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Tree-ring Analysis and Radiocarbon Wiggle-matching of Oak Timbers from the Chancel

Martin Bridge, Alex Bayliss, Michael Dee, and Sanne Palstra

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Front Cover: View of the Church of St Michael Coslany from the south-east in Norwich. Photograph: Domenico D'Alessandro, Historic England

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SUMMARY

Twelve oak timbers were sampled from the chancel roof. Only four samples had more than 60 rings, but some matching was found between ring-width series resulting in three groups of timbers being identified. A number of matches were found for the series composed of three timbers with a tentative end date of AD 1426, but these were not very strong, and were matched only with local chronologies, so were not accepted as an independent secure dendrochronological date.

Radiocarbon dating was undertaken on four single-ring samples from one of the timbers represented in the tentatively dated site master chronology. Wiggle-matching of these results suggests that the final ring of this sequence formed in *cal AD 1419–1432 (95% probability)* or *cal AD 1422–1430 (68% probability)*.

The tentative matching identified for the site master chronology by ring-width dendrochronology is thus supported independently by the radiocarbon wiggle-matching, giving a chronology spanning AD 1339–1426_{DR}. The three timbers represented in this site master chronology, with a mean heartwood/sapwood boundary date of AD 1425_{DR}, were likely felled in the period of AD 1434–1466_{DR}.

CONTRIBUTORS

Martin Bridge, Cathy Tyers, Alex Bayliss, Michael Dee, and Sanne Palstra

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ARCHIVE LOCATION

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INTRODUCTION

The Church of St Michael Coslany is a Grade I Listed redundant church (LEN 1372474 here), often considered to be the grandest of the churches in north Norwich (Fig 1) and noted for its flint flushwork of early sixteenth-century and nineteenth-century date. Internally there are arcade pillars of the late Perpendicular style. The chancel roof (Fig 2) of five bays is arch-braced with the wall posts terminating on corbels. The roof has been tentatively dated to around AD 1500, but repair works offered the opportunity to sample timbers from the stripped roof, and dendrochronology was requested by the Historic England architect Domenico D'Alessandro to inform repairs and gain a better understanding of the development of the church.

RING-WIDTH DENDROCHRONOLOGY

Sampling

An assessment of the timbers for dendrochronological potential sought accessible oak timbers with more than 50 rings and where possible traces of sapwood, although slightly shorter sequences are sampled if little other material is available. Those timbers judged to be potentially useful (Fig 3) were cored using a 16mm auger attached to an electric drill. The cores were labelled and stored for subsequent analysis.

Methodology

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 (2004a). Cross-matching was attempted by a combination of visual matching and a process of qualified statistical comparison by computer. 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 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 derivation 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 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 9–41 rings (Miles 1997, fig 5). 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

The ring-width series (Table 1) were mostly quite short, with only four exceeding 60 rings. Two cores (mcos06 and mcos09) fractured, and have two measured sections each, an inner section designated (i), and an outer section (ii). In the case of mcos09, the break was thought to be clean, and a combined series was produced. Two samples were taken from mcos08 (a and b) to maximise the information gained; these matched at $t = 6.0$ with a 34 year overlap and were combined to make a single mean timber series. The ring-width data for all measured series are provided in the Appendix.

Some cross-matching was found between individual series (Figs 4a–c; Tables 2a–c) and three site chronologies were formed (mcos0204, mcos0305, and MCOSt3, the latter being the three-timber mean from samples mcos10, mcos11, and mcos12). All three site chronologies, and the unmatched individual series, were compared with the database of reference chronologies but only MCOSt3 gave any matches that were thought worthy of further investigation (Table 3), although these were relatively weak, and not well-replicated. They were, however, with one exception, all matched with local Norfolk chronologies.

There was a potential match noted between the two-timber mean sequence mcos0204 and MCOSt3. Combining these two ring-width master sequences led to an overall decrease in the levels of cross-matching with reference chronologies and it was notable that mcos0204 showed very little similarity with any reference chronologies at this implied potential date. Hence this potential match between MCOSt3 and mcos0204 was not pursued.

RADIOCARBON DATING

Following the failure of the ring-width dendrochronology to provide secure calendar dating for site master chronology, MCOSt3, sample mcos11 was selected for radiocarbon dating and wiggle-matching. This core has 76 growth rings that span relative rings 13–88 of this tree-ring chronology (Fig 4c).

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).

Four radiocarbon measurements have been obtained from single annual tree-rings from timber mcos11 (Table 4; Fig 5). 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 Centre for Isotope Research, University of Groningen (GrM-), the Netherlands in 2022. Each ring was converted to α-cellulose using an intensified aqueous pretreatment (Dee *et al* 2020) and combusted in an elemental analyser (IsotopeCube NCS), coupled to an Isotope Ratio Mass Spectrometer (Isoprime 100). The resultant CO_2 was graphitised by hydrogen reduction in the presence of an iron catalyst (Wijma *et al* 1996; Aerts-Bijma *et al* 1997). The graphite was then pressed into aluminium cathodes and dated by Accelerator Mass Spectrometry (AMS) (Synal *et al* 2007; Salehpour *et al* 2016).

Data reduction was undertaken as described by Wacker *et al* (2010), and the facility maintains a continual programme of quality assurance procedures (Aerts-Bijma *et al* 2021), 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 Accelerator Mass Spectrometry (Stuiver and Polach 1977; Table 4).

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 mcos11, derived from the probability method (Stuiver and Reimer 1993), are shown in outline in Figures 6 and 7.

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 Figures 6 and 7 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 6 illustrates the chronological model for mcos11. This model incorporates the gaps between each dated annual ring known from tree-ring counting (eg that the carbon in ring 15 of the measured tree-ring series (GrM-30238) was laid down 23 years before the carbon in ring 38 of the series (GrM-30239); Fig 5), with the radiocarbon measurements (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: 161.2, An: 35.4, n: 4; Fig 6), with all radiocarbon dates having good individual agreement (A > 60). It suggests that the final ring of mcos11, and thus the final ring of the site master sequence, MCOSt3, formed in *cal AD 1419–1432 (95% probability; mcos11 h/s*; Fig 6*) or cal AD 1422–1430 (68% probability).*

When the last surviving ring of this timber is constrained to have formed in AD 1426, as suggested tentatively by the ring-width dendrochronology, the model again has good overall agreement (Acomb: 184.9, An: 31.6, n: 5; Fig 7), with all the radiocarbon dates again having good individual agreement (A > 60).

DISCUSSION

The radiocarbon wiggle-matching allows the tentative dating indentified by the ring-width dendrochronology to be considered as a radiocarbon supported dendrochronological date, with the site master chronology spanning AD 1339–1426_{DR}. The subscript $_{DR}$ indicates that this is not a date determined independently by ring-width dendrochronology, and that the master sequence, MCOSt3, should not be utilised as a ring-width master sequence for dating other sites.

Adding the appropriate sapwood estimate (Miles 1997) to the last surviving ring of each dated timber, provides individual felling date estimates for each timber (Table 1; Fig 8). Given that the heartwood/sapwood boundaries of the two timbers that retain this ring in this chronology vary by only two years, however, it is possible to use the mean heartwood/sapwood boundary date of AD 1425_{DR} to provide a likely felling date range of AD 1434–66_{DR} for these common rafters, thus identifying the presence of timbers to around half a century earlier than the expected date of the roof.

A further pair of common rafters, mcos03 and mcos05, appear to be at least broadly coeval with each other, as do the principal rafter mcos02 and the common rafter mcos04, but the two site master chronologies represented by these two pairs of timbers remain undated.

The radiocarbon supported dendrochronological date is of interest as the ring-width matching with reference material was relatively weak, but the strongest matches found when compared with well over two thousand chronologies from all over England and Wales were, with one exception in Peterborough, with sites in Norfolk (Table 3). This suggests there may be some unique Norfolk microclimates, or other factors (soils, genetics etc) influencing growth of some sites in the area. A chronology from a church roof at Beeston-next-Mileham created several years ago (Bridge 2007) had over 90 rings and was internally well replicated, with no apparent anomalous growth patterns, but this also has so far remained undated.

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TABLES

Table 1: *Details of the samples taken from the chancel roof at the Church of St Michael Coslany, Norwich. The trusses and timbers had been previously numbered from the west end, N denoting the north side, and S the south side, so the trusses run ST1–6 and NT1-6, with common rafters being numbered from the west truss, hence common rafter ST1-3 is the third common rafter east of truss 1 on the south side*

Sample No	Location	No rings	Sapwood	Mean ring width (mm)	Mean sensitivity	Date (AD) or relative date	Felling date (AD)
mcos01	Principal rafter ST4	56	?h/s	2.15	0.31	-	-
mcos02	Principal rafter ST3	75	-	1.76	0.25	8–82^{0204}	-
mcos03	Common rafter ST4-3	50	?h/s	1.68	0.21	10–59^{0305}	-
mcos04	Common rafter ST3-2	57	?h/s	2.55	0.30	1–57^{0204}	-
mcos05	Common rafter NT5-3	53	?h/s	1.49	0.21	1–53^{0305}	-
mcos06i	Inner rings, principal rafter NT5	23	-	4.40	0.11	-	-
mcos06ii	Outer rings, principal rafter NT5	10	-	5.12	0.27	-	-
mcos07	Principal rafter NT6	59	h/s	2.33	0.22	-	-
mcos08a	Common rafter NT4-3	38	-	1.75	0.14	-	-
mcos08b	*ditto*	47	15	1.24	0.17	-	-
mcos08	Mean of 08a and 08b	51	15	1.46	0.16	-	-
mcos09i	Inner rings, principal rafter NT2	43	-	1.77	0.23	-	-
mcos09ii	Outer rings, principal rafter NT2	20	-	1.70	0.22	-	-
mcos09	Combined 09i and 09ii	63	-	1.75	0.23	-	-
mcos10	Common rafter NT1-2	86	h/s	1.59	0.22	1339–1424$_{\mathrm{DR}}$	AD 1433–65$_{\mathrm{DR}}$
mcos11	Common rafter NT1-4	76	h/s	2.17	0.25	1351–1426$_{\mathrm{DR}}$	AD 1435–67$_{\mathrm{DR}}$
mcos12	Common rafter NT3-2	54	-	2.11	0.21	1369–1422$_{\mathrm{DR}}$	after AD 1431$_{\mathrm{DR}}$

Key: h/s = heartwood/sapwood boundary; ?h/s = possible heartwood/sapwood boundary; ^{0204} = relative years within mcos0204; ^{0308} = relative years within mcos0305

Table 2a: Cross-matching between samples mcos02 and mcos04

t-*value / years overlap*	
Sample No	mcos04
mcos02	7.6 / 50

Table 2b: Cross-matching between samples mcos03 and mcos08

t-*value / years overlap*	
Sample No	mcos05
mcos03	5.7 / 44

Table 2c: Cross-matching between samples mcos10, 11, and 12 (forming MCOSt3)

	t-*value / years overlap*	
Sample No	mcos11	mcos12
mcos10	5.3 / 74	6.8 / 54
mcos11		7.6 / 54

Table 3: Potential matches between series MCOSt3 and dated reference material at AD 1339–1426

Source region:	Chronology name:	Publication reference:	File name:	Span of chronology (AD)	Overlap (years)	*t*-value
Norfolk	Oxburgh Hall west range	Tyers 2004b	OXWR_T6	1221–1427	88	6.2
Norfolk	New Buckenham	Cooper *et al* 2012	NEWBUCK1	1271–1472	88	5.6
Norfolk	Wiggenhall St Mary Magdalen	Bridge 2008	WGGNHLL	1278–1394	56	5.2
Cambridgeshire	Peterborough Cathedral Presbytery	Tyers 2004c	PCF6-T4	1208–1500	88	5.2
Norfolk	*New Buckenham Old Vicarage**	*Tyers 2004d*	*NBOV-T5*	*1271–1451*	*88*	*5.2*
Norfolk	Norwich St James Pockworth rood screen Helen	Tyers 2012	OS0729A	1332–1436	88	5.2
Norfolk	*New Buckenham Oak and Yellow Cottages**	*Tyers 2004d*	*NBOY-T3*	*1346–1472*	*81*	*4.8*
Norfolk	Norwich St James Pockworth rood screen Blida	Tyers 2012	OS0729B	1326–1448	88	4.5

* - components of New Buckenham (Cooper *et al* 2012)

Table 4: Radiocarbon measurements from oak sample mcos11

Laboratory Number	Sample	Radiocarbon Age (BP)
GrM-30238	mcos11, ring 15 (*Quercus* sp., heartwood)	643±17
GrM-30239	mcos11, ring 38 (*Quercus* sp., heartwood)	628±18
GrM-30241	mcos11, ring 52 (*Quercus* sp., heartwood)	564±18
GrM-30244	mcos11, ring 72 (*Quercus* sp., heartwood)	513±17

FIGURES

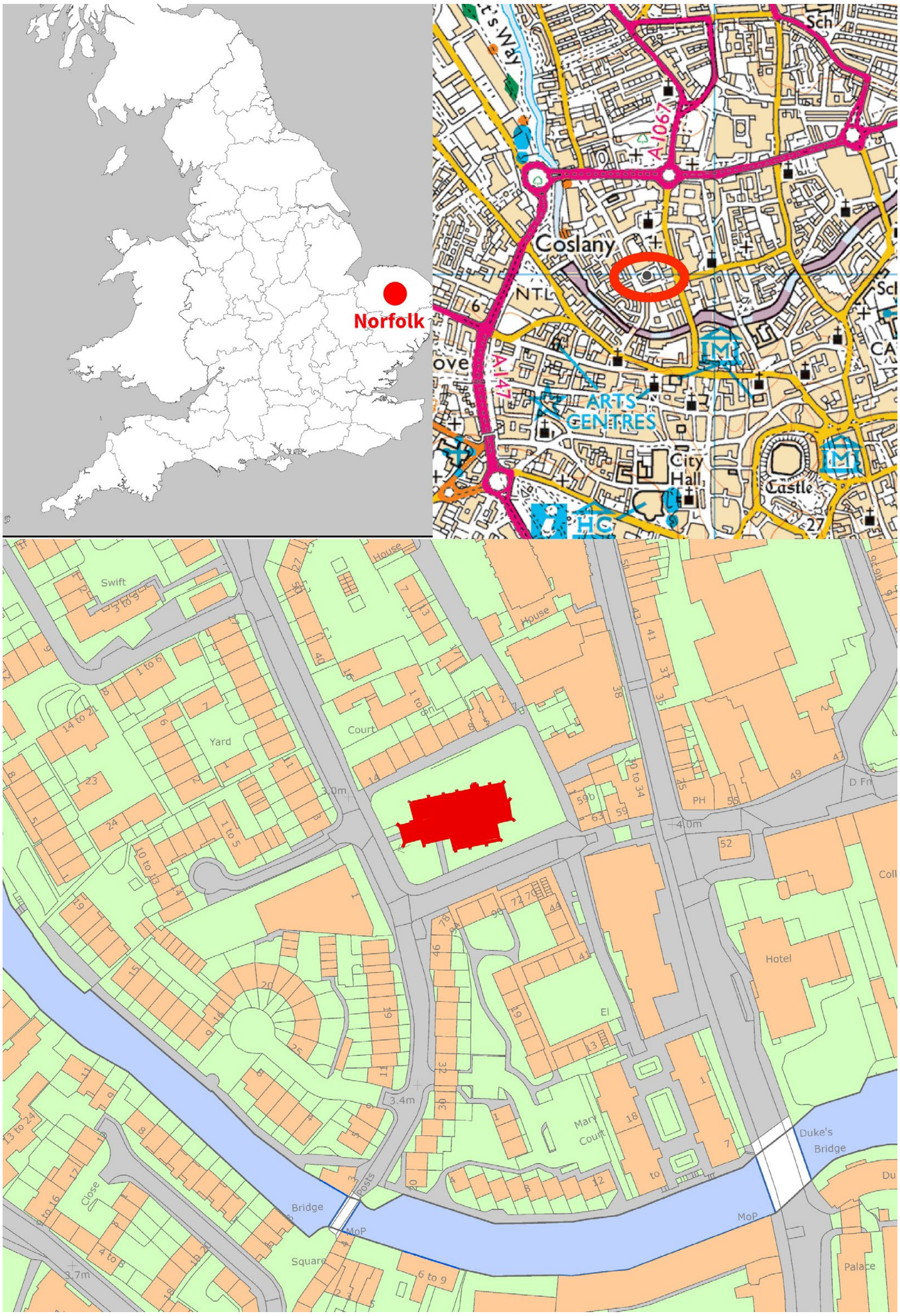

Figure 1: Maps to show the location of the Church of St Michael Coslany in Norwich, Norfolk, in red. Scale: top right 1:13,000; bottom 1:1,600. © Crown Copyright and database right 2022. All rights reserved. Ordnance Survey Licence number 100024900

Figure 2: View of the south slope of the chancel roof (looking east), showing the exposed rafters (photograph Martin Bridge)

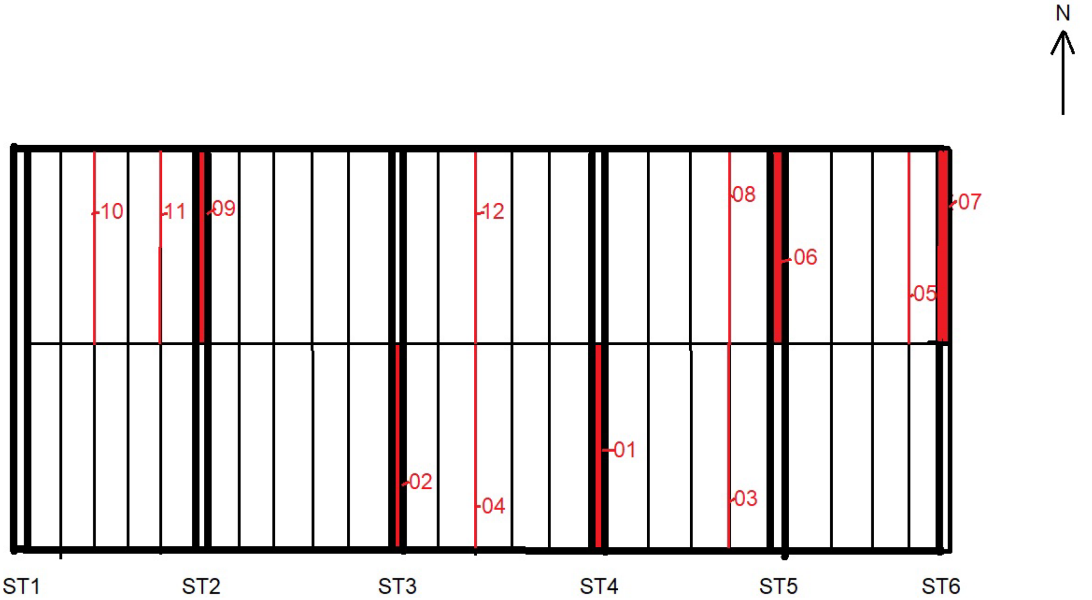

Figure 3: Sketch plan of the roof (not to scale) indicating the rafters sampled (red). Note there are four common rafters in the three western bays, and only three common rafters in the two eastern bays

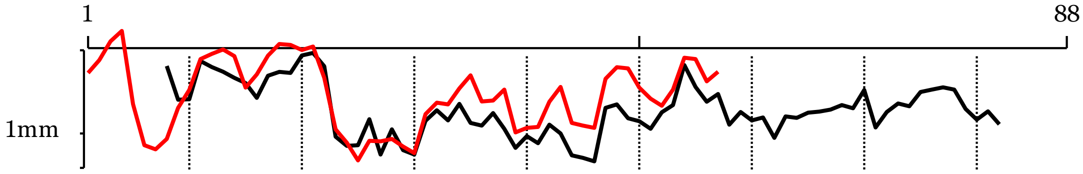

Figure 4a: Plots of the two matching ring series, mcos02 (black; relative years 8–82) and mcos04 (red; relative years 1–57), showing the similarity in growth and their relative overlaps. The y-axis is ring width (mm) on a logarithmic scale, the x-axis is relative years.

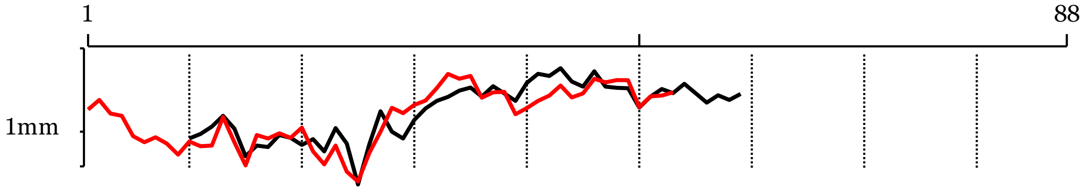

Figure 4b: Plots of the two matching ring series, mcos03 (black; relative years 10–59) and mcos05 (red; relative years 1–53), showing the similarity in growth and their relative overlaps. The y-axis is ring width (mm) on a logarithmic scale, the x-axis is relative years.

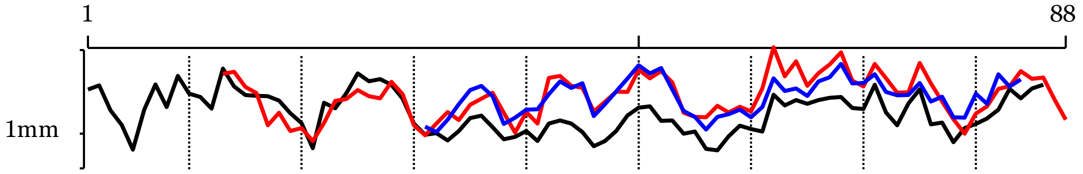

Figure 4c: Plots of the three matching ring series, mcos10 (black; relative years 1–86), mcos11 (red; relative years 13–88), and mcos12 (blue; relative years 31–84), showing the similarity in growth and their relative overlaps. The y-axis is ring width (mm) on a logarithmic scale, the x-axis is relative years.

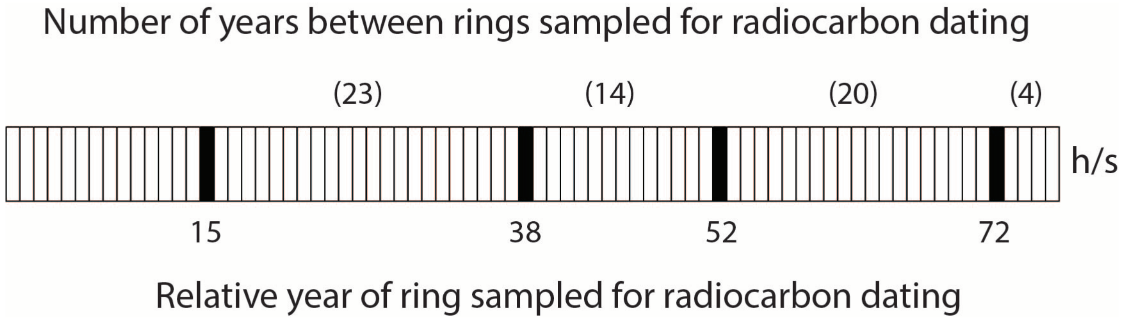

Figure 5: Schematic illustration of sample mcos11 to locate the single-ring sub-samples submitted for radiocarbon dating (h/s = heartwood/sapwood boundary)

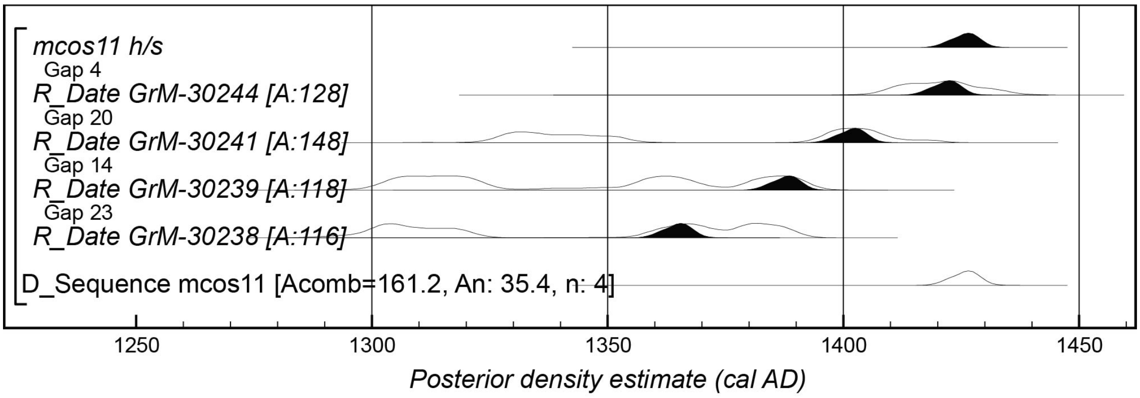

Figure 6: Probability distributions of dates from sample mcos11. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. Distributions other than those relating to particular samples correspond to aspects of the model. For example, the distribution 'mcos11 h/s' is the estimated date when the heartwood/sapwood boundary of timber mcos11 formed. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly

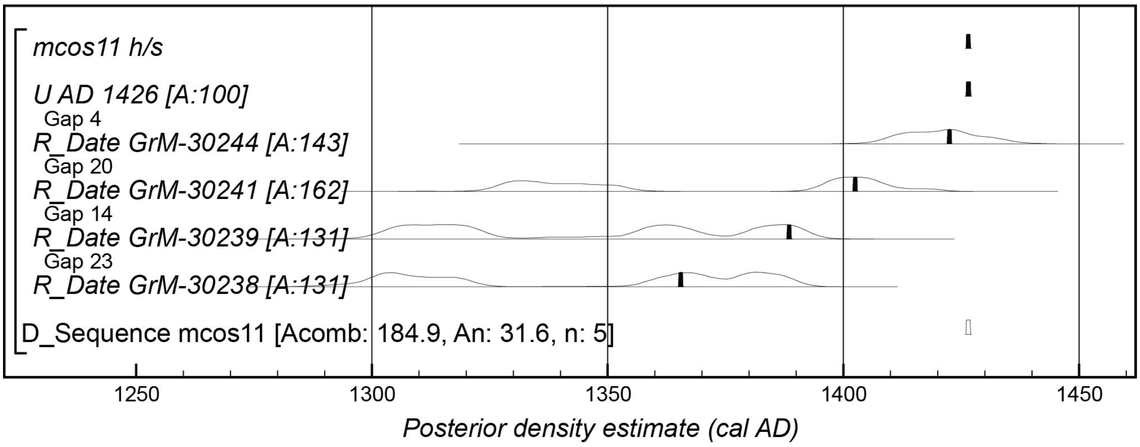

Figure 7: Probability distributions of dates from mcos11, including the tentative date produced by ring-width dendrochronology for the formation of its last surviving ring in AD 1426. The format is identical to that of Fig 5. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly

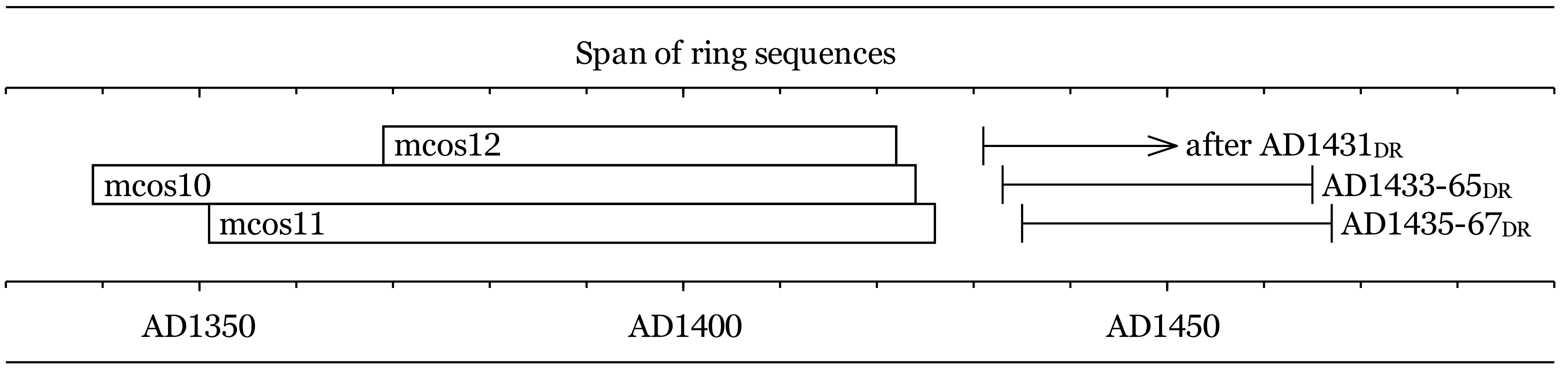

Figure 8: Bar diagram showing the relative positions of overlap of the components of MCOSt3 with their estimated likely felling date ranges. White bars = heartwood rings

APPENDIX

Ring width values (0.01mm) for the sequences measured

mcos01

161	285	182	261	301	362	263	359	291	263
282	306	225	449	166	138	301	155	204	164
95	105	56	99	92	115	120	145	193	242
396	209	235	210	186	258	179	202	174	157
254	201	117	214	179	157	231	272	192	224
176	145	213	387	210	270				

mcos02

358	189	191	393	351	321	286	259	196	298
320	314	437	458	356	94	79	80	131	67
108	73	67	127	155	128	175	122	116	147
109	76	95	83	118	100	66	63	59	162
173	133	126	109	149	171	364	241	182	211
118	150	128	135	92	138	134	148	151	157
171	161	227	112	150	176	167	219	229	239
229	159	130	152	119					

mcos03

88	96	110	135	106	63	77	75	94	89
78	87	69	107	80	37	79	147	100	88
125	155	179	193	217	230	194	236	206	179
251	298	286	331	258	234	313	234	229	227
158	194	224	207	247	207	173	199	182	204

mcos04

314	400	571	695	174	80	74	90	162	228
408	450	489	431	238	305	436	542	533	484
517	286	108	84	60	87	86	90	78	69
144	179	173	234	300	183	186	229	102	111
113	182	241	122	116	111	281	350	342	238
193	169	229	418	408	268	321			

mcos05

152	182	141	135	92	82	90	80	65	83
76	77	132	82	53	94	88	97	89	108
69	54	77	47	39	67	100	157	142	166
180	228	297	272	286	190	210	212	139	156
179	198	239	191	206	272	254	265	264	159
195	198	210							

mcos06i

198	201	244	327	335	303	318	381	328	307
374	378	410	387	379	324	510	720	742	767
737	701	753							

mcos06ii
443 474 610 803 793 456 220 450 462 412

mcos07
426 408 361 321 303 255 201 274 339 263
404 349 217 265 299 242 397 252 343 299
177 141 119 127 230 217 169 200 194 314
315 183 120 123 172 187 137 139 114 117
137 116 105 213 184 125 138 186 230 263
229 283 314 402 313 301 148 166 160

mcos08a
261 238 229 179 173 187 137 116 129 115
93 96 118 157 183 199 164 178 147 195
189 149 151 188 165 212 131 144 162 166
147 150 175 239 236 224 269 244

mcos08b
100 142 109 82 116 112 68 68 60 76
107 124 134 122 126 159 125 120 112 150
120 150 102 113 130 124 125 128 137 190
222 175 182 148 124 106 119 85 151 147
113 117 128 127 109 106 126

mcos09i
194 172 344 240 220 179 249 178 137 278
203 246 194 187 101 156 229 212 145 152
136 143 197 218 214 162 140 188 169 145
112 106 197 183 172 93 93 85 124 158
180 188 193

mcos09ii
165 172 137 158 158 173 197 206 281 294
284 320 83 148 75 102 95 91 130 123

mcos10
229 248 155 118 74 157 252 165 296 212
199 160 340 243 207 204 202 186 147 122
76 179 161 214 310 268 279 250 193 121
98 101 88 105 134 140 113 90 94 105
87 121 128 121 103 79 87 105 141 163
167 127 128 100 104 75 73 95 116 109
104 208 170 188 175 188 196 199 162 159
251 149 117 176 230 119 123 85 111 120
133 157 232 194 234 251

mcos11

```
308  320  241  214  117  148  105  111  87   122
185  192  227  202  194  265  210  117  97   121
150  129  172  193  216  148  102  150  121  285
296  246  237  152  182  220  219  332  283  324
262  148  137  136  169  149  166  152  234  508
294  390  246  312  367  462  271  243  371  284
216  218  378  257  183  131  100  146  167  232
244  324  280  287  190  130
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mcos12

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114  103  130  174  227  245  202  120  135  157
158  210  267  236  258  139  174  221  282  362
310  343  229  153  137  108  137  144  157  136
165  283  223  234  203  267  289  371  257  259
306  219  206  207  259  183  200  136  135  212
175  305  242  277
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