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Great Gransden Windmill, Mill Road, Great Gransden, Cambridgeshire

Further Tree-ring Dating and Oxygen Isotope Dendrochronology of Oak Timbers

Martin Bridge, Cathy Tyers, Neil J Loader, Danny McCarroll, Darren Davies, and Giles H F Young

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Front Cover: Aerial view of Great Gransden June 2018 (c) Martin Bridge.

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SUMMARY

Samples were taken from 18 timbers forming various elements of the mill, including two *ex situ* timbers, a brake handle, and an offcut found during ongoing repairs. Documentary evidence suggests that the mill was present in AD 1612, but the main post dated, by ring-width dendrochronology, to the mid-seventeenth century, and is likely to have been put in place at the same time as the crown-tree, which had a felling date of winter AD 1644/5I derived by isotope dendrochronology. The *ex situ* brake handle was dated isotopically to a felling date range of AD 1757–90I, and a sheer had a likely felling date range of AD 1771–1804 provided by ring-width dendrochronology, suggesting they may be contemporaneous. Three timbers from the buck were from trees felled in the first third of the nineteenth century, and the windshaft was from a tree likely felled in the mid-nineteenth century. An offcut dated using ring-width dendrochronology proved to be part of the modern repair programme with a felling date of after AD 1974.

CONTRIBUTORS

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ARCHIVE LOCATION

Historic England Archive
The Engine House
Fire Fly Drive
Swindon SN2 2EH

HISTORIC ENVIRONMENT RECORD LOCATION

Cambridgeshire Historic Environment Record
Cambridgeshire County Council
Historic Environment Team
Sackville House
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CONTENTS

INTRODUCTION

This report updates a previous programme of ring-width dendrochronology carried out on the site, which is reported in Bridge (2015). This post and open-trestle windmill is a Scheduled Ancient Monument (List Entry Number 1006820) and Grade II* Listed Post Mill (List Entry Number 1211279), situated on the east side of the settlements of Great and Little Gransden in the District of Huntingdon in Cambridgeshire (Fig 1). The list description suggests that this may be the oldest such mill in England with a documentary reference suggesting construction in *c* AD 1612. As has been pointed out elsewhere (Bridge 2006), however, the concept of age in windmills is problematic because of the degree of rebuilding and repair associated with such structures, especially the re-use of the large main posts which are generally exceptional timbers.

In the first study, 13 samples were taken from this mill, including one *ex situ* timber of uncertain origin lying on the upper floor. Six of the nine samples considered suitable for analysis were successfully dated, although these results have been slightly amended here by using a local sapwood estimate of 12–45 rings (Miles 1997), rather than the estimate of 9–41 rings used in the previous study. Three dated timbers from the buck appeared to be coeval and had a likely felling date range of AD 1803–36. The dated right sheer appeared to be a little older, with a likely felling date range of AD 1771–1804, whilst the windshaft is slightly later, with a likely felling date range of AD 1848–81. The final dated timber was the main post, which was clearly substantially earlier. Its outermost ring potentially marked the heartwood/sapwood boundary, giving a possible felling date range of AD 1631–64.

In late 2016, at the request of Trudi Hughes, Historic England Heritage at Risk Architect, previously inaccessible exposed timbers, which it was thought might be primary were assessed and further sampling was carried out. This report presents both the initial work and subsequent sampling and analysis.

RING-WIDTH DENDROCHRONOLOGY

Methodology

Those timbers judged to be potentially useful were cored using a 16mm auger attached to an electric drill. The cores were labelled, and stored for subsequent analysis.

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, supported by visual checks. The ring-width series were compared for statistical cross-matching, using a variant of the Belfast CROS program (Baillie and Pilcher 1973). Ring sequences 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 in the range 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.

Ascribing felling dates and date ranges

Once a tree-ring sequence has been firmly dated in time, a felling date, or 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 earlywood 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 with a given confidence limit. If no sapwood or heartwood/sapwood boundary survives then the minimum number of sapwood rings from the appropriate sapwood estimate is added to the last measured ring to give a *terminus post quem* (*tpq*) or felled-after date.

A review of the geographical distribution of dated sapwood data from historic timbers has shown that a sapwood estimate relevant to the region of origin should be used in interpretation, which in this area is 12–45 rings (Miles 1997). It must be emphasised that dendrochronology can only date when a tree has been felled, not when the timber was used to construct the structure or object under study.

Results and Interpretation

Details of the samples taken from the 18 oak (Quercus sp.) timbers assessed as the most promising for ring-width dendrochronology are given in Table 1. The locations of the samples are illustrated, where possible, in Figures 2 and 3. Sample 10 is from the right-hand side girt, not illustrated in these figures, but it is the equivalent timber to the left-hand side girt (ggm16) shown in Figure 2. Two samples, ggm15 and ggm17, were from *ex situ* timbers and so are not located on the figures. The exposed end of the left stone bearer (ggm18) is illustrated in Figure 4. Three timbers yielded cores with ring sequences too short to justify further analysis.

The measured ring-width sequences were compared. Those from the three cores from the crown-tree cross-matched (Table 2a; Fig 5), and were combined to form the 90-ring series, ggm04. The two cores from the right side girt cross-matched as shown in (Table 2b; Fig 6), and were combined to from the 53-ring series, ggm10. The two cores from the break handle also cross-matched (Table 2c; Fig 7), and were combined to from the 48-ring series, ggm17.

The ring-sequences from each timber were then compared and cross-matching was found between five of these (Table 2d), and confirmed by comparison of each individual ring-width sequence to the database of reference chronologies. The level of cross-matching was so good between three samples (ggm06, ggm11, and ggm13) that the timbers represented are thought to potentailly have been derived from the same parent tree, despite the variation in the dates of their heartwood/sapwood boundaries. These three ring-width series were therefore combined prior to being incorporated with the other two matching series into a single site chronology, GRANSDEN, which dates to the period AD 1706–1836. The dating evidence is shown in Table 3a.

The three dated timbers (ggm06, ggm11, and ggm13) from the frame of the buck, all thought to be potentially derived from the same parent tree, have a mean heartwood/sapwood boundary date of AD 1791. This results in a likely felling date range for these timbers of AD 1803–36.

The ring sequence of the right sheer (ggm02) dates to the period AD 1708–63 and includes four sapwood rings, making the likely felling date range for this timber AD 1771–1804. The right sheer may be a re-used timber, but it is difficult to draw any firm conclusions on the basis of a single dated timber. However, the slightly earlier felling date suggests there may have been an earlier superstructure than the current buck, the only dated parts of which are early nineteenth century.

The ring sequence from the windshaft (ggm09) dates to the period AD 1731–1836 with the outermost ring marking the heartwood/sapwood boundary. The likely felling date range of AD 1848–81 makes it younger than the other dated timbers. This is not surprising, as this element of the mill has to take a lot of strain and is often replaced. The dating of the windshaft therefore suggests another phase of repair within the extant structure.

The main post (ggm01) yielded a sequence of 124 years which was thought to potentially end at the heartwood/sapwood boundary. This boundary was evident on the timber itself, but not positively identified on the core. Series ggm01 was dated individually to AD 1496–1619 (Table 3b). If the outermost ring is taken as the heartwood/sapwood boundary, this gives a likely felling date range of AD 1631–64.

One further sample, ggm15, was an offcut with 80 rings of uncertain origin within the mill. This was securely dated by ring-width dendrochronology to the period AD 1883–1962 (Table 3c), giving a likely felling date of after AD 1974, and it was therefore assumed to be part of the current repair programme.

The crown tree, an important element of the mill which failed to date in the first investigation, was re-sampled and additional 83-year sequence retaining complete sapwood was obtained, along with a shorter sequence. The 90-year mean sequence for this timber, ggm04, failed to securely date using conventional ring-width dendrochronology, and a sample was submitted for oxygen isotope analysis (see below). Table 3d does, however, show the ring-width matches for the combined ring-width series ggm04 at the position corresponding to the date produced by isotopic analysis. This cross-matching is compatible with the isotopic analysis, but not on its own enough for independent dating by ring-width dendrochronology.

The new samples taken in 2016 included a second core from the right side girt (ggm10b) which had failed to date initially. The resulting 53-year combined sequence (ggm10) also failed to date. Similarly, ggm14, a horizontal brace between angled side braces on the left side of the buck, yielded a sequence of 93 rings, but this failed to give satisfactory matches against the database, and remains undated. Two other timbers, ggm16 and ggm18 (Table 1; Figs 2 and 4) also failed to date from the new sampling programme, joining ggm05 and ggm08 as undated timbers with measured ring-width sequences from the mill.

Two samples from the brake handle (ggm17a and ggm17b) yielded relatively short sequences (48 and 41 rings respectively; Table 2c; Fig 7), the longest of which was submitted for oxygen isotope analysis (see below). The relatively short, combined ring-width sequence, ggm17, gave statistically significant matches at two potential positions ending in the sixteenth century, as well as at AD 1745, as indicated by the isotopic analysis (Table 3e) and thus was not dated securely by ring-width dendrochronology.

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

OXYGEN ISOTOPE DENDROCHRONOLOGY

The two samples from Great Gransden Mill selected for oxygen isotope analysis were ggm04c, from the crown post, and ggm17a, a sample from the *ex situ* brake handle. Both samples were oak (Quercus sp.). Timber ggm04 comprised 90 measured ring-widths with complete sapwood and bark edge and timber ggm17 had 48 measured ring-widths stopping at a break in the core positioned near the heartwood/sapwood boundary with 11 sapwood rings not measured (Table 1).

Oxygen isotope ratios were obtained from a total of 76 and 46 rings from samples ggm04c and ggm17a respectively (Table 4; Appendix 2). For sample ggm04c stable isotope measurements covered the rings 10–85. Sample ggm17a had four additional latewood increments visible at the start of the core (pith end), which were not measured in the initial ring-width measurements as they were atypically wide. These rings were also excised and prepared for isotopic analysis. The resulting isotope series for sample ggm17a covered rings –3 to 42. Where rings exhibited no latewood, or where the sample was degraded or showed signs of possible contamination, isotopic analyses were not attempted.

Methodology

Oxygen isotope dendrochronology relies upon the same fundamental principles, limitations, and assumptions as conventional (ring-width-based) dendrochronology. However, rather than using ring-width measurements it uses the ratio of heavy to light oxygen isotopes (McCarroll and Loader 2004) in the latewood cellulose (δ18O). The isotopes can have a higher signal to noise ratio than ring-width measurements and strong signals do not require the trees to be growing under any environmental stress (Young *et al* 2015).

The method relies on a regional master chronology (Loader *et al* 2019) constructed using dendrochronologically-dated oak timbers sourced from across a c 45,200km2 (20,000 mile2) region centred on Oxfordshire, in south-central England. The chronology was developed as part of a Leverhulme Trust funded project (RPG-2014-327) and currently covers a period from AD 1200–2000 with annual replication (sample depth) of 10 trees throughout the chronology period. A thin slice (4mm) is removed from the base of the sample cores selected for isotopic analysis to retain the original measured surface and ensure its preservation for future dendrochronology and archiving.

Several physiological studies of oak trees have shown that the earlywood is partially formed from carbohydrates fixed in previous years (Richardson *et al* 2013; McCarroll *et al* 2017). To avoid this chemical carry-over effect in oak, only the latewood of each tree-ring is prepared for chemical analysis and dating. Each latewood ring is carefully removed as thin slivers (approximately 40μm thick) using a scalpel and dissecting microscope.

Wood samples are converted to α-cellulose using an acidified sodium chlorite solution with removal of hemicelluloses by sodium hydroxide (Loader *et al* 1997). Samples are homogenised using an ultrasonic probe and vacuum-dried at –50˚C for 48 hours. 0.30–0.35mg of dry α-cellulose are weighed into individual silver foil capsules for pyrolysis to carbon monoxide (CO) at 1400°C (Woodley *et al* 2012). The resulting carbon monoxide is analysed using a Delta V isotope-ratio mass spectrometer. Data are expressed as per mille (‰) deviations relative to the Vienna Standard Mean Ocean Water (VSMOW) international standard. Analytical precision is typically 0.30‰ (σn-1, n=10) (Loader *et al* 2015). The master chronology was prepared as two independent pools of five trees to ensure quality control and the resulting data combined to form the ten-tree master chronology. Individual samples for dating are prepared and analysed separately, using identical preparation protocols. The resulting stable isotopic data are presented as chronologies (time series).

Tree-ring oxygen isotope data have statistical properties that are quite different from ring-widths, requiring different pre-treatment. The Baillie-Pilcher filter that works well for ring width dating (Baillie and Pilcher 1973) is not appropriate for isotope data and would result in unrealistically high *t*-values (Loader *et al* 2019). The isotope data are filtered using a simple nine-year rectangular filter, with indices derived by subtraction. Degrees of freedom are corrected for autocorrelation and filtering resulting in *t*-values that conform to a Student's *t*-distribution and can be used to calculate one-tail probabilities of error. The probabilities are corrected for multiple testing by division by the number of possible matches against the master chronology (a 'Bonferroni' correction) (Dunn 1959; 1961). The ratio of probabilities for the first and second highest *t*-values provides an 'isolation factor'. Potential dates are only considered for acceptance when the corrected probability of error is less than one in a hundred and the probability for the best match is more than an order of magnitude less likely to be in error than the next best match. All *t*-values pertaining to isotope data in this report are Student's *t*-values.

Cross-matching between isotope samples is achieved using the same approach, with the number of possible matches determined by setting a minimum size of overlap. Student's *t*-values, corrected one-tail probabilities and the isolation factor are reported as well as the highest correlation coefficient, offset in ring number, and size of overlap.

In isotope dendrochronology it is not always necessary or possible to measure isotopically each tree-ring, in which case the last ring measured isotopically must be placed within the context of the entire sample. This may require addition of years identifiable in the sample, but not measured isotopically. Once a date for the last ring has been calculated, a felling date or sapwood estimate may be assigned using identical methods to those in ring-width dendrochronology (see above).

Results

The oxygen isotope series from ggm04c comprises isotopic measurements from 76 rings (ring 10 to ring 85 of the mean timber series, ggm04). The series from ggm17a comprises isotopic measurements from 46 rings (ring –3 to ring 42 of the mean timber series, ggm17).

Table 5 shows the cross-dating statistics for the individual isotopic series from each of the two sampled timbers from Great Gransden Mill. Individually, both timbers ggm04c and ggm17a produce dates that independently pass the thresholds for consideration as dated suggested by Loader *et al* (2019) and both cross-date securely against the isotopic reference chronology (Table 5; Figs 8 and 9). Sample ggm04c returns a date of AD 1639I for ring 85 which relates to a date of AD 1644I for the last ring-width measurement (ring 90). As complete sapwood is present a felling date of winter AD 1644/45I can be assigned to this timber. Sample ggm17a returns a date of AD 1739I for ring 42 which relates to a date of AD 1745I for the last measured ring-width (ring 48). As there are 11 rings not measured, an estimated felling date range of AD 1757–1790I can be assigned using the same sapwood estimate as above of 12–45 rings (Miles 1997).

DISCUSSION

There appear to be four possible phases of construction represented within the eight dated historic samples (Tables 1, 3a–b, 3d–e, and 5; Fig 10).

The felling date for the main post (ggm01, ?AD1631–64) provided by ring-width dendrochronology is later than the date of c AD 1612 suggested in the list description, which was derived from a documentary source. The main post is an exceptionally large timber, and such timbers were probably relatively rare. They were therefore potentially a valuable commodity re-used several times, as seen elsewhere at Pitstone Mill (Miles *et al* 2004), Nutley Mill (Bridge 2006), and Drinkstone Mill (Bridge 2001a). These three examples are all older than the post at Great Gransden, and indeed they have older buck timbers, suggesting that in fact this mill is not the oldest of its type in the country. The date appears to be confirmed, and indeed be refined, by the felling date of the cross tree (ggm04, winter AD 1644/5I), derived by oxygen isotope dendrochronology, as it is likely that the two major timbers were put in place at the same time.

The buck timbers are from timbers felled in the first third of the nineteenth century, with the right sheer and brake handle probably derived from trees felled slightly earlier. The windshaft dates to the mid-nineteenth century. If sample ggm06 is indeed from the same tree as ggm11 and 13, it would have had fewer sapwood rings than the others, although sapwood numbers can vary within the same tree. An off-cut was found to be part of the modern repair timbers.

Most of the historic timbers appear to be relatively local in origin, as shown by the matches obtained and detailed in Tables 3a, 3b, and 3e. However, the ring-width cross-matching for the cross tree (Table 3d), dated by oxygen isotope dendrochronology, suggests that it may have come from an area to the west of the site. The recent sample, ggm15 (Table 3c) was bought from Suffolk.

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TABLES

Table 1: Details of the samples taken from Great Gransden Windmill and dates produced by ring-width and oxygen isotope dendrochronology

Sample No	Location	No of rings	Date of sequence (AD)	Sapwood	Mean ring width (mm)	Mean sensitivity	Felling date range (AD)
ggm01	Main post	124	1496–1619	?h/s	2.38	0.31	?1631–64
ggm02	Right sheer	56	1708–63	4	2.94	0.19	1771–1804
ggm03	Left sheer	<30	-	-	NM	-	-
ggm04a	Crown tree	90	-	29C	1.97	0.20	-
ggm04b	*ditto*	36	-	1	2.13	0.26	-
ggm04c	*ditto*	83	-	16	2.14	0.23	-
ggm04	Mean of 04a, 04b, and 04c	90	1555–1644$_{I}$	29C	2.14	0.19	winter AD 1644/5$_{I}$
ggm05	Front sheer spacer	53	-	8 (+1NM)	3.40	0.25	-
ggm06	Stud, right upper front	63	1740–1802	h/s	2.33	0.33	1803–36
ggm07	Stud, right front lower section, inner	38	-	-	1.57	0.24	-
ggm08	Stud, right front lower section, outer	<30	-	-	NM	-	-
ggm09	Windshaft	106	1731–1836	h/s	1.95	0.19	1848–81
ggm10a	Right side girt	44	-	h/s	2.23	0.24	-
ggm10b	*ditto*	52	-	h/s	3.14	0.21	-
ggm10	Mean of 10a and 10b	53	-	h/s	2.71	0.21	-
ggm11	Rear right post, upper floor	85	1706–90	h/s	1.70	0.32	1803–36
ggm12	*Ex situ* timber of unknown origin	<30	-	-	NM	-	-
ggm13	Rear left post	69	1716–84	2	2.04	0.32	1803–36
ggm14	Horizontal brace between angled side braces, left side of buck	93	-	?h/s	1.65	0.21	-
ggm15	*Ex situ* offcut	80	1883–1962	-	1.97	0.26	after 1974
ggm16	Left side girt (possible re-used timber)	48	-	-	4.65	0.20	-
ggm17a	Brake handle (*ex situ*)	48	-	h/s	1.74	0.27	-
ggm17b	*ditto*	41	-	h/s (+11NM)	1.97	0.28	-
ggm17	Mean of 17a and 17b	48	1698–1745$_{I}$	h/s (+11NM)	1.87	0.27	1757–90$_{I}$
ggm18	Left stone bearer	61	-	5	2.74	0.22	-

Key: h/s = heartwood/sapwood boundary; NM = not measured; ¼C = complete sapwood, felled the following spring; C = complete sapwood, felled the following winter; I = date derived from oxygen isotope dendrochronology

Table 2a: Cross-matching between the three cores from ggm04, the crown tree

					t-values
Sample			ggm04a	ggm04b	ggm04c
	Relative start year	Relative end year			
ggm04a	1	90	-	3.9	2.6
ggm04b	50	85			9.2
ggm04c	5	87			-

Table 2b: Cross-matching between the two cores from ggm10, the right side girt

				t-values
Sample			ggm10a	ggm10b
	Relative start year	Relative end year		
ggm10a	10	53	-	4.9
ggm10b	1	52		-

Table 2c: Cross-matching between the two cores from ggm17, the brake handle

				t-values
Sample			ggm17a	ggm17b
	Relative start year	Relative end year		
ggm17a	1	48	-	17.3
ggm17b	8	48		-

Table 2d:Cross-matching between dated elements from the site master chronology GRANSDEN. t*-values in excess of 3.5 are significant*

Sample	ggm06	ggm09	ggm11	ggm13
ggm02	1.9	3.1	6.0	3.9
ggm06		4.3	10.4	14.4
ggm09			4.6	3.6
ggm11				17.9

Table 3a: Dating evidence for the ring-width site master chronology, GRANSDEN, AD 1706–1836

Source region:	Chronology name:	Publication reference:	File name:	Span of chronology (AD)	Overlap (years)	*t*-value
Regional Reference Chronologies						
England	South Central England	Wilson *et al* 2012	SCENG	663–2009	131	12.5
Hampshire	Hampshire Master Chronology	Miles 2003	HANTS02	443–1972	131	9.1
Southern England	Southern England Master	Bridge 1998	SENG98	944–1790	85	8.5
East Anglia	East Anglia Master Chronology	Bridge 2003	ANGLIA03	944–1789	84	7.7
Individual Site Chronologies						
Bedfordshire	Chicksands Priory	Howard *et al* 1998	CHKSPQ02	1611–1814	109	10.3
Leicestershire	Church Farm, Bringhurst	Groves *et al* 2004	BRNGHST1	1664–1781	76	10.2
Buckinghamshire	The Hovel, Ludgershall	Miles and Worthington 1999	THEHOVEL	1671–1811	106	9.5
Oxfordshire	Oriel College Tennis Court	Miles and Haddon-Reece 1994	ORIEL1	1534–1776	71	9.0
Cambridgeshire	Houghton Mill	Loader 1999 unpubl	HGHTNMLL	1683–1764	59	8.8
Hampshire	H.M.S. Victory	Barefoot 1978	VICTORY	1640–1800	95	8.7
Cambridgeshire	Ely Cathedral	Arnold *et al* 2005a	ELYCSQ05	1592–1794	89	8.7
Essex	Tilbury Fort	Groves 1993	TILBURY	1678–1777	72	8.5
Oxfordshire	Kiln Farm House, Upper Basildon	Miles and Bridge 2011	KILNFMHS	1692–1798	93	8.3
Northamptonshire	158 Watling Street East, Towcester	Bridge and Tyers 2022	TOWSt6	1702–1805	100	8.3

Table 3b: Dating evidence for ring-width series, ggm01, AD 1496–1619

Source region:	Chronology name:	Publication reference:	File name:	Span of chronology (AD)	Overlap (years)	*t*-value
Regional Reference Chronologies						
England	South Central England	Wilson *et al* 2012	SCENG	663–2009	124	6.4
Hampshire	Hampshire Master Chronology	Miles 2003	HANTS02	443–1972	124	5.8
East Anglia	East Anglia Master Chronology	Bridge 2003	ANGLIA03	944–1789	124	5.8
East Midlands	East Midlands Master	Laxton and Litton 1988	EASTMID	882–1981	124	5.2
Individual Site Chronologies						
London	White Tower, Tower of London	Miles 2007	WHTOWR7	1463–1616	121	6.7
Bedfordshire	Woburn Abbey, primary phase	Miles 2021 unpubl	WOBURN1	1515–1625	105	6.2
Leicestershire	Church Farm, Bringhurst	Groves *et al* 2004	BRNGHST2	1520–1572	53	6.1
Northants	Apethorpe Hall, Apethorpe	Arnold *et al* 2008	APTASQ01	1292–1639	124	6.1
Suffolk	St Mary's Church bellframe, Cratfield	Bridge 2008	CRATFLD1	1503–1639	117	6.0
Leicestershire	St Nicholas, Bringhurst	Arnold *et al* 2005b	LBFFSQ01	1502–1687	118	5.9
Rutland	Oakham Castle	Arnold and Howard 2013	OKMCSQ02	1383–1620	124	5.7
Buckinghamshire	34-35 Crown Court, West Wycombe	Miles and Bridge 2013	WWB	1550–1647	70	5.6
Oxfordshire	Wadham College	Miles *et al* 2010	WADHAM	1426–1610	115	5.6
Hampshire	Blaegrove Cottage, Up Nately	Bridge *et al* 2011	BLAEGROV	1347–1610	115	5.6

Table 3c: Dating evidence for the ring-width series, ggm15, AD 1883–1962

Source region:	Chronology name:	Publication reference:	File name:	Span of chronology (AD)	Overlap (years)	*t*-value
Regional Reference Chronologies						
S Central England	South Central England	Wilson *et al* 2012	SCENG	663–2009	80	7.3
Oxfordshire	Oxfordshire Master Chronology	Haddon-Reece *et al* 1993	OXON93	632–1987	80	5.1
Individual Site Chronologies						
Cambridgeshire	Buff Wood	Rackham pers comm	BUFFWOOD	1886–1985	77	6.8
Cambridgeshire	Hayley Wood	Bridge 1983	HAYLEY	1777–1981	80	6.8
Cornwall	SWPeninsula4	Barsoum *et al* 2015	SWPEN4	1780–2010	80	6.3
Norfolk	Hethersett	Cooper *et al* 2012	HETHRSTT	1828–2008	80	6.2
Greater London	Old Park Wood, Hillingdon	Bridge and Winchester 2000	OLDPARK	1786–1994	80	6.1
Lincolnshire	Tattershall Castle	Arnold *et al* 2018	TATCSQ01	1759–1981	80	6.1
Suffolk	Sotterley Park	Briffa *et al* 1986	SOTTERLY	1586–1981	80	5.9
Oxfordshire	Oxford Living Trees	Pilcher and Baillie 1980	OXFORD	1787–1978	80	5.7
Ceredigion	Allt Lanlas, Llanerchaeron	Bale 2005	LANLAS	1779–2001	80	5.5
London	Epping Forest	Wilson pers comm	EPPING	1812–2011	80	5.1

Table 3d: Tentative dating evidence for the ring-width series, ggm04, AD 1555–1644

Source region:	Chronology name:	Publication reference:	File name:	Span of chronology (AD)	Overlap (years)	*t*-value
Individual Site Chronologies						
Gloucestershire	100 Church St, Tewkesbury	Nayling 2000	TEWKES2	1484–1664	90	5.5
London	Breakspear House, Harefield	Arnold and Howard 2010	HFDBSQ01	1574–1694	71	5.2
Hampshire	Hensting Farm Barn	Miles *et al* 2009	HENSTING	1514–1651	90	5.2
Somerset	8 Market Place, Shepton Mallet	Miles 2002	SHPTNMLT	1518–1677	90	4.6
Wiltshire	Salisbury Cathedral	Miles 2005	SARUM12	1556–1703	89	4.6

Table 3e: Tentative dating evidence for the ring-width series, ggm17, AD 1698–1745

Source region:	Chronology name:	Publication reference:	File name:	Span of chronology (AD)	Overlap (years)	*t*-value
Individual Site Chronologies						
Northants	Apethorpe Hall, Apethorpe	Arnold *et al* 2008	APTASQ02	1574–1749	43	5.6
Kent	Longport Farmhouse	Tyers 1996	LPH2T7	1617–1760	48	5.1
Hertfordshire	Clothall Bury Farmhouse, Wallingford	Arnold *et al* 2003	CLBBSQ01	1636–1753	48	4.8
Leicestershire	Kibworth Harcourt mill	Arnold *et al* 2004	KIBASQ01	1582–1773	48	4.5
Essex	St Mary's Church, Saffron Walden	Bridge 2001b	SAFFRON2	1701–1789	45	4.3
London	Dovecote, Breakspear House	Arnold and Howard 2011	HFDCSQ01	1695–1769	48	4.3
Northamptonshire	12 Park Street, Towcester	Bridge and Tyers 2020	PARK12t7	1635–1747	48	4.2

Table 4: Sample description: timber type and position, material analysed, number of complete tree rings (N), number (N_i) and range of rings for which $\delta^{18}O$ measurements were undertaken, and laboratory code. The presence of a zero/negative ring number indicates rings identified and measured isotopically but not included in the ring-width analyses

Sample	Timber and Position	Species	N	N_i	$\delta^{18}O$ (Measured rings)	Code
ggm04c	Crown post (29C)	Latewood α-cellulose *Quercus* spp	90	76	10–85	SWAN-72a
ggm17a	Brake handle (*ex situ*) h/s (+11NM)	Latewood α-cellulose *Quercus* spp	52	46	–3–42	SWAN-72b

Key: h/s=heartwood/sapwood boundary; (3) = number of sapwood rings preserved; C = sapwood complete (bark edge); NM rings not measured.

Table 5: Stable oxygen isotope dating of the composite and individual samples from Great Gransden Mill Hall against the south-central England master chronology (Loader et al *2019) over the period AD 1200–AD 2000. Number of whole rings present in core sample (N), number of rings on which $\delta^{18}O$ measurements were undertaken (N_i), Pearson's correlation coefficient (r), degrees of freedom (adjusted for autocorrelation and multiple sampling), Student's* t*-value, probability (1/p), isolation factor (IF), and date.*

Sample	Description	N	N_i	R	df	*T*	1/p	IF	Date
ggm04c	Crown post	90	76	0.737	65	8.79	>1Million	>1000	1639
ggm17a	Brake Handle (*ex*-situ)	52	46	0.787	38	7.86	>1Million	>1000	1739

FIGURES

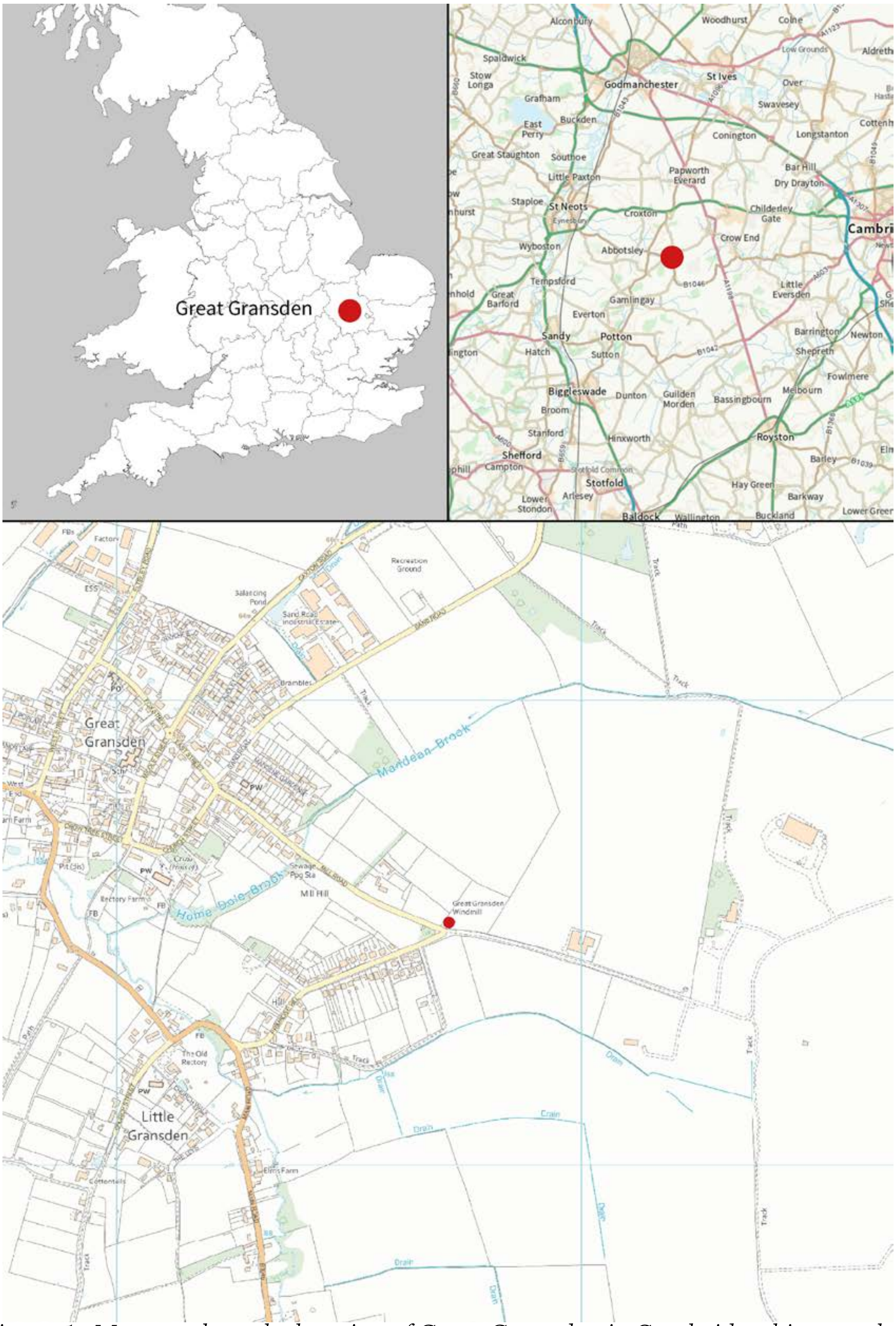

Figure 1: Maps to show the location of Great Gransden in Cambridgeshire, marked in red. © Crown Copyright and database right 2024. All rights reserved. Ordnance Survey Licence number 100024900

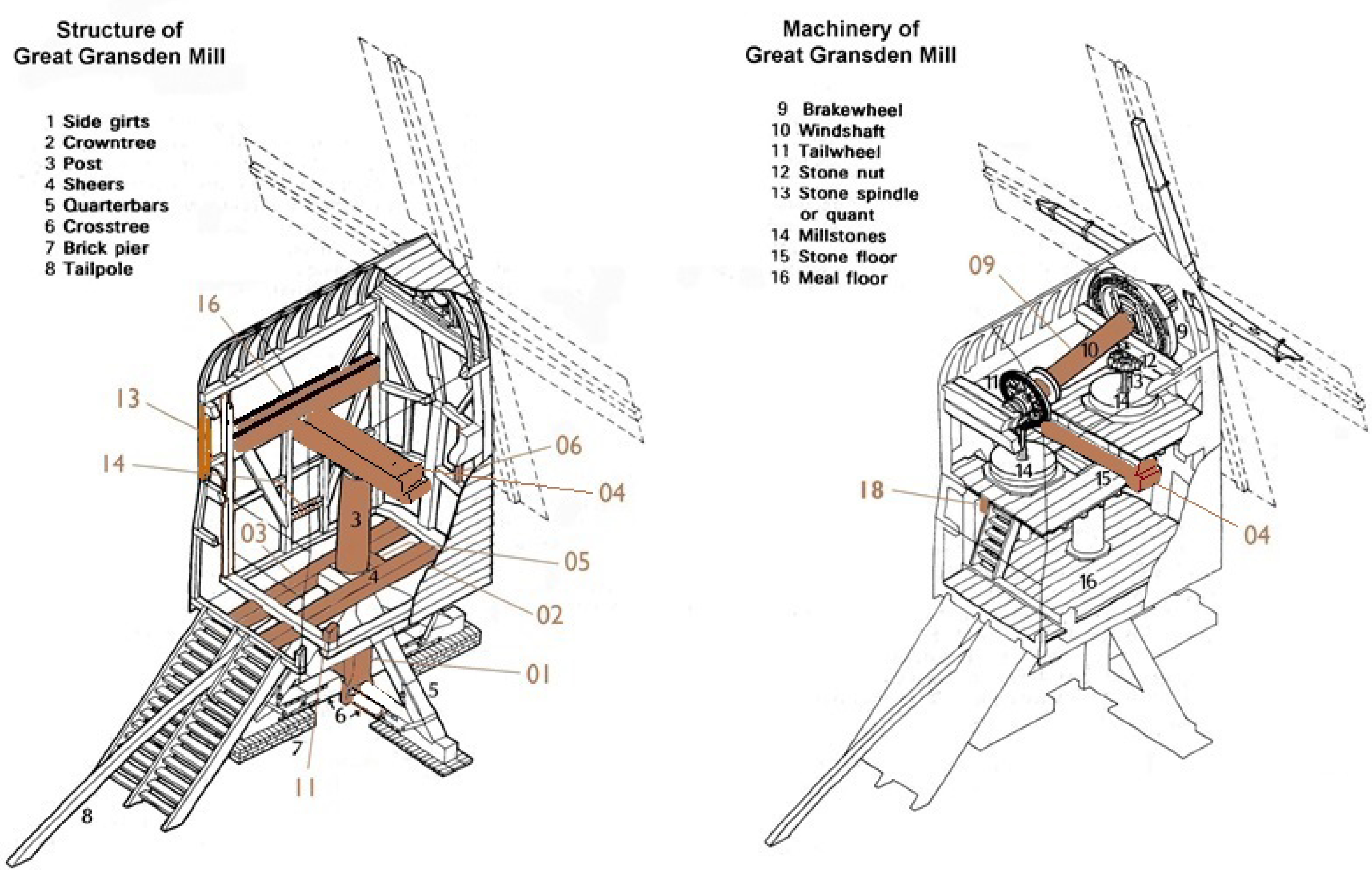

Figure 2: Timbers sampled from the mill (labelled in brown), located on isometric drawings by Graham Black

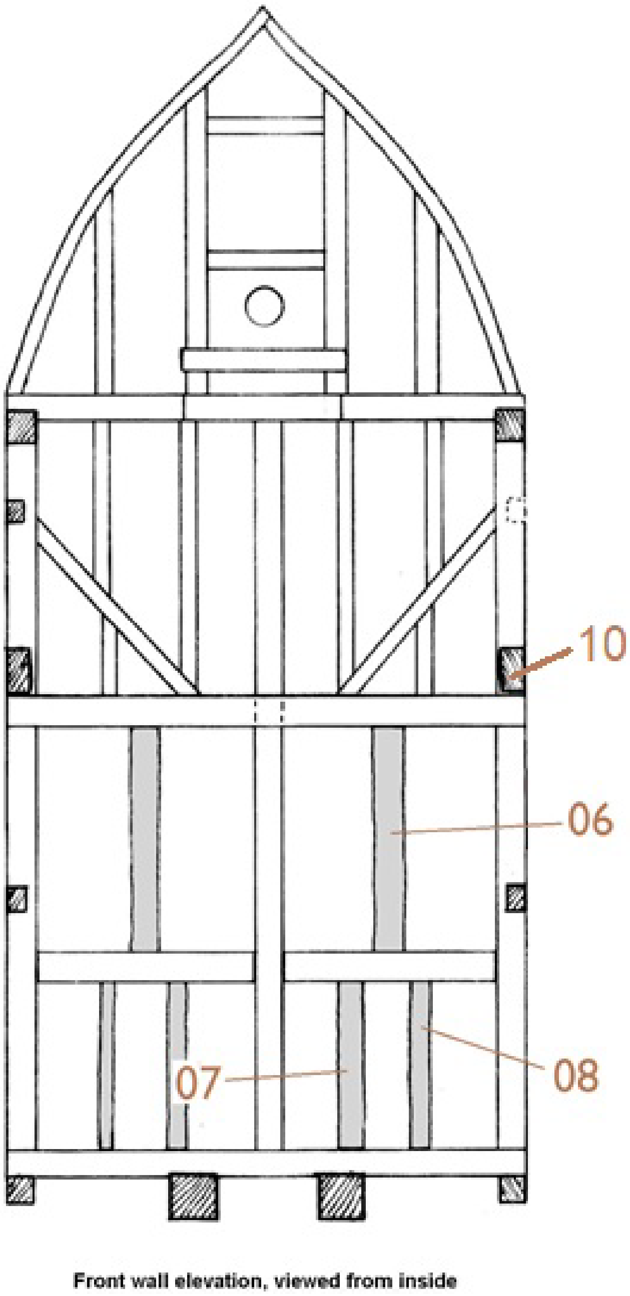

Figure 3: Timbers ggm06-08, and ggm10 (labelled in brown) located on a drawing of the front elevation by Luke Bonwick

Figure 4: Exposed end of the left stone bearer (ggm18), sampled further along inside the buck (photograph by Martin Bridge)

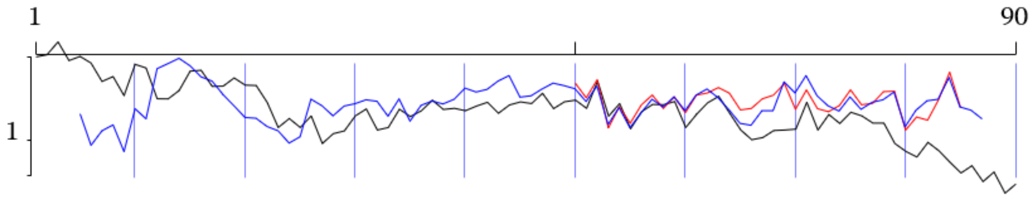

Figure 5: Plots of the three samples taken from ggm04 (04a – black, 04b – red, 04c – blue) showing their similarity in growth and relative positions of overlap (see Table 2a). The y-axis is ring width in mm on a logarithmic scale, the x-axis is relative years

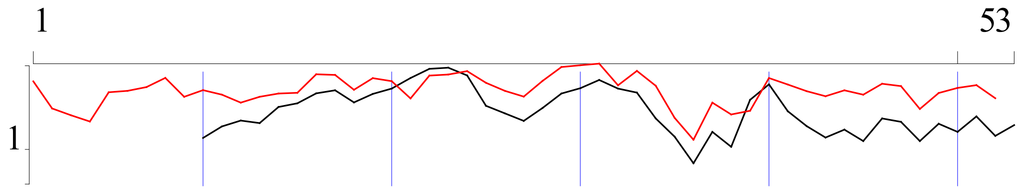

Figure 6: Plots of the two samples taken from ggm10 (10a – black, 10b – red) showing their similarity in growth and relative positions of overlap (see Table 2b). The y-axis is ring width in mm on a logarithmic scale, the x-axis is relative years

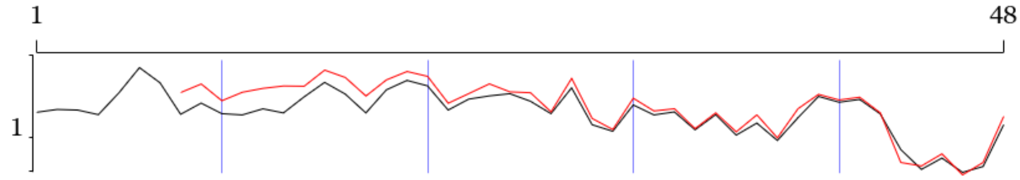

Figure 7: Plots of the two samples taken from ggm17 (17a – black, 17b – red) showing their similarity in growth and relative positions of overlap (see Table 2c). The y-axis is ring width in mm on a logarithmic scale, the x-axis is relative year

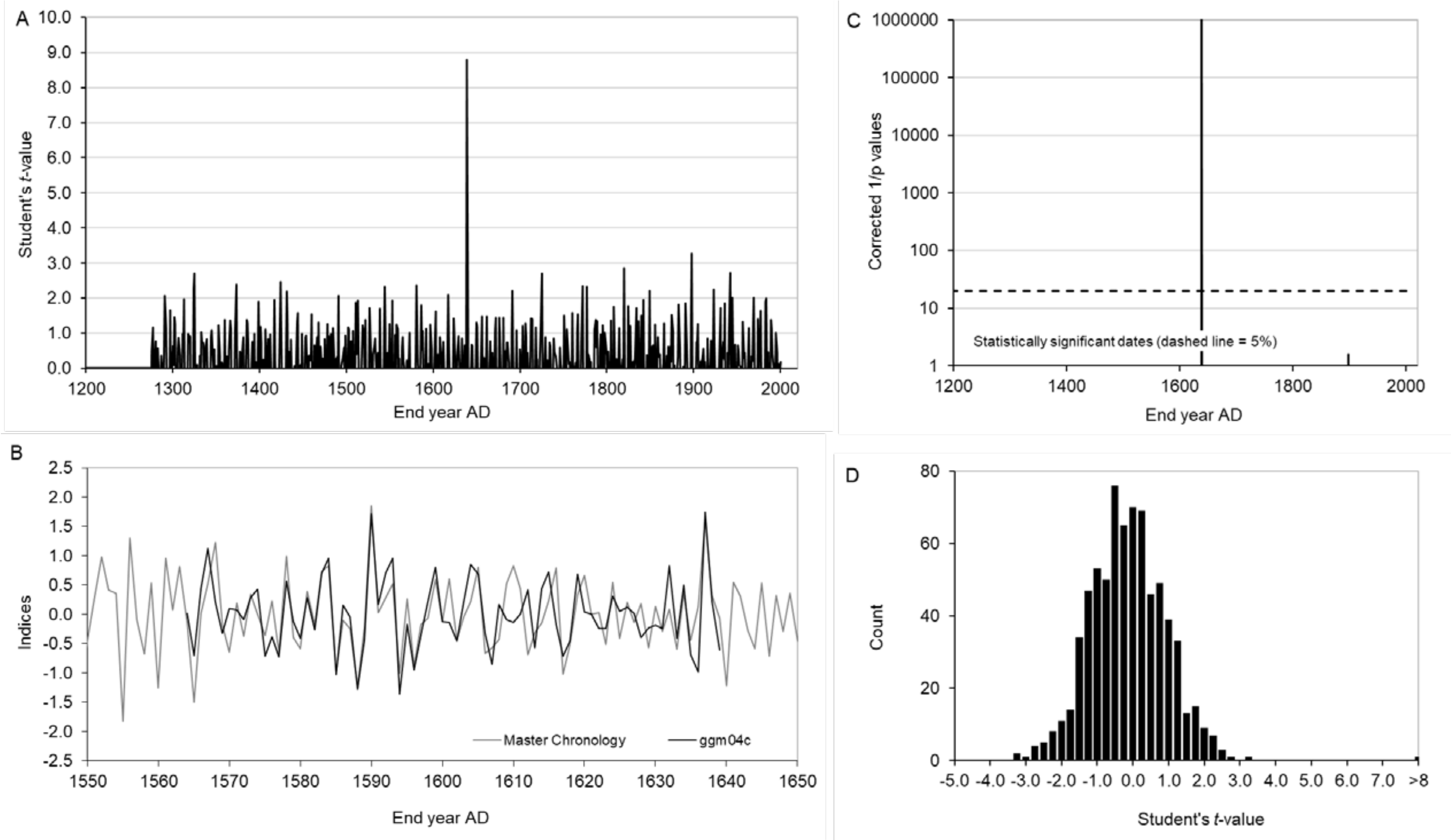

Figure 8: Dating results for the 76-year isotope chronology (ggm04c A: Student's t-values for all possible end dates with full overlap against the master chronology. B: Time series of the site isotopic mean plotted against the master chronology. C: End dates with corrected probabilities (1/p) of more than one. Those below the dashed line (1/p = 20) are not statistically significant. D: Distribution of Student's t-values for all possible matches

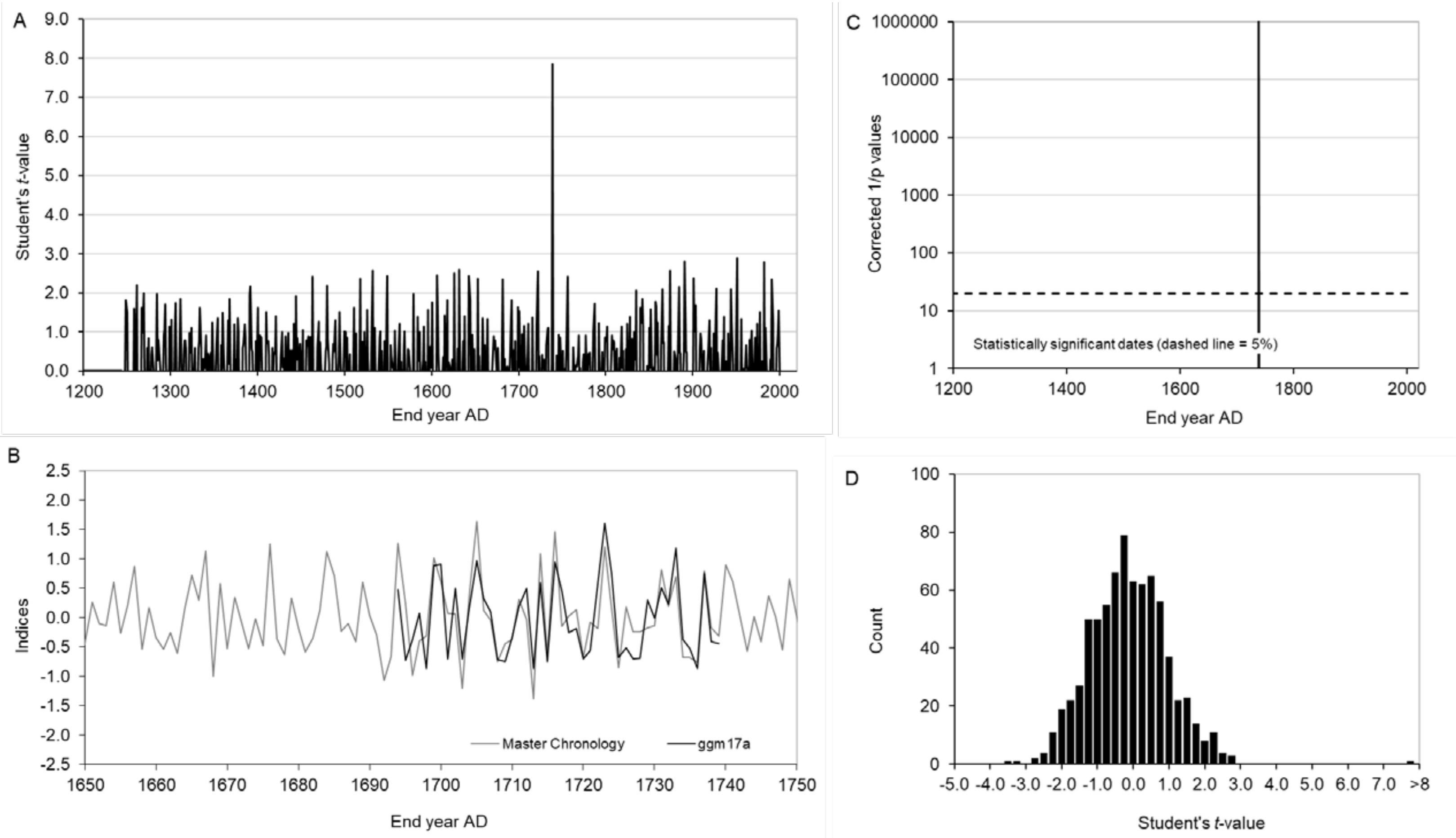

Figure 9: Dating results for the 46-year isotope chronology (ggm17a A: Student's t-values for all possible end dates with full overlap against the master chronology. B: Time series of the site isotopic mean plotted against the master chronology. C: End dates with corrected probabilities (1/p) of more than one. Those below the dashed line (1/p = 20) are not statistically significant. D: Distribution of Student's t-values for all possible matches

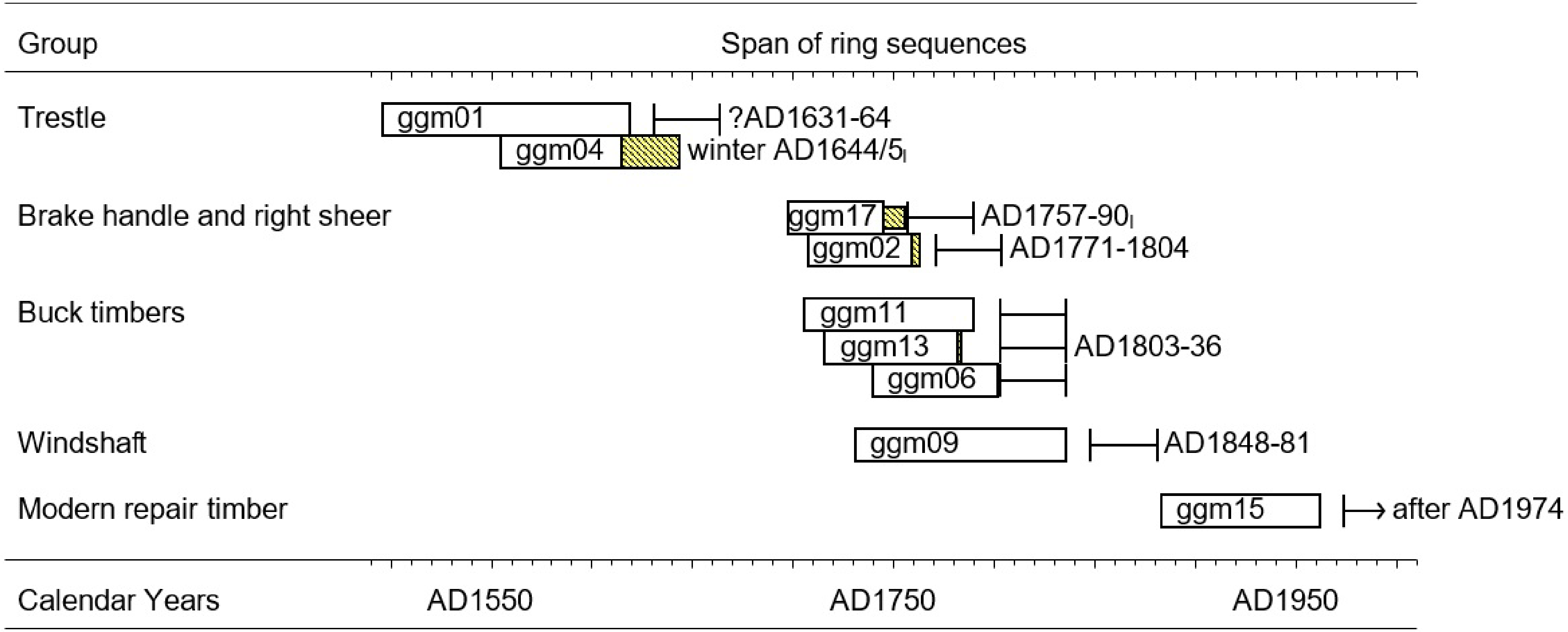

Figure 10: Bar diagram showing the relative positions of overlap of the dated timbers and their likely felling date ranges. White bars represent heartwood rings and yellow hatched sections represent sapwood rings. Narrow sections of bar represent additional unmeasured rings, and a date followed by subscript I represents an oxygen isotope date.

APPENDIX 1

Ring-width values (0.01mm) for the sequences measured

ggm01

324	224	198	365	305	366	310	498	484	462
337	340	99	62	54	75	114	119	147	102
124	107	150	127	171	157	130	150	125	92
126	114	158	171	143	274	70	51	59	70
80	84	128	199	238	163	110	149	223	297
247	192	426	573	123	110	75	108	130	137
64	130	150	200	254	97	181	92	129	149
140	124	158	221	334	286	157	220	256	254
232	337	243	273	377	154	241	217	206	266
423	352	431	276	176	249	171	355	496	644
621	564	521	499	386	195	271	308	326	223
582	370	467	210	148	158	209	479	460	365
338	289	212	249						

ggm02

305	368	180	248	319	344	223	238	264	288
257	269	396	448	426	323	453	515	462	430
304	263	268	202	264	260	276	369	309	286
446	429	289	249	193	162	170	280	322	278
264	181	170	280	332	212	253	297	272	268
253	266	251	268	194	335				

ggm04a

478	497	633	446	482	426	301	330	231	416
388	218	217	254	366	372	275	276	322	281
279	203	127	150	127	158	94	113	119	158
180	121	127	179	156	174	212	178	182	174
190	204	166	194	205	199	241	181	206	212
182	303	157	199	124	171	196	195	207	127
163	202	228	166	121	101	105	120	121	123
204	121	162	137	169	158	138	138	94	81
73	96	82	66	54	62	46	55	37	44

ggm04b

293	222	311	126	188	138	194	234	182	226
168	233	243	269	242	177	182	218	233	290
179	257	181	171	192	258	195	200	249	251
121	155	146	214	359	184				

ggm04c

165	91	120	134	81	182	150	387	427	471
409	332	306	238	192	154	152	130	120	95
107	218	192	159	191	200	215	209	158	219
144	194	210	199	217	268	249	262	306	340
226	232	264	295	281	265	208	279	135	186
127	168	217	188	227	175	235	264	224	178
138	133	175	175	302	245	340	232	192	174
227	180	205	215	249	129	177	211	217	327
188	177	150							

ggm05

276	462	681	661	547	651	450	441	697	587
484	499	443	272	402	534	686	400	248	459
550	513	315	227	323	304	253	260	279	225
220	189	285	322	177	130	223	218	303	208
196	223	201	230	153	191	249	161	219	189
269	184	169							

ggm06

80	70	108	144	132	270	381	314	144	98
176	186	342	263	246	208	283	155	105	323
242	284	169	299	211	165	251	498	501	388
326	201	165	260	331	322	354	379	267	188
133	210	357	237	332	151	123	186	231	382
240	247	166	178	98	213	238	221	225	188
122	178	203							

ggm07

232	187	151	223	233	289	200	134	247	197
115	147	183	122	100	101	115	115	84	70
114	206	201	189	225	140	99	131	157	221
184	165	169	94	95	110	99	124		

ggm09

120	88	86	230	336	286	253	384	289	187
204	213	240	210	348	308	327	175	137	172
223	209	172	324	242	276	193	267	210	241
245	202	393	310	214	268	274	292	232	241
220	152	209	243	260	245	295	202	194	213
156	216	194	220	131	121	130	140	184	158
151	250	156	169	212	172	211	144	136	130
127	108	136	162	192	165	193	142	121	133
132	167	178	163	158	153	166	139	165	135
161	151	181	136	129	138	119	139	181	159
152	141	151	159	133	153				

ggm10a

124	154	172	164	222	238	287	304	242	284
314	383	455	465	402	227	197	171	218	286
316	369	314	291	179	127	77	139	105	254
340	205	155	125	145	117	179	168	117	162
139	186	129	158						

ggm10b

360	216	190	169	293	301	323	384	269	305
280	241	269	286	290	411	406	307	382	361
261	401	409	436	350	301	270	363	471	487
502	334	438	331	181	120	241	193	207	383
339	299	272	304	280	344	329	214	289	318
335	262								

ggm11

220	234	277	249	203	222	346	516	181	257
247	215	126	88	130	219	210	122	151	213
182	131	320	262	275	220	205	145	110	270
232	172	299	215	97	47	100	85	108	226
323	295	133	91	112	200	216	150	128	156
152	113	81	150	150	189	110	146	110	104
124	241	314	213	163	92	70	152	156	169
149	170	148	76	65	109	130	129	117	70
42	42	65	113	99					

ggm13

242	256	186	140	182	288	333	143	184	218
154	115	282	295	253	241	236	176	129	264
281	204	302	299	116	80	105	113	136	245
315	318	141	97	135	239	310	210	187	131
168	122	85	267	231	203	143	181	116	115
127	320	428	335	277	146	107	196	292	276
278	280	198	109	85	130	245	136	171	

ggm14

387	339	324	326	285	221	326	308	309	394
274	263	185	246	292	174	159	151	156	206
217	296	212	175	242	232	226	224	229	217
163	124	99	99	80	80	144	130	140	174
121	114	140	133	211	146	75	67	110	105
163	126	136	153	131	119	87	54	46	120
127	123	184	115	127	104	94	88	86	73
104	96	89	124	122	148	171	145	148	174
205	135	118	131	119	252	176	117	115	94
78	135	76							

ggm15

352	260	237	293	189	188	245	330	258	317
207	237	185	138	191	201	250	285	227	180
229	203	171	221	177	247	178	359	231	254
304	207	134	130	265	184	208	204	116	118
114	145	224	161	165	150	92	133	210	220
140	134	185	216	222	130	259	142	199	231
155	128	162	230	196	146	151	201	173	196
198	134	201	163	122	192	147	198	140	161

ggm16

525	396	499	684	571	323	547	418	496	432
721	681	802	725	391	490	571	630	564	493
306	474	475	402	368	406	645	546	429	447
437	443	392	436	432	420	357	496	391	479
361	359	308	354	278	316	337	262		

ggm17a

161	170	168	154	233	378	283	155	192	157
153	172	159	216	285	228	159	247	296	267
168	207	220	230	199	157	257	127	112	185
153	162	115	154	104	131	94	145	218	195
206	156	79	54	67	51	57	127		

ggm17b

234	275	200	235	253	265	264	358	311	219
298	349	318	191	229	276	237	233	162	306
143	116	210	165	172	118	159	111	153	99
172	226	203	214	159	62	58	73	49	62
149									

ggm18

235	287	239	283	169	126	206	231	422	258
197	266	218	328	209	222	288	248	254	253
249	226	165	283	472	410	399	318	322	296
283	397	330	280	252	250	199	209	218	247
194	268	338	268	211	203	268	371	481	504
259	324	284	283	272	258	285	169	212	198
367									

APPENDIX 2

Oxygen isotope ratios (δ^{18}O) for the measured tree ring series. Data are reported as per mille (‰) deviations relative to the VSMOW standard (Coplen 1995).

ggm04c

Ring	δ^{18}O	Ring	δ^{18}O	Ring	δ^{18}O
1		31	29.20	61	30.57
2		32	30.61	62	29.59
3		33	30.48	63	28.92
4		34	29.27	64	29.16
5		35	30.14	65	30.18
6		36	32.29	66	29.42
7		37	30.69	67	29.34
8		38	31.11	68	29.14
9		39	31.42	69	29.13
10	30.43	40	29.13	70	29.54
11	29.74	41	30.18	71	29.22
12	30.96	42	29.35	72	29.27
13	31.71	43	29.88	73	29.14
14	30.80	44	30.31	74	28.83
15	30.25	45	31.07	75	28.95
16	30.76	46	30.26	76	29.09
17	30.54	47	30.45	77	29.00
18	30.13	48	30.14	78	30.03
19	30.33	49	30.72	79	29.09
20	30.49	50	31.30	80	30.12
21	29.24	51	31.11	81	28.95
22	29.48	52	30.02	82	28.77
23	29.16	53	29.49	83	31.50
24	30.41	54	30.48	84	30.07
25	29.77	55	30.01	85	29.24
26	29.70	56	29.87	86	
27	30.36	57	30.07	87	
28	29.97	58	30.49	88	
29	30.95	59	29.32	89	
30	31.14	60	30.25	90	

ggm17a

Ring	δ^{18}O	Ring	δ^{18}O	Ring	δ^{18}O
−3	29.06				
−2	27.93				
−1	28.39				
0	28.79				
1	27.94	21	28.68	41	28.02
2	29.64	22	28.90	42	28.02
3	29.80	23	28.57	43	
4	28.32	24	28.54	44	
5	29.54	25	29.61	45	
6	28.42	26	30.58	46	
7	29.10	27	29.62	47	
8	29.67	28	28.26	48	
9	29.00	29	28.46		
10	28.66	30	28.23		
11	27.90	31	28.06		
12	27.71	32	29.10		
13	28.07	33	28.81		
14	28.50	34	29.29		
15	28.92	35	28.95		
16	27.70	36	30.05		
17	29.26	37	28.37		
18	28.01	38	28.13		
19	29.72	39	27.73		
20	29.18	40	29.34		

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