publication reference:	File name:	Span of chronology (AD)	Overlap (years)	*t*-value
Hertfordshire	Cromer windmill	Tyers 1998	CROMER2	1692–1831	118	6.5
Buckinghamshire	Mill Pond planks, Stowe	Miles *et al* 2003	STOWE5	1712–1891	120	5.7
Staffordshire	Cannock Chase	Briffa *et al* 1986	CANNOCK	1639–1979	120	5.6
Warwickshire	Stoneleigh Abbey	Howard *et al* 2000	STOISQ04	1646–1813	100	5.4
Northamptonshire	Kirby Hall	Arnold *et al* forthcoming	KRBHSQ01	1378–1795	82	5.3
Suffolk	Sotterley Park	Briffa *et al* 1986	SOTTERLY	1586–1981	120	5.2
Cambridgeshire	Great Chishill windmill	Bridge 2015	CHISHILL	1732–1817	86	5.2
Bedfordshire	Woburn Abbey	Miles pers comm	WBRNM1	1548–2016	120	5.2
Buckinghamshire	The Hovel, Ludgershall	Miles and Worthington 1999	THEHOVEL	1671–1811	98	5.2
Northamptonshire	158 Watling Street East, Towcester	Bridge and Tyers 2022	TOWSt6	1702–1805	92	5.1

Table 4: Radiocarbon measurements and associated δ¹³C values from kibw04

Laboratory Number	Sample	Radiocarbon Age (BP)	$\delta^{13}C_{AMS}$ (‰)
ETH-120579	kibw04, ring 10 (Quercus sp., heartwood)	335±13	−24.1
ETH-120580	kibw04, ring 20 (Quercus sp., heartwood)	305±13	−25.3
ETH-120581	kibw04, ring 30 (Quercus sp., heartwood)	322±13	−25.4
ETH-120582	kibw04, ring 40 (Quercus sp., heartwood)	296±13	−24.7
ETH-120583	kibw04, ring 50 (Quercus sp., heartwood)	310±13	−25.6
ETH-120584	kibw04, ring 60 (Quercus sp., heartwood)	325±13	−25.7

FIGURES

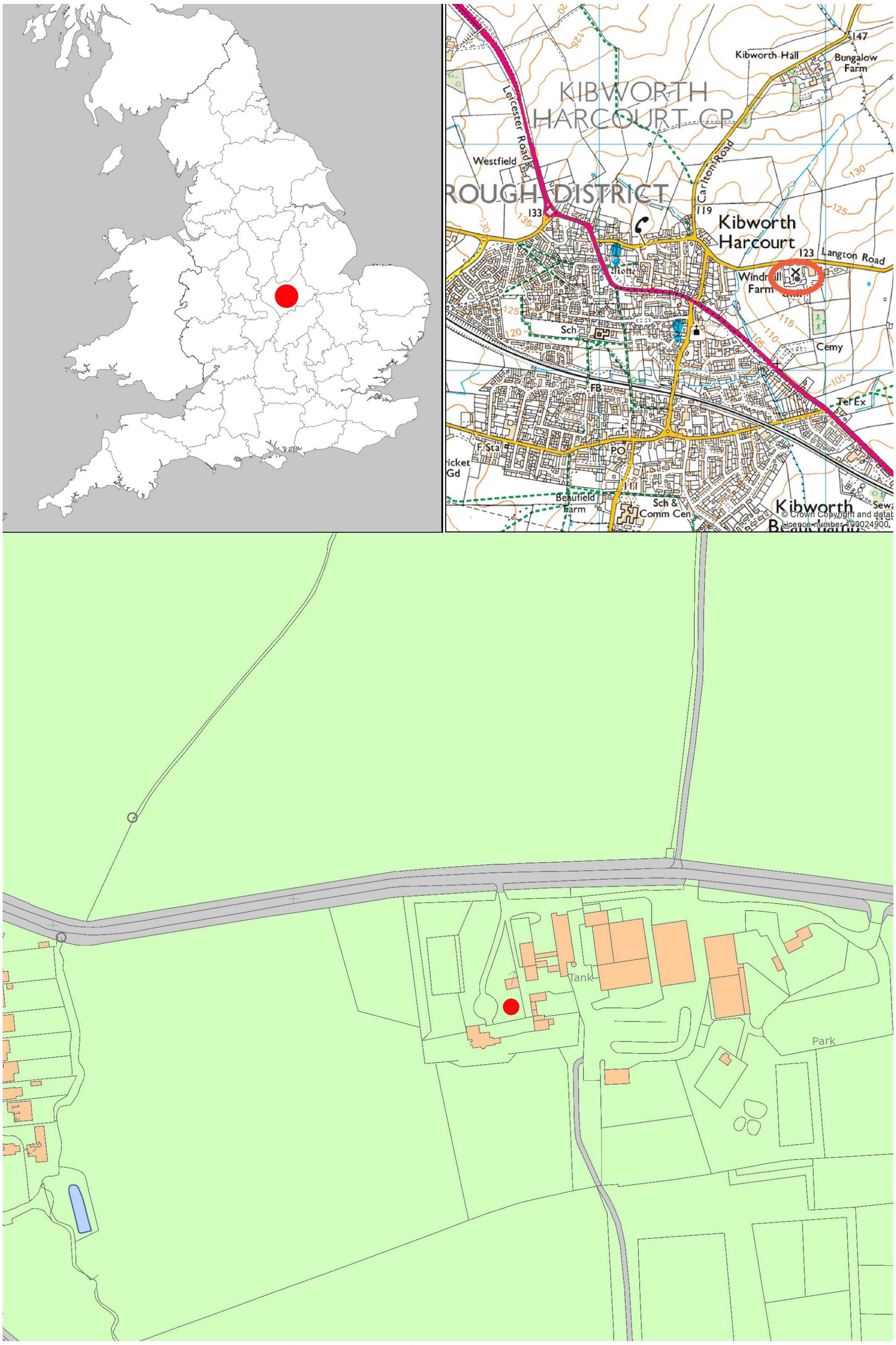


Figure 1: Maps to show the location of Kibworth Harcourt Mill in Harborough, Leicestershire, marked in red. Scale: top right 1:13,500, bottom 1:3000 © Crown Copyright and database right 2022. All rights reserved. Ordnance Survey Licence number 100024900

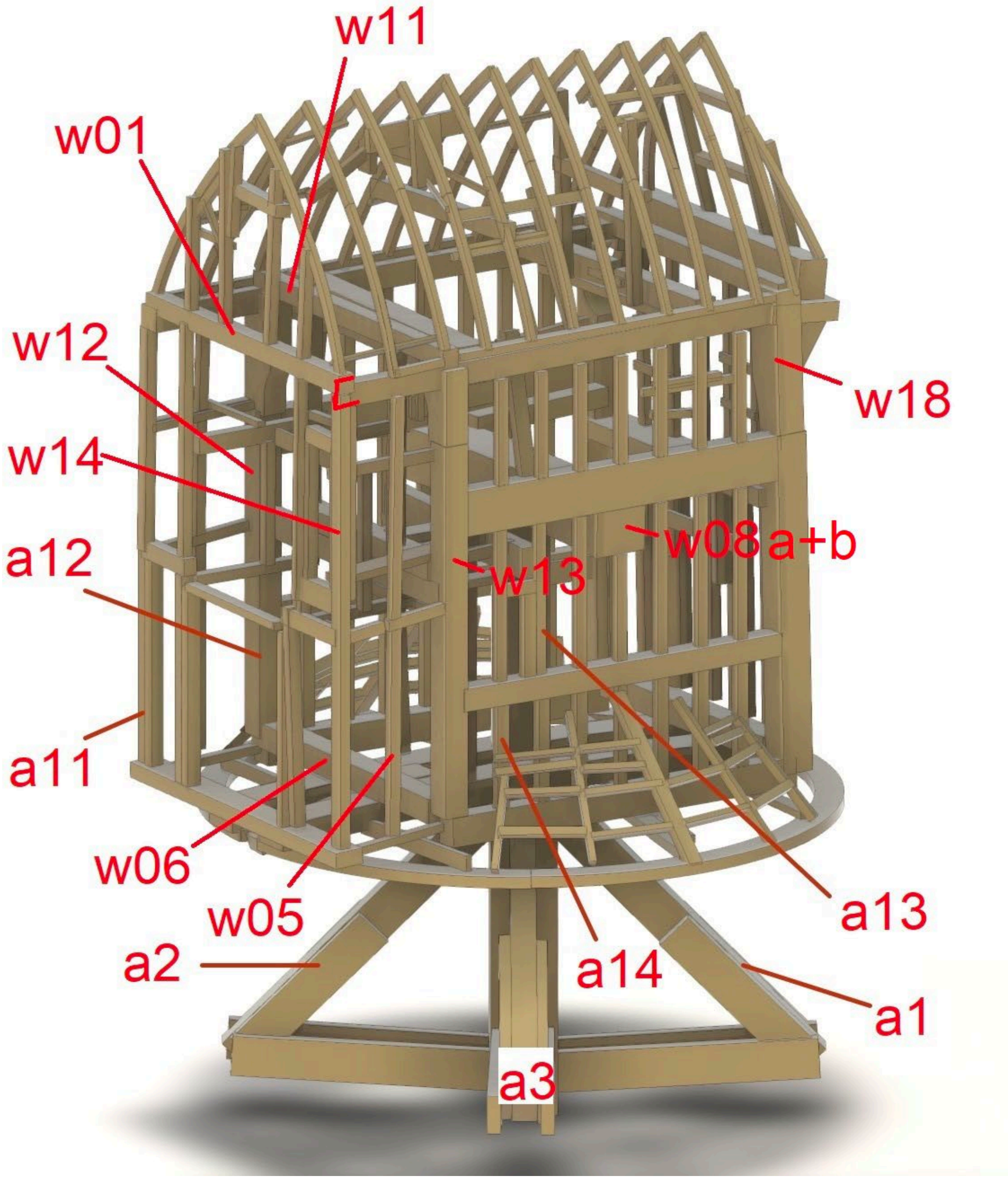


Figure 2: Right-hand side rear elevation showing the positions of some original (2004) samples prefixed a, and 2021 samples prefixed w, with the inaccurate rendering of the right top-plate highlighted (adapted from an original Terra Measurement Ltd. image supplied by SPAB)

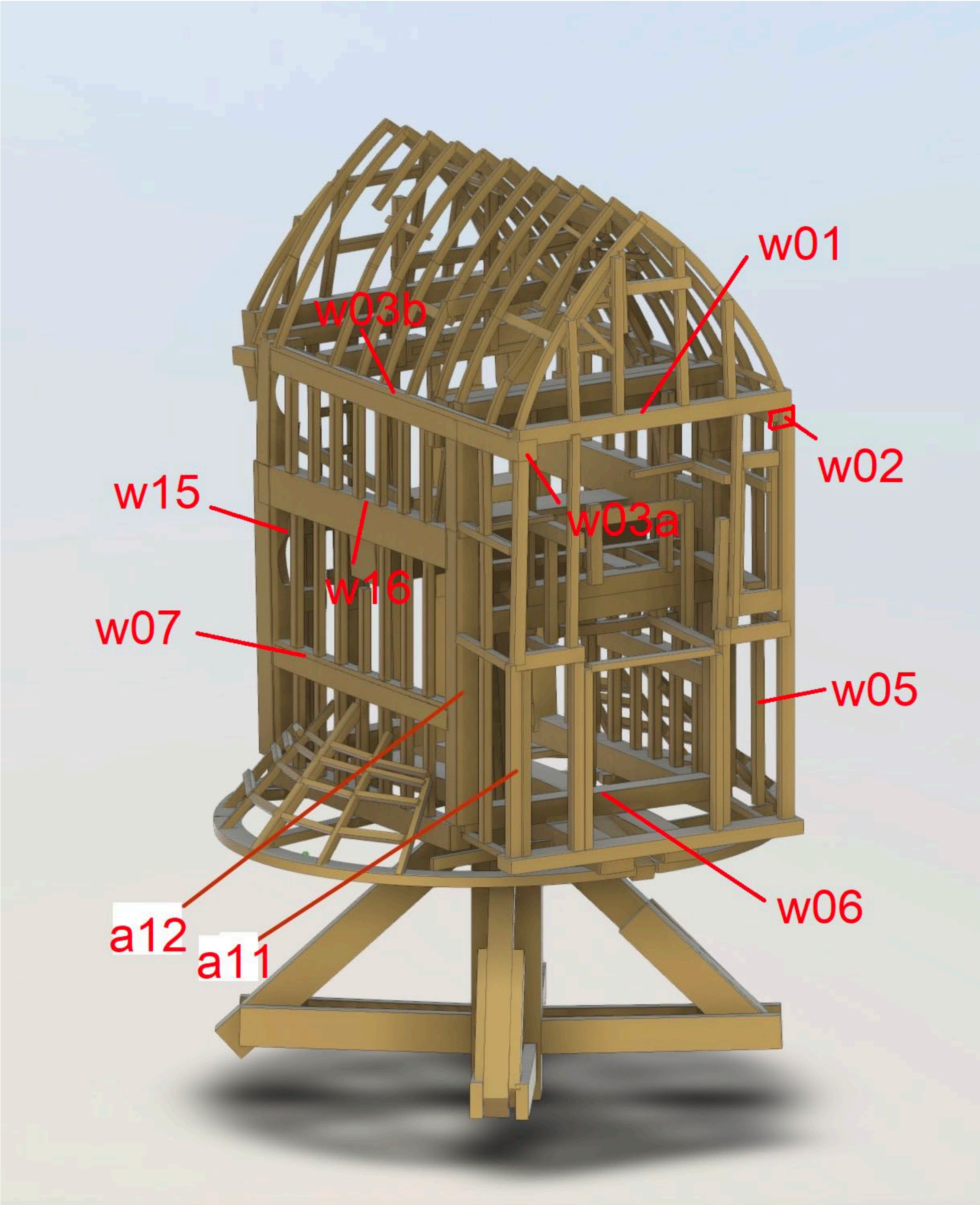


Figure 3: Left-hand side rear elevation, showing the positions of some original (2004) samples prefixed a, and 2021 samples prefixed w highlighted (adapted from an original Terra Measurement Ltd. image supplied by SPAB)

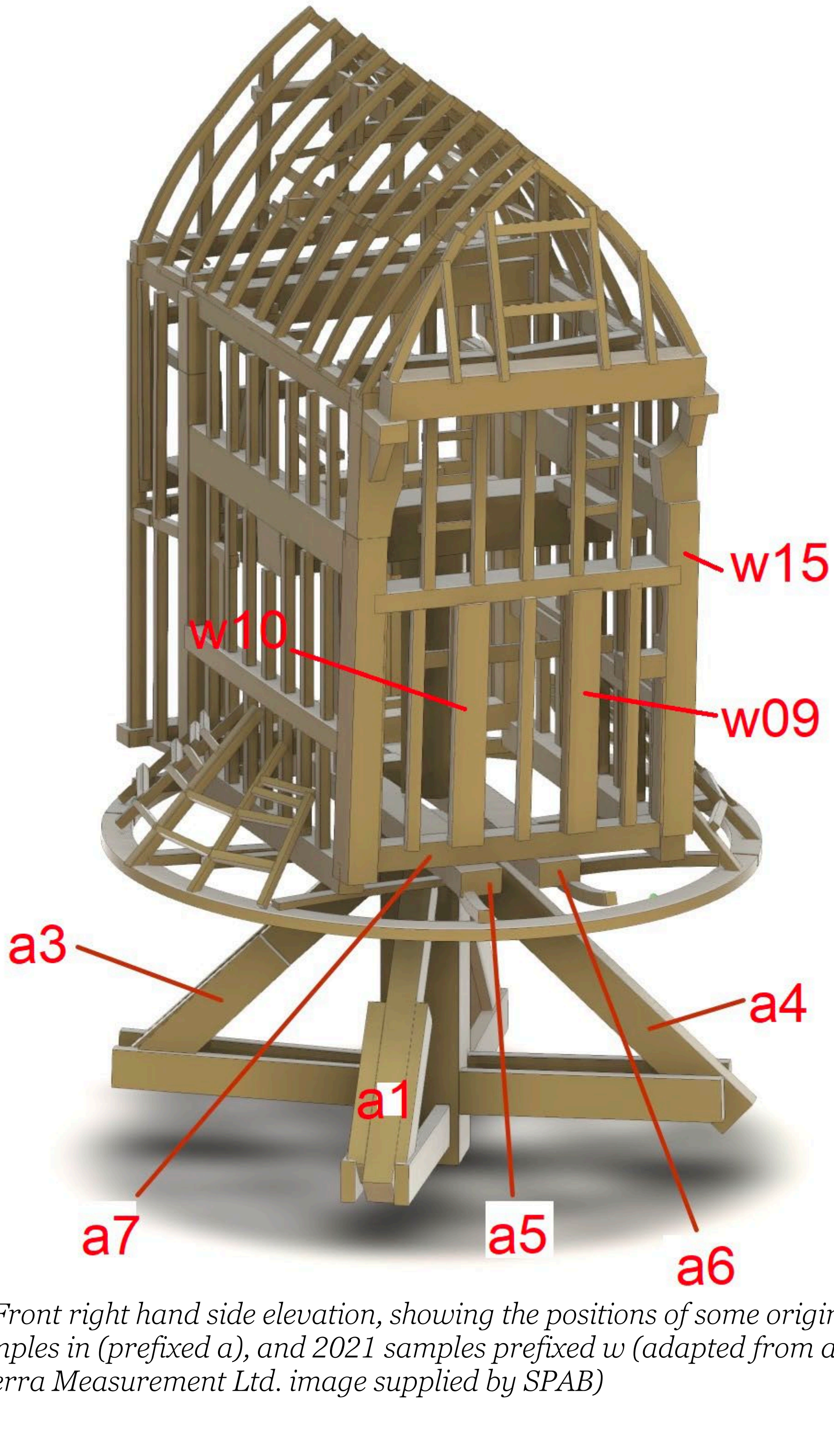


Figure 4: Front right hand side elevation, showing the positions of some original (2004) samples in (prefixed a), and 2021 samples prefixed w (adapted from an original Terra Measurement Ltd. image supplied by SPAB)

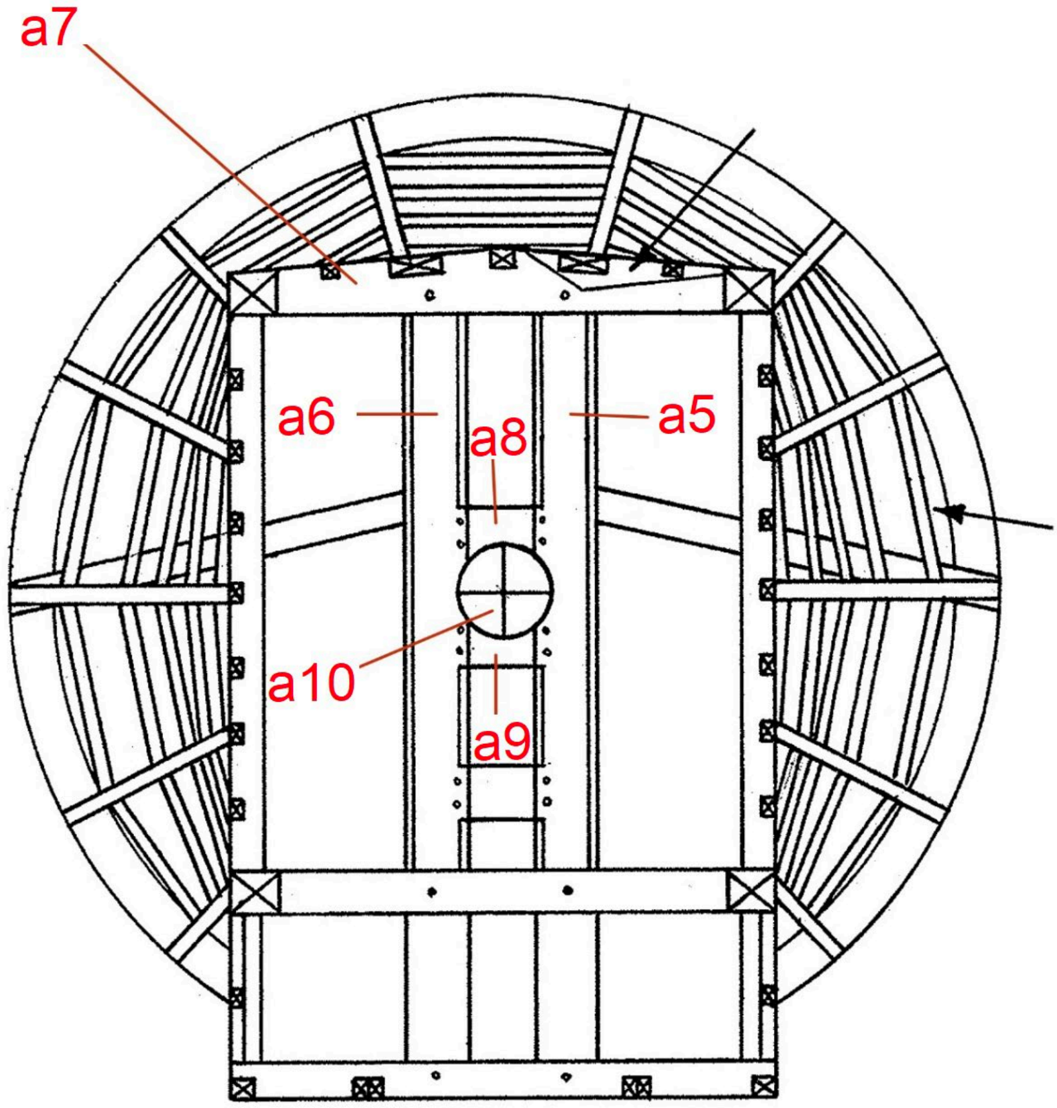


Figure 5: Drawing of the spout floor, showing positions of the original 2004 samples (adapted from a drawing supplied by SPAB)

Figure 6: Position of the core from the main post (kibw04) being indicated. (photograph by Martin Bridge)

Figure 7: The windshaft, with the position of core kibw17 highlighted in chalk (photograph by Martin Bridge)

Figure 8a: Ex situ *slices from the cross-trees (kibw19 and kibw20), and* ex situ *packing piece (kibw21)(photograph by Martin Bridge)*

Figure 8b: Part of the photographic sequence for kibw22, the cross tree section C (photograph by Martin Bridge)

Figure 9: View of the main post below the quarter bars showing the weathered painted surface and knotty nature of the timber (photograph by Martin Bridge)

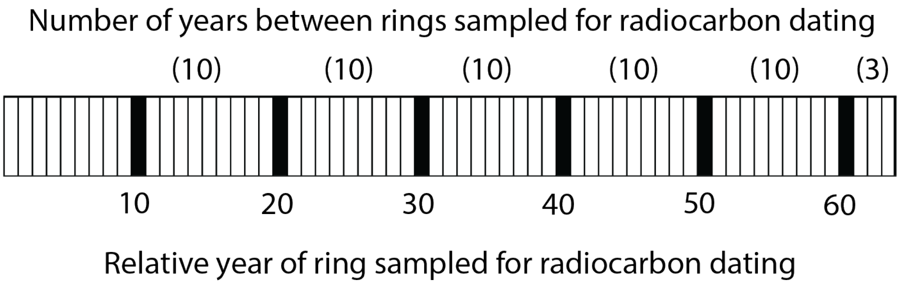


Figure 10: Schematic illustration of the relative positions of the rings sampled for radiocarbon dating within kibw04

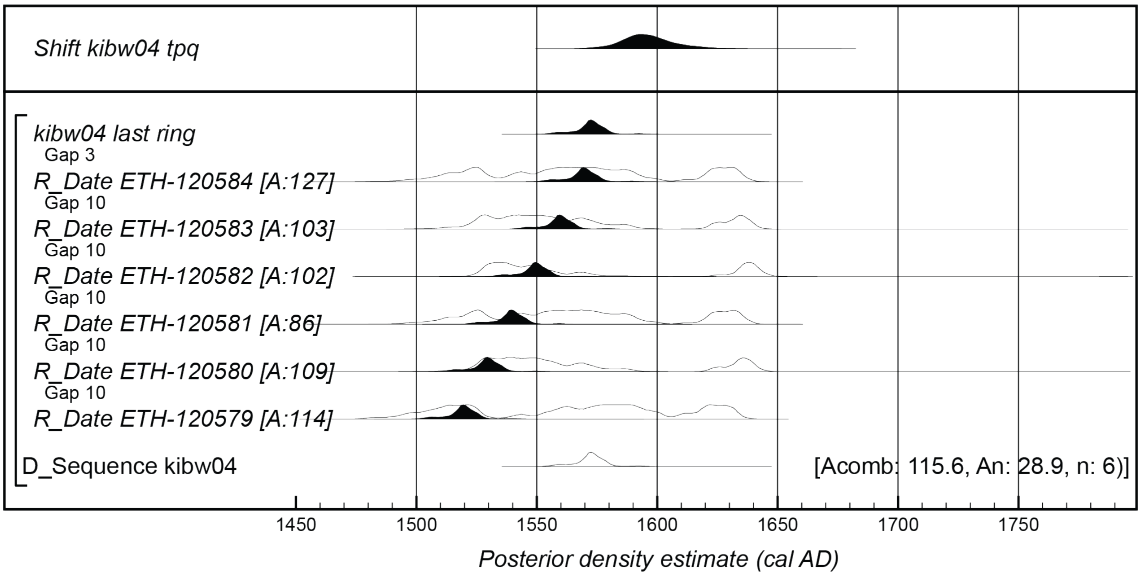


Figure 11: Probability distributions of dates from kibw04, the main post. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. Distributions other than those relating to particular samples correspond to aspects of the model. For example, the distribution 'kibw04 last ring' *is the estimated date when the last surviving ring of sample kibw04 formed. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly*

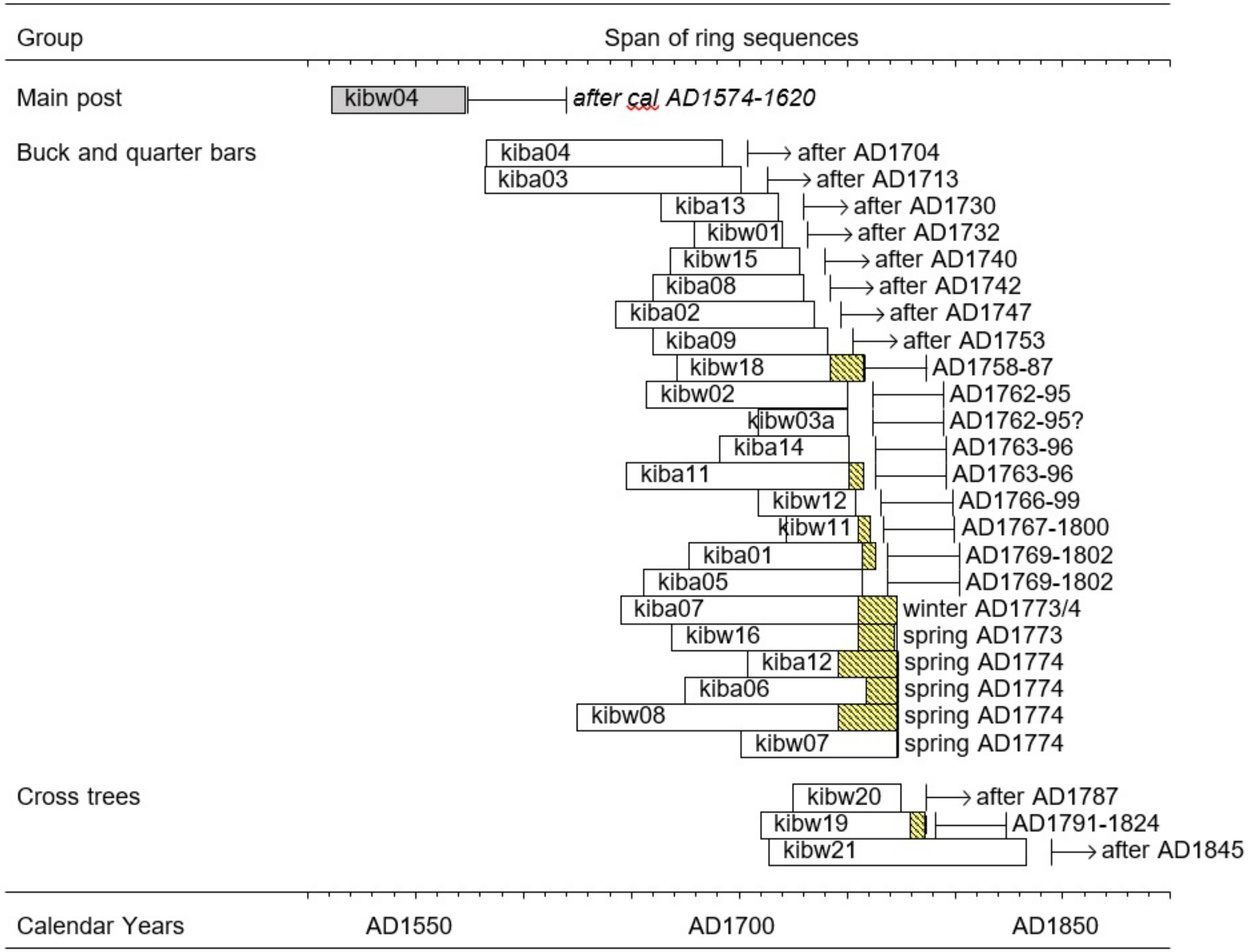


Figure 12: Bar diagram showing the relative positions of overlap of the dated timbers, with their felling dates or date ranges. White bars represent measured heartwood rings, yellow hatched sections are measured sapwood rings; the grey bar represents the position of the radiocarbon wiggle-matched timber

APPENDIX

Ring width values (0.01mm) for the sequences measured

kiba01

174	304	221	309	202	273	259	177	258	292
323	324	331	296	340	269	250	226	271	290
268	150	75	78	98	122	142	131	141	175
105	132	161	113	177	202	195	152	233	219
251	156	133	198	300	263	206	328	169	176
233	199	216	195	205	260	214	187	189	220
184	254	321	141	122	144	184	142	143	195
197	181	135	138	150	195	203	242	213	216
226	261	225	269	222	197	231			

kiba02

347	301	204	301	245	347	238	402	283	312
247	224	390	246	294	289	268	197	199	223
193	140	164	158	171	275	219	267	312	247
241	184	168	136	163	232	187	252	160	298
331	174	162	389	306	288	232	174	233	152
211	106	134	187	205	206	150	162	122	218
299	291	160	184	134	178	180	94	130	133
129	86	123	116	137	142	86	127	155	137
78	82	87	80	103	106	103	182	119	170
123	143	144							

kiba03

343	341	352	346	314	407	427	368	243	255
229	172	275	302	281	241	295	262	208	190
145	171	233	171	359	419	286	247	310	337
282	317	266	347	305	389	382	264	232	141
247	328	246	210	200	136	174	302	142	175
222	204	178	164	136	140	151	167	181	303
238	238	216	217	271	219	212	169	127	209
169	162	206	263	285	244	214	211	331	184
256	237	134	95	133	170	217	251	216	323
214	234	172	129	158	236	240	226	169	154
215	195	153	158	292	227	196	145	110	165
112	176	136	114	149	150	175	138	123	176

kiba04

245	299	345	300	396	390	305	205	211	200
171	258	292	246	208	220	224	170	142	133
151	233	142	236	303	213	206	216	294	241
229	226	351	277	354	351	252	152	127	219
310	256	164	218	159	165	300	172	188	232
221	103	101	73	66	78	122	143	219	200
179	170	175	233	182	176	138	113	149	156
134	186	267	257	242	225	237	303	210	269
246	140	108	155	170	221	266	257	287	217
222	193	179	159	225	203	237	167	182	194

184	144	143	266	235	207	163	121	85	137

kiba05

224	218	244	333	292	299	216	299	327	226
305	237	306	211	342	267	225	249	244	175
159	245	198	239	273	309	343	275	202	307
339	313	405	354	250	450	364	316	232	247
297	283	302	224	258	210	173	229	237	150
204	192	303	304	209	250	290	243	143	153
183	170	149	180	128	165	149	105	129	107
87	131	113	95	95	91	104	80	162	182
166	103	145	180	137	111	119	153	153	176
173	112	112	146	157	198	171	213	185	221
225	205								

kiba06

221	140	334	329	281	292	165	298	287	144
130	250	325	362	327	218	246	192	181	130
186	302	295	252	199	151	167	213	378	292
193	216	176	223	176	130	188	260	219	181
255	207	155	169	162	204	217	159	151	170
128	167	193	239	231	218	178	229	224	208
209	167	132	199	189	139	110	132	153	160
186	187	185	193	200	150	197	156	162	192
161	178	174	205	212	148	182	187	182	231
171	175	175	201	177	180	144	172	200	

kiba07

121	152	112	332	316	272	214	185	233	182
373	311	289	303	250	350	238	226	258	213
190	159	235	457	264	282	340	267	215	131
183	104	159	158	73	111	102	212	153	104
81	207	165	160	142	88	100	106	87	67
61	124	157	138	86	84	99	95	218	155
191	265	240	307	270	178	272	338	321	220
300	265	296	251	246	226	324	319	170	288
248	188	345	221	233	338	249	257	277	303
339	293	112	282	286	183	180	193	221	238
304	259	236	233	228	177	210	305	211	246
232	203	197	187	175	120	142	126	217	220
201	190	166	243	198	147	151	149	160	

kiba08

298	364	340	239	206	160	169	194	233	164
170	213	189	179	140	130	96	126	173	143
166	136	222	232	157	141	280	281	288	266
184	187	98	147	107	119	119	136	128	102
115	78	100	152	149	111	122	105	141	149
90	118	134	108	71	120	95	101	86	91
114	164	109	66	65	75	89	120	133	116
131									

kiba09

210 581 493 434 276 156 222 221 207 145
241 365 223 212 149 181 111 215 287 327
429 234 374 398 160 100 288 290 289 221
165 328 216 288 176 133 139 149 133 97
115 75 97 166 195 134 149 84 101 113
62 93 111 96 71 91 94 83 88 75
108 100 116 62 84 100 100 123 96 102
121 101 128 95 115 81 94 78 140 114
95 132

kiba11
112 175 130 221 243 131 151 208 155 161
188 130 102 96 57 71 83 64 81 145
310 266 307 334 343 223 174 136 104 232
228 130 130 191 346 237 123 95 256 271
298 218 129 191 121 144 94 136 231 252
280 185 191 139 114 231 245 234 300 279
326 239 153 242 295 307 204 232 284 300
267 207 189 340 388 236 376 258 319 368
201 248 375 307 210 182 256 286 324 364
516 483 188 104 119 155 215 148 150 125
148 135 188 189 200 250 295 172 221 199
222

kiba12
134 77 142 93 119 135 103 168 165 224
125 138 120 102 97 95 114 165 237 105
130 137 154 275 192 157 203 110 128 128
183 204 247 166 266 221 99 74 79 84
75 109 105 88 91 70 69 88 109 101
116 123 135 116 134 145 76 91 77 124
115 70 114 104 97 81 96 115 120 131

kiba13
189 131 150 211 297 204 246 150 154 203
132 168 128 241 287 153 198 110 242 224
97 80 284 218 260 212 133 129 129 175
112 116 127 192 211 212 165 134 105 221
131 79 145 98 125 124 104 161 160 224
134 134 122 100 102

kiba14
515 421 401 326 293 383 328 288 249 320
257 273 311 306 216 305 246 287 344 259
192 266 270 178 198 224 234 216 217 183
202 243 161 174 162 166 162 169 214 146
140 129 111 130 148 132 95 124 151 108
84 104 102 100 137 153 107 133 136 144
213

kibw01
312 206 121 196 208 209 259 245 242 312
333 291 462 325 300 307 221 162 142 162

82 78 115 73 160 178 141 253 219 335
270 130 211 248 256 155 210 215 211 134
120 176

kibw02
268 296 192 327 221 154 197 153 141 138
255 423 265 321 287 221 207 172 157 93
182 179 97 211 91 201 173 90 63 173
126 198 137 95 109 78 101 66 81 110
100 92 66 77 196 185 343 262 183 228
180 266 213 92 163 165 167 117 189 167
165 129 124 118 163 196 99 155 151 160
210 164 153 251 114 180 153 203 204 141
137 188 183 104 91 98 133 137 119 135
136 153 130 90

kibw03a
237 115 155 183 186 151 233 201 234 198
170 207 270 264 131 219 277 281 357 335
245 338 286 386 339 333 463 219 266 403
408 249 231 197 270 272 381 298 311 366
281 202

kibw04
879 786 709 674 683 607 255 228 176 227
229 212 123 127 134 132 166 179 245 167
169 247 302 270 411 466 394 632 542 582
589 537 425 413 503 439 532 471 371 521
509 432 391 440 382 443 426 360 301 283
481 359 429 597 481 509 443 329 304 481
253 394 395

kibw05
287 233 231 247 190 220 319 217 293 229
181 238 242 197 172 139 209 170 187 196
141 169 181 145 212 209 145 218 168 172
181

kibw06
261 351 438 392 480 592 520 578 488 439
568 523 525 427 358 516 564 417 548 476
455 551 569 525 351 450 439 281 304 315
301 292 303 327

kibw07
99 119 255 225 156 271 189 233 256 145
223 246 213 142 210 167 162 137 114 156
179 209 101 115 135 146 181 188 175 250
163 191 162 199 209 133 130 182 176 81
63 61 89 93 117 120 109 123 88 66
87 88 78 77 76 71 68 70 72 39
118 67 176 126 96 107 110 153 142 142
114 164 192

kibw08

511	469	676	841	717	455	488	646	406	289
450	365	203	256	293	298	343	195	192	164
165	192	139	120	155	158	158	133	70	62
120	119	82	189	205	384	399	437	247	184
122	114	186	334	208	219	108	117	120	105
98	100	191	235	143	167	102	282	198	80
57	171	123	174	154	107	135	115	145	84
107	115	167	183	210	144	123	86	173	129
68	146	91	182	177	123	172	175	207	122
140	107	80	79	82	122	120	204	92	106
105	135	203	167	149	192	116	152	130	191
195	227	164	239	215	98	76	86	81	79
100	108	103	100	76	72	122	125	125	118
104	125	121	131	138	79	92	78	117	103
75	119	97	112	79	97	64	86	107	

kibw09

265	326	210	217	221	342	412	468	435	415
355	400	413	417	353	374	394	416	380	433
386	425	280	348	378	327	359	322	275	238
263	313	383	233	230	326	299	212	170	269
258									

kibw11

602	281	446	357	394	556	439	559	556	380
452	418	360	380	380	209	373	303	177	110
139	185	195	228	228	196	266	228	226	375
150	213	154	176	177	124	64	43	49	51

kibw12

374	137	220	260	371	281	343	352	290	230
243	198	235	314	208	248	226	324	374	249
306	378	292	246	231	288	418	356	314	304
298	112	61	75	176	167	135	145	128	137
201	176	185	187	231	236				

kibw14

634	557	592	400	395	341	362	364	306	259
397	423	230	224	225	352	264	268	220	214
251	176	149	185	226					

kibw15

206	174	132	143	143	184	93	86	61	120
101	90	96	91	163	149	110	85	139	129
185	124	94	138	114	96	90	80	130	98
86	53	77	83	63	191	229	198	208	213
267	159	114	182	231	249	155	218	210	226
187	199	250	293	239	147	232	212	206	338
312									

kibw16

161	190	294	244	185	138	117	128	227	159
124	139	104	180	153	94	59	156	181	216
182	133	196	148	216	119	172	276	245	251
180	159	209	346	432	381	302	361	242	385
280	161	255	300	241	181	198	219	130	109
77	126	193	147	143	181	162	275	255	292
262	231	201	203	241	219	292	203	106	160
176	105	93	87	154	155	163	190	150	175
180	110	226	147	155	143	126	143	148	162
169	114	115	118	191	179	142	129	112	174
109	164	129	127						

kibw17

270	307	400	429	242	446	466	366	409	309
411	506	497	384	315	322	279	366	234	320
366	264	293	300	326	260	217	477	470	388
200	205	392	503	312	666	281			

kibw18

364	402	452	270	153	145	177	250	186	232
193	313	327	184	142	377	346	345	215	148
190	126	159	117	148	233	244	237	173	180
218	143	325	309	235	253	286	262	253	143
198	266	321	281	305	308	271	279	301	279
260	306	215	294	279	361	378	417	411	390
406	404	408	458	649	561	441	574	569	439
398	334	584	481	480	474	340	421	325	259
380	373	351	329	383	289	348	233		

kibw19

210	281	269	323	216	288	274	274	255	205
272	258	265	180	244	201	240	316	255	258
258	214	235	243	219	244	104	78	149	195
149	139	135	117	152	140	176	262	197	196
139	110	147	104	140	165	142	197	147	130
116	143	107	110	138	97	174	167	183	146
193	129	139	225	186	200	216	190	250	210
147	103	144	114	114	106	105			

kibw20

288	333	396	312	256	312	232	248	288	344
377	127	127	245	285	162	133	123	134	239
232	355	370	393	430	406	360	378	333	306
317	302	286	399	307	242	351	208	330	281
157	315	286	325	238	260	191	215	192	196
186									

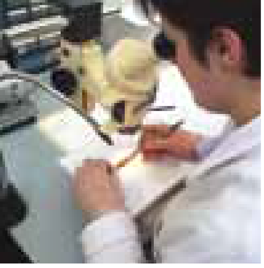
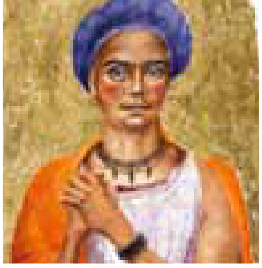
kibw21

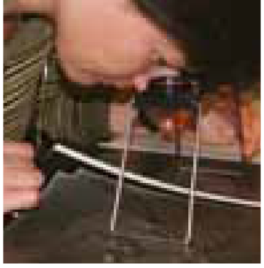
121	202	212	196	237	260	277	314	279	229
296	235	178	294	229	303	254	286	281	280
304	346	229	234	218	182	181	120	119	122
149	143	220	183	191	216	152	248	211	137
175	141	174	180	181	171	116	128	103	130

121	108	146	111	124	121	112	118	115	130
113	130	109	115	84	79	105	76	107	80
84	55	79	63	80	96	79	98	112	64
62	88	59	67	75	95	97	82	56	73
96	101	102	119	79	110	95	82	88	88
74	54	49	67	61	92	84	58	87	91
62	63	53	57	55	51	48	44	41	37

kibw22

361	447	533	677	637	578	520	526	613	486
533	489	389	643	465	445	361	452	426	384
570	619	456	536	446	586	505	455	487	572
646	330	484	494	454	429	361	529	527	527
570	565	563	579	549	577	509	362	335	449
422	533	588	425	654	563	455	438	673	737
635	659	749	742	474	443	498	600	491	589
617	713	515							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