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Belsay Castle, Belsay, Near Morpeth, Northumberland
Tree-ring and radiocarbon analysis of oak timbers

Alison Arnold, Robert Howard, Cathy Tyers, Christopher Bronk Ramsey, Elaine Dunbar and Peter Marshall

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NORTHUMBERLAND

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SUMMARY
Tree-ring analysis was undertaken on samples taken from the coach house/stables range, the castle tower, and the castle annexe resulting in the construction of a single site sequence representing two tiebeams from the tower. This site sequence could not be conclusively dated through dendrochronology alone but tentative dating obtained has now been supported by radiocarbon wiggle-match dating. These two tiebeams are now known to have been felled in AD 1439–64$_{DR}$.

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INTRODUCTION

The Belsay Castle complex, located in Belsay, *c* 22 km north west of Newcastle upon Tyne (Figs 1–2), is designated a Scheduled Ancient Monument (List Entry No. 1015517). It includes, at the western edge of the site, the medieval castle and associated buildings (Fig 3). In AD 1614 Thomas and Dorothy Middleton added a mansion range to the west side of the castle tower, which may have replaced an earlier manor house. A further wing, now ruined, was added to this house in the early-eighteenth century with walled gardens laid out to the front. A new mansion in the Greek revival style was built to replace the old castle in the early-nineteenth century.

Tower

The castle is dominated by a fortified, three-storey 'pele tower' (Fig 4) constructed from squared stone with ashlar detail and thought to date to *c* AD 1370 (Grade I listed: List Entry No. 1042837). The ground floor consisted of a tunnel vaulted kitchen, complete with a large fireplace, and a spiral staircase which provided access to the upper levels. The first floor was dominated by the Great Hall whilst the upper level provided high status accommodation and possibly a small chapel. The extant roof (Fig 5) is thought to be a re-roofing dating to AD 1896–7 but Arthur Middleton states in his AD 1907 account of this re-roofing of the tower that three of the original cambered oak roof beams were re-used in the new roof.

Castle annexe

Running northwards from the tower is a two-storey barn, known as the 'annexe' (Fig 4). This is thought to have been altered in the eighteenth and nineteenth centuries, which probably included the insertion of the softwood floors (Fig 6), but its medieval masonry suggests earlier origins.

Stables/coach house

This is a long north-south aligned range located approximately 100m to the north west of the castle (Grade II listed: List Entry No. 1370665). The southern end served as stables whilst the northern end was the coach house (Fig 7). Historic timbers survive as lintels, floor joists, and supporting beams to a hearth (Figs 8–10).

The estate is the subject of a 'Belsay Awakes' project, which aims to transform the visitor experience at Belsay Hall, Castle, and Gardens by enhancing the presentation and interpretation of the site, and its visitor facilities.

SAMPLING

Dendrochronological analysis was requested by Simon Taylor, Historic England's Senior Architectural Investigator who is working with the English Heritage Trust Properties Curators' team to better understand the buildings' sequence and significance of surviving fabric across the site, particularly the castle, manor house, north range, stables and other buildings within the castle courtyard. It was hoped that successful tree-ring analysis would provide independent dating evidence to better understand the development and significance of the structures and to inform the current conservation and restoration programme of works.

Twenty-one core samples were taken from timbers in the stables/coach-house range, the ground-floor ceiling of the castle annexe, and the roof and lintels in the castle tower, in accordance with the conditions of the Scheduled Ancient Monuments Consent. Each sample was given the code BEL-C and numbered 01–21. Further details relating to the samples can be found in Table 1. The location of all samples has been marked on Figures 11–13. Trusses in the castle tower and ceiling joists in the annexe were numbered from north to south.

ANALYSIS AND RESULTS

Three of the samples, one from the annexe, one from the stables/coach house, and one from the castle tower had too few rings for secure dating and so were rejected prior to measurement. The remaining 18 samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. The samples were then divided into pine and oak and the measurements from each group then compared with each other by the Litton/Zainodin grouping programme (see Appendix), resulting in two of the oak samples matching at a value of $t = 6.4$.

These two samples were combined at the relevant offset positions to form BELCSQ01, a site sequence of 102 rings (Fig 14). This site sequence was compared against a series of relevant reference chronologies for oak but this was inconclusive as very unusually two tentative dates were obtained, one mostly against reference chronologies from the north-east and north-west regions (Table 2), the other mostly against reference chronologies from more southern sites (Table 3). Thus these timbers remained undated by dendrochronology.

Attempts were also made to date the remaining ungrouped samples by individually comparing them against the reference chronologies but no secure matches could be identified and these are also undated.

RADIOCARBON DATING

Following the failure of the dendrochronology to provide calendar dating for the felling of the timbers in site sequence BELCSQ01, a single ring (ring 80) was sampled from timber BEL-C17 for radiocarbon dating and wiggle-matching.

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).

Two radiocarbon measurements have been obtained from a single annual tree-ring from timber BEL-C17 (Table 4; Fig 15), that was split and dated at two different laboratories. 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 annual ring, including both earlywood and latewood, 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.

Sub-samples of the single ring were submitted to the Oxford Radiocarbon Accelerator Unit (ORAU) and Scottish Universities Environmental Research Centre (SUERC) for Accelerator Mass Spectrometry (AMS) dating. The sample submitted to the Oxford University Radiocarbon Accelerator Unit was pretreated using the acid-base-acid protocol followed by bleaching with sodium chlorite (Brock *et al* 2010, Table 1 (UW)). It was combusted and graphitised as described by Brock *et al* (2010, 110) and Dee and Bronk Ramsey (2000) and dated by AMS (Bronk Ramsey *et al* 2004). The sample submitted to SUERC was converted to α-cellulose, combusted, graphitised, and dated by AMS as described by Dunbar *et al* (2016).

Both facilities maintain continual programmes of quality assurance procedures in addition to participation in international inter-comparison exercises (Scott *et al* 2017). The two results on ring 80 are statistically consistent (Table 4) and a weighted mean has been taken of them before calibration. This demonstrates 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). The $\delta^{13}C$ values quoted by both laboratories were measured by Isotope Ratio Mass Spectrometry, and more accurately reflect the natural isotopic composition of the sampled wood.

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 IntCal13 calibration curve (Reimer *et al* 2013). For the period covered by this study, this is constructed from radiocarbon measurements on tree-ring samples dated absolutely by dendrochronology. The probability distribution of the calibrated radiocarbon date from BELCSQ01, derived from the probability method (Stuiver and Reimer 1993) is shown in outline in Figure 15.

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 date (Christen and Litton 1995). It has been implemented using the program OxCal v4.3 (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 15 and quoted in italics in the text. The Acomb statistic shows how closely the calibrated radiocarbon date agrees 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 15 illustrates the chronological model for BELCSQ01. This model incorporates the radiocarbon date, calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal13 (Reimer *et al* 2013), and the relative number of years derived from the tree-ring analysis to the tentative dendrochronological date of AD 1428 (Table 2) for the formation of the final ring of the sequence. The other tentative tree-ring date of AD 1590 (Table 3) for the formation of the final ring of the sequence is clearly too late given the radiocarbon date.

The model has good overall agreement (Acomb: 81.4, An: 70.7, n:1), with the date on the single ring having good individual agreement (A > 60) with its positions in the sequence. The radiocarbon date is therefore in agreement with the potential dendrochronological date for the final ring of BELCSQ01 of AD 1428 (Fig 14).

INTERPRETATION

The tentative tree-ring date for site sequence BELCSQ01 against north-east and north-west reference chronologies has now been supported by the radiocarbon wiggle-match dating. Thus dates can be assigned to the ring sequences derived from samples BEL-C17 and BEL-C18 based on a combination of dendrochronological and radiocarbon dating evidence. Both of the samples in the site sequence have the heartwood/sapwood boundary ring, the dates of which are similar and suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1424_{DR} (This is distinguished from a date derived from ring-width dendchronology alone by the subscript $_{\mathrm{DR}}$), giving an estimated felling date for the two timbers represented of AD 1439–64_{DR}.

DISCUSSION

Two of the tiebeams of the castle tower roof are now known to have been felled in AD 1439–64_{DR}. As stated above, the present roof is thought to be a re-roofing undertaken in AD 1896–7 with the tower itself dating to *c* AD 1370. If this is the case then these tiebeams cannot be survivals from the original roof. It may be that the tower is somewhat later than previously thought and these mid-fifteenth century beams do represent primary timbers or alternatively that they have been salvaged from a completely different structure.

The poor level of dating from this site is unfortunate but perhaps not unsurprising given that there is likely to be several phases of felling represented amongst the samples and that a number of them may be quite late and, therefore, belong to a period in time which is currently underrepresented within our reference databanks.

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TABLES

Table 1: Details of samples taken from Belsay Castle, Belsay, Northumberland, and associated buildings

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD_{DR})	Last heartwood ring date (AD_{DR})	Last measured ring date (AD_{DR})
Annexe: pine						
BEL-C01	Shop – joist 6	95	43	----	----	----
BEL-C02	Shop – joist 8	45	h/s	----	----	----
BEL-C03	Shop – Joist 9	199	65C	----	----	----
BEL-C04	Shop – joist 10	47	h/s	----	----	----
BEL-C05	Storeroom – joist 1	118	--	----	----	----
BEL-C06	Store room – joist 8	NM	--	----	----	----
Coach-house and stables: oak						
BEL-C07	East hearth supporting beam	62	h/s	----	----	----
BEL-C08	West hearth supporting beam	60	13	----	----	----
BEL-C09	North lintel R1/2	175	21C	----	----	----
BEL-C10	South lintel R1/2	56	--	----	----	----
Coach-house and stables: pine						
BEL-C11	R1 – lintel (south half) over entrance	NM	--	----	----	----
BEL-C12	R1 – lintel (north half) over entrance	73	--	----	----	----
BEL-C13	R1 – floor beam	74	43	----	----	----
BEL-C14	R3 -floor beam	91	50	----	----	----
BEL-C15	R4 – north joist	112	51	----	----	----
BEL-C16	R4 – south joist	54	01	----	----	----
Castle tower: oak						
BEL-C17	Tiebeam 2	84	h/s	1345	1428	1428
BEL-C18	Tiebeam 6	93	h/s	1327	1419	1419
BEL-C19	Ridge, bay 2	49	h/s	----	----	----
BEL-C20	Outer lintel	NM	--	----	----	----
BEL-C21	Inner lintel	64	--	----	----	----

NM = not measured; h/s = the heartwood/sapwood boundary is the last-measured ring; C = complete sapwood retained on sample, AD_{DR}= radiocarbon-supported ring-width dendrochronology

Table 2: Results of the cross-matching of site sequence BELCSQ01 and the reference chronologies when the first-ring date is AD 1327$_{DR}$ *and the last-ring date is AD 1428*$_{DR}$

Reference chronology	*t*–value	Span of chronology	Reference
Hallgarth Manor Cottages, Hallgarth, Pittington, County Durham	6.9	AD 1336–1624	Howard *et al* 2001
The Hallgarth, HM Prison, Durham, County Durham	5.8	AD 1349–1464	Howard *et al* 1992
Central Tower, Durham Cathedral, Durham, County Durham	5.6	AD 1345–1628	Bridge and Tyers 2019
Calverley Old Hall, Calverley, West Yorkshire	5.3	AD 1261–1585	Arnold *et al* forthcoming
Tunstall Hall Farm, Hartlepool, Cleveland	5.2	AD 1316–1484	Howard *et al* 2002
Witton Hall Farm, Witton Gilbert, County Durham	5.2	AD 1342–1441	Howard *et al* 1996
Auckland Castle, Bishop Auckland, County Durham	5.1	AD 1370–1520	Arnold and Howard 2013
St Lawrence's Church, Warkworth, Northumberland	4.7	AD 1324–1443	Arnold and Howard 2010
Aisled Barn, Newark, Nottinghamshire	4.7	AD 1249–1399	Laxton *et al* 1984
Kepier Farm Hospital, Durham	4.6	AD 1304–1522	Howard *et al* 1996

Table 3: Results of the cross-matching of site sequence BELCSQ01 and the reference chronologies when the first-ring date is AD 1489 and the last-ring dates is AD 1590

Reference chronology	*t*–value	Span of chronology	Reference
Wimpole Church, Cambridgeshire	7.1	AD 1469–1615	Bridge 1998
De Grey Mausoleum, Flitton, Bedfordshire	5.6	AD 1510–1726	Arnold *et al* 2003
Knole, Kent	5.5	AD 1323–1541	Arnold *et al* 2008
Old Coach House, London	5.2	AD 1504–1591	Arnold and Howard 2012
Sherborne House, Newland, Dorset	5.1	AD 1540–1670	Bridge 2014
Aslackby Manor, Lincolnshire	5.0	AD 1525–1598	Arnold and Howard 2011 unpubl
Ballingdon Bridge, Sudbury, Suffolk	4.9	AD 1484–1790	Tyers 2002
Old Clarendon Building, Oxford, Oxfordshire	4.9	AD 1539–1711	Miles and Worthington 2006
Crowle Court Barn, Worcestershire	4.7	AD 1497–1589	Hillam 1997
Riding House, St Giles House, Wimborne St Giles, Dorset	4.7	AD 1411–1615	Bailiff *et al* 2017

Table R4: Belsay Castle radiocarbon and stable isotope results. Replicate measurements have been tested for statistical consistency and combined by taking a weighted mean before calibration as described by Ward and Wilson (1978; T'(5%)=3.8, ν=1)

Laboratory number	Sample reference	Material & context	$\delta^{13}C_{IRMS}$ (‰)	Radiocarbon Age (BP)
OxA-36582	BEL-C17, Ring 80A	*Quercus* sp. heartwood, BEL-C17 ring 80 , relative year 98 of the 102 year chronology BELCSQ01	−25.4±0.2	466±24
SUERC-76340	BEL-C17, Ring 80B	Replicate of OxA-36582	−23.9±0.2	499±24
^{14}C: 483±17 BP, T'=0.9; $\delta^{13}C$: −24.2±0.15‰, T'=4.5				

FIGURES

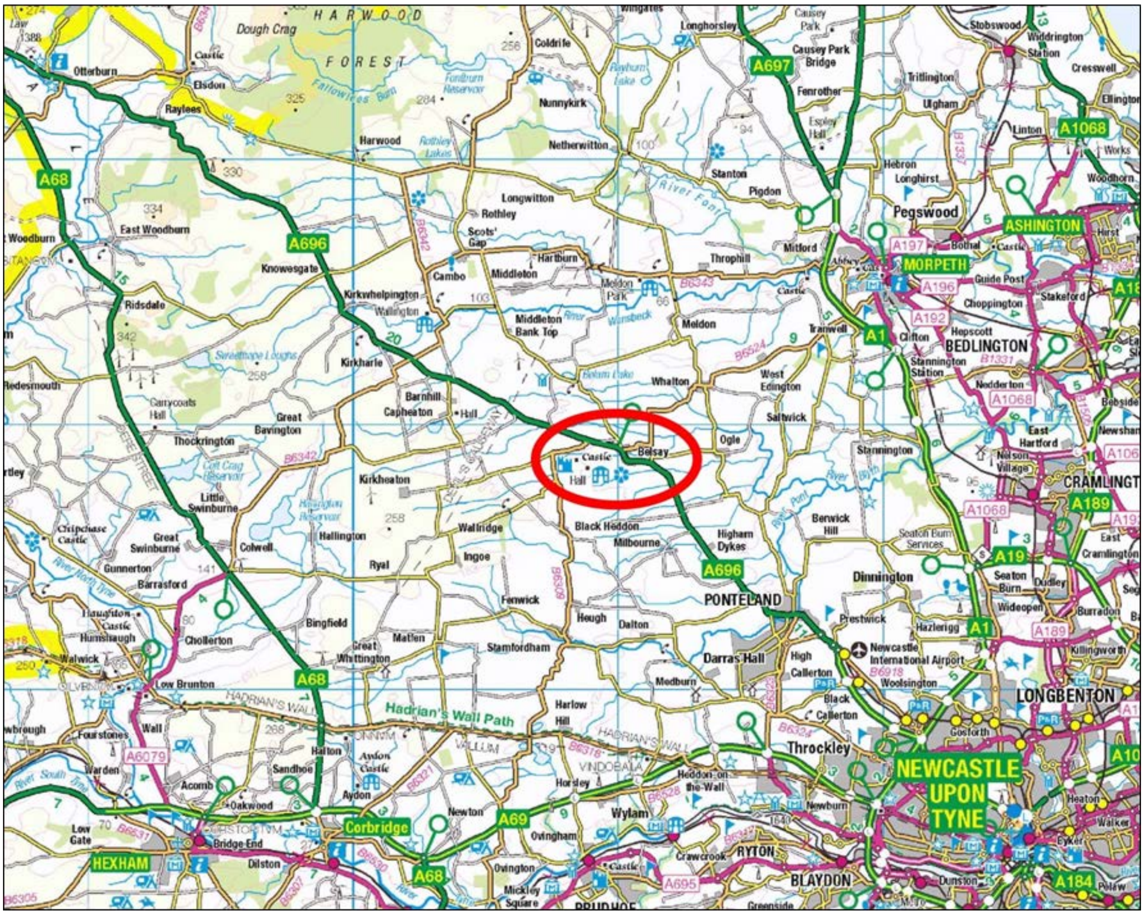

Figure 1: Map to show the general location of Belsay, Northumberland (red ellipse). ©Crown Copyright and database right 2018. All rights reserved. Ordnance Survey Licence number 100024900

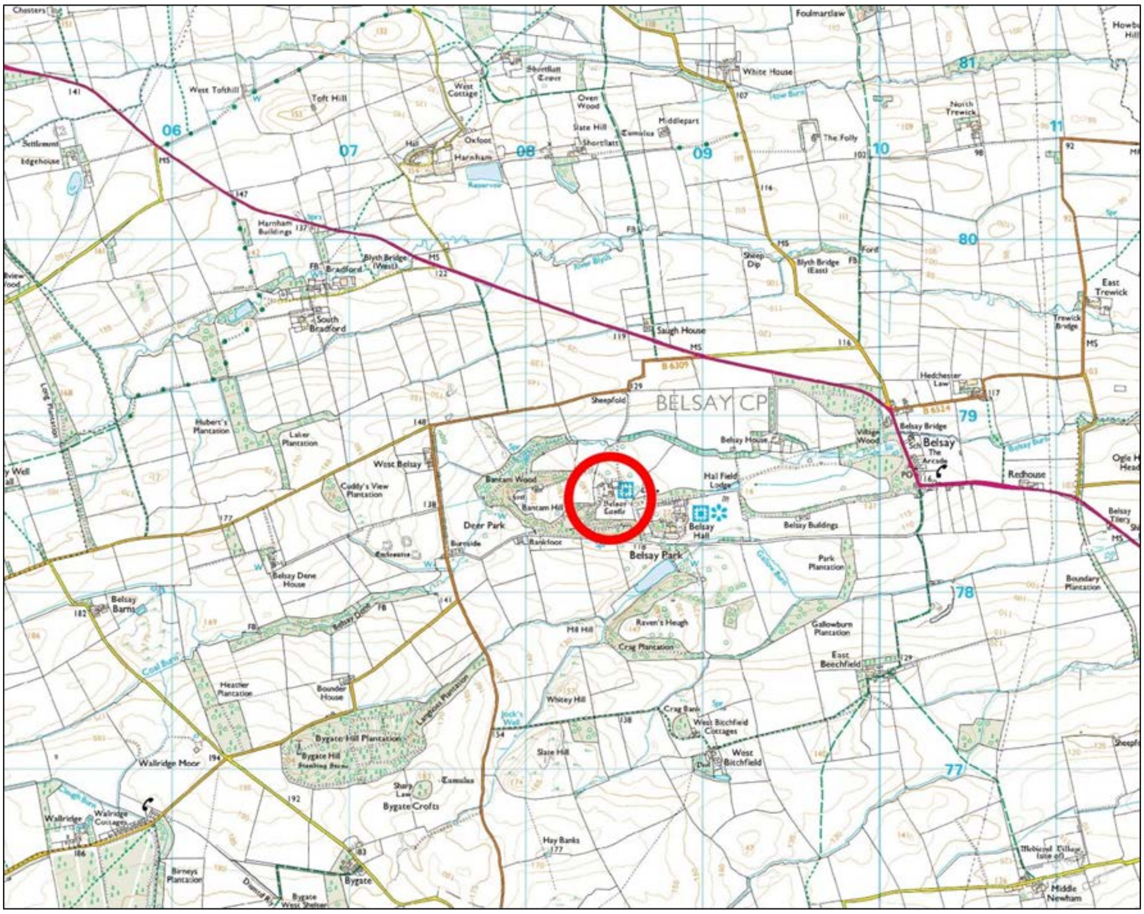

Figure 2: Map to show the location of Belsay Castle in relation to Belsay (red ellipse). ©Crown Copyright and database right 2018. All rights reserved. Ordnance Survey Licence number 100024900

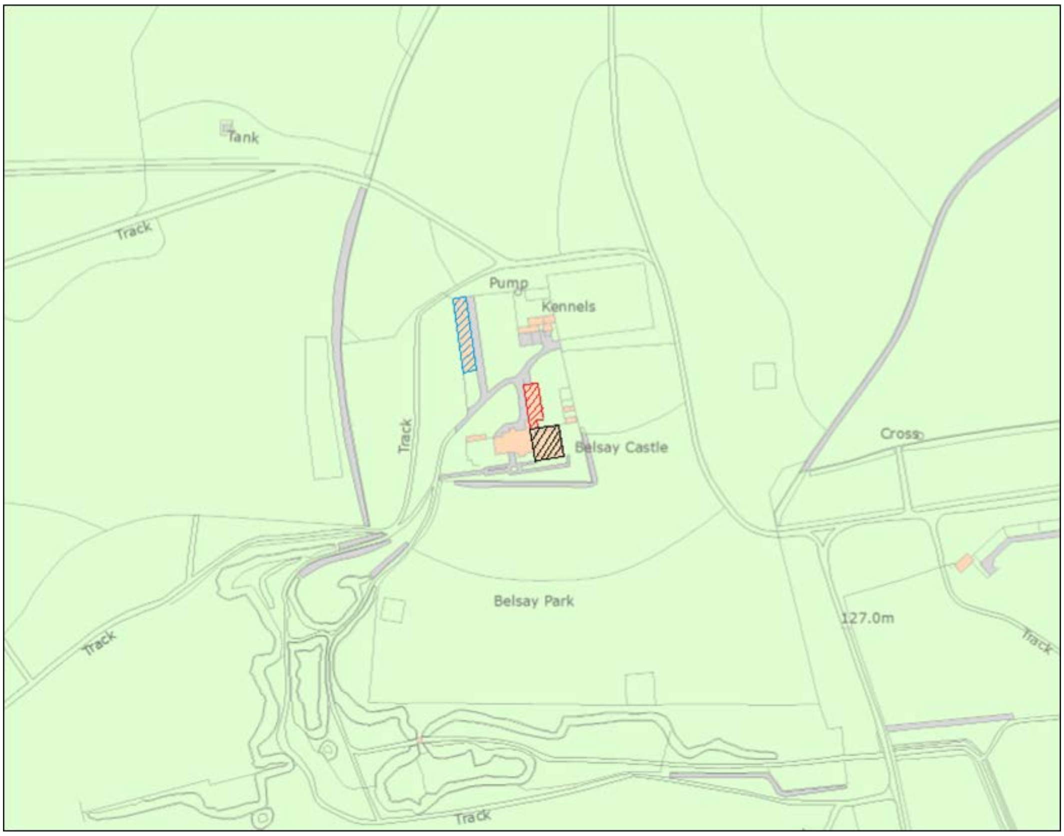

Figure 3: Map to show the Castle tower (black), the annexe (red), and the Stables/Coach house (blue). ©Crown Copyright and database right 2018. All rights reserved. Ordnance Survey Licence number 100024900

Figure 4: Castle tower and annexe, photograph taken from the south (Alison Arnold)

Figure 5: Castle tower; roof, truss 5 in foreground, photograph taken from the north (Alison Arnold)

Figure 6: Portion of exposed floor frame from the annexe, photograph taken from the east (Alison Arnold)

Figure 7: Coach house (to the right) & stables, photograph taken from the west (Alison Arnold)

Figure 8: Lintels over the Coach house entrance, photograph taken from the east (Alison Arnold)

Figure 9: Surviving historic timbers; door lintel, supporting beams, and a floor beam, photograph taken from the north (Alison Arnold)

Figure 10: Stable block; remnants of floor joists, photograph taken from the west (Alison Arnold)

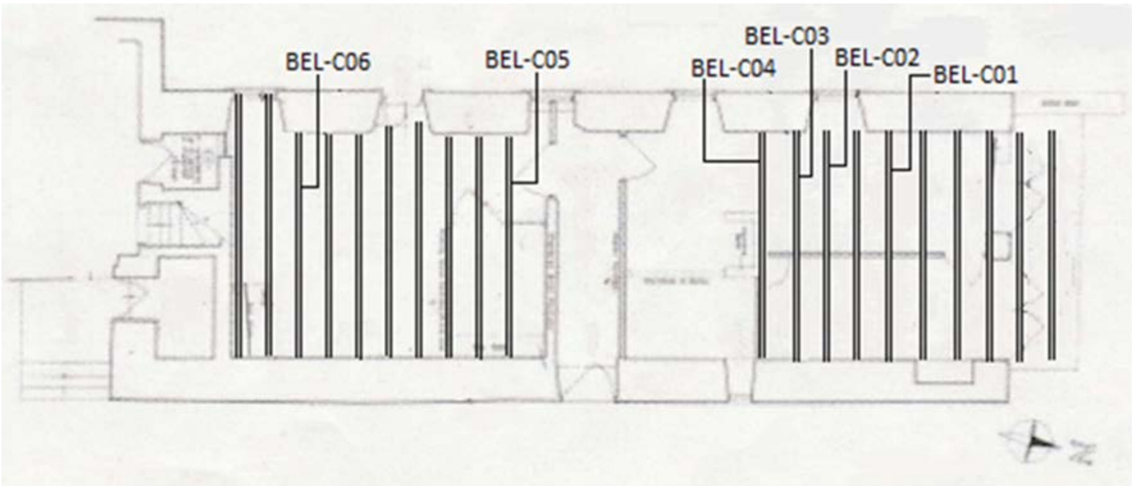

Figure 11: Ground-floor plan of the annexe, showing the location of samples BEL-C01–06 (provided by Simon Taylor)

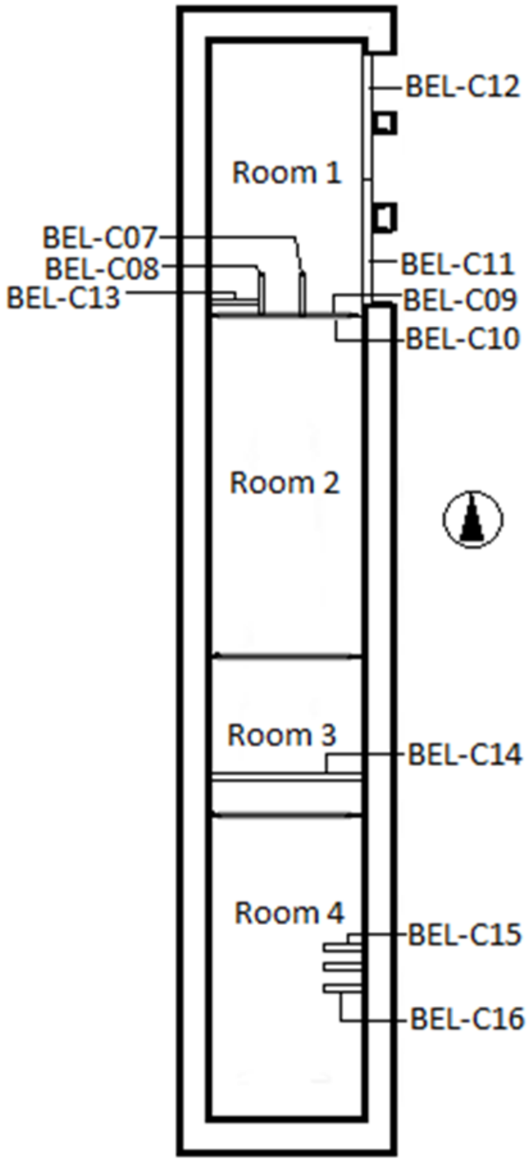

Figure 12: Sketch plan of the Coach house & Stables, showing the location of samples BEL-C07–16

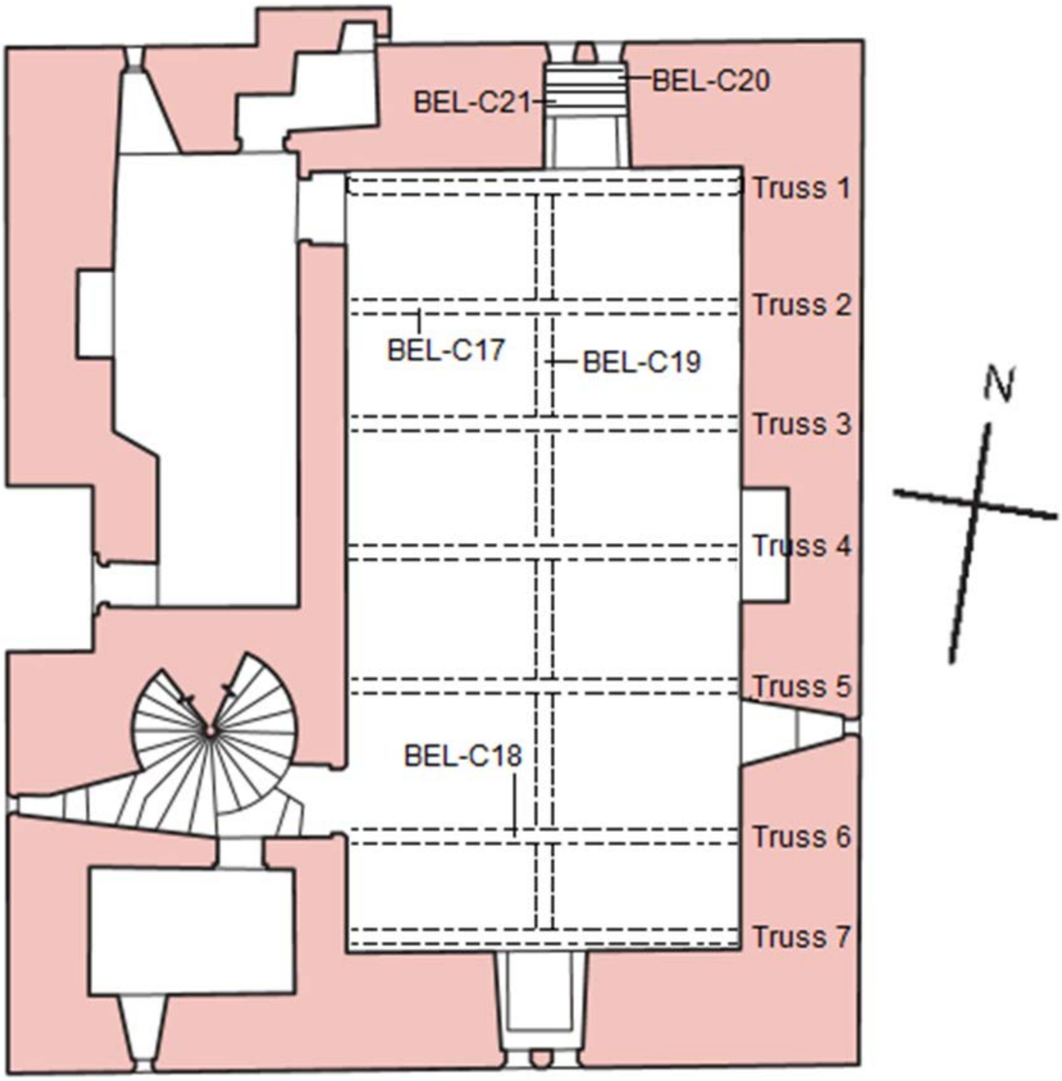

Figure 13: Plan of Castle tower, showing the location of samples BEL-C17–21

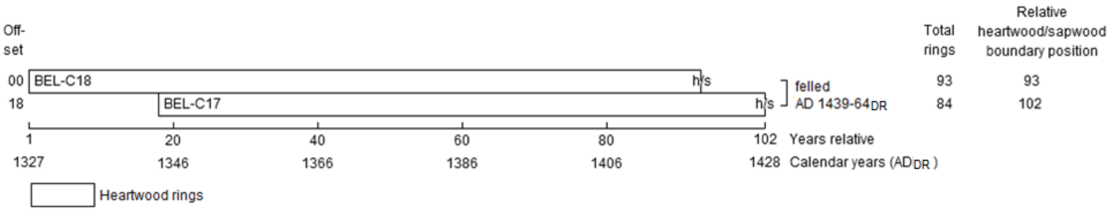

Figure 14: Bar diagram to show the relative position of samples in site sequence BELCSQ01

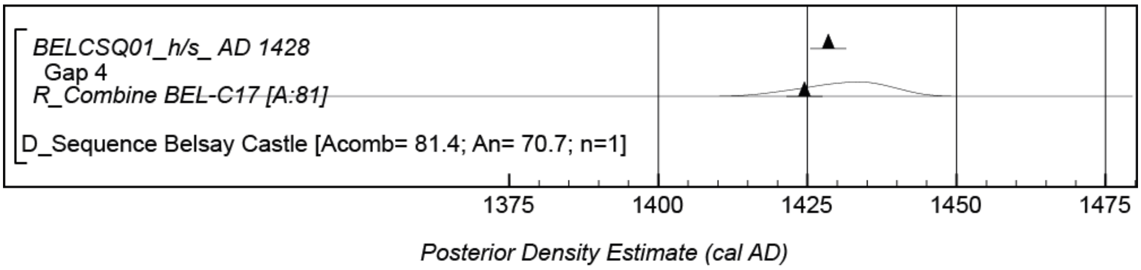

Figure 15: Probability distribution of the date from BELCSQ01. The distribution represents the relative probability that an event occurs at a particular time. For the date two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence incorporating the potential tree-ring date for the final ring of undated site sequence BELCSQ01 - AD 1428. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

DATE OF MEASURED SAMPLES

BEL-C01A 95
238 174 133 147 133 164 115 101 106 107 115 139 127 125 150 186 148 185 164 176
171 160 126 142 82 84 95 117 177 128 128 119 117 92 109 67 123 124 109 105
65 72 81 102 110 105 79 57 51 63 51 67 46 53 34 36 47 36 28 31
31 33 36 37 32 37 36 47 49 28 32 41 33 38 29 27 12 18 18 23
25 30 30 33 34 29 26 36 63 51 46 27 30 33 37
BEL-C01B 94
236 178 133 150 141 168 112 102 109 110 115 144 125 126 152 188 156 185 164 177
171 163 125 136 86 84 100 114 177 123 135 118 118 96 110 66 106 114 112 106
69 65 84 103 107 103 72 62 53 56 54 67 43 51 35 39 38 41 28 27
35 33 36 37 34 38 35 41 56 24 31 42 33 37 35 23 14 15 18 22
28 26 29 33 35 28 25 38 51 51 54 30 26 52
BEL-C02A 45
360 341 328 202 261 261 227 273 288 187 254 225 267 287 240 220 171 178 219 229
221 215 191 157 214 270 237 233 214 134 138 126 148 168 140 121 174 141 174 122
119 115 139 98 122
BEL-C02B 45
421 353 326 203 268 251 224 269 293 187 253 223 263 291 231 222 179 171 226 227
235 214 202 172 207 266 242 228 211 143 144 119 154 168 135 123 172 147 173 128
117 115 135 92 117
BEL-C03A 199
66 105 52 58 55 47 37 20 17 31 18 22 30 27 27 21 27 19 32 39
59 54 103 80 57 55 49 76 44 35 65 42 67 108 96 72 94 55 94 59
77 93 48 42 54 72 52 41 61 45 55 44 71 99 79 86 103 89 95 69
82 83 66 124 109 99 87 64 65 78 59 59 79 69 80 61 66 66 75 66
61 55 43 47 64 55 59 56 76 70 70 37 64 57 63 44 69 94 54 53
29 22 22 21 18 30 21 19 19 20 26 29 19 24 34 20 24 26 30 26
44 32 47 37 44 52 60 75 69 63 53 40 70 103 43 44 63 35 47 67
59 44 15 14 27 37 33 39 25 35 38 30 23 32 40 31 34 45 46 53
27 34 26 34 62 44 90 65 43 53 56 64 78 98 87 93 67 107 101 121
120 191 108 103 90 74 63 50 69 64 58 51 49 40 59 70 72 63 61
BEL-C03B 199
79 105 51 58 59 49 34 22 18 28 19 24 33 26 26 20 22 28 31 51
60 53 101 86 60 52 53 90 44 34 61 37 69 91 97 86 98 64 93 66
74 88 52 41 49 68 55 36 56 40 53 44 69 92 90 99 109 88 96 64
94 79 64 125 111 98 82 69 76 71 62 56 81 76 81 53 64 65 73 74
63 53 43 57 68 53 60 49 80 66 68 44 68 61 56 40 69 85 58 58
25 23 26 24 19 32 20 16 18 21 25 31 24 18 31 19 28 29 26 31
41 30 41 43 49 56 59 75 70 69 48 43 75 97 40 51 56 33 49 61
63 41 15 13 27 32 33 35 27 37 37 35 22 29 40 29 32 52 49 48
22 35 27 33 57 50 85 61 48 55 58 65 85 88 98 94 65 93 100 123
118 209 97 114 88 78 59 53 72 56 60 54 48 39 65 53 85 63 52
BEL-C04A 47
301 297 316 278 242 241 321 342 277 330 209 290 353 338 280 355 309 212 202 286
169 190 156 154 163 175 167 130 119 182 117 117 124 178 128 179 176 147 114 128
120 139 106 123 165 97 99
BEL-C04B 47
326 296 305 282 240 250 322 324 267 327 208 296 351 340 274 359 308 205 200 291
164 190 154 155 163 173 168 132 118 181 116 114 117 175 132 184 172 144 117 120
136 120 129 120 160 99 104
BEL-C05A 118
314 127 135 186 92 61 111 129 140 103 51 62 74 60 56 72 94 85 98 129
166 121 174 145 154 79 93 89 73 86 97 81 103 71 88 106 140 118 122 140
113 102 101 104 102 103 82 89 107 121 123 123 78 54 44 30 51 68 103 89
111 103 99 110 62 50 37 39 46 57 48 52 59 89 105 150 132 111 107 83
74 63 55 45 48 52 57 45 27 22 12 41 13 19 25 22 18 14 18 13

17 16 18 15 23 17 22 15 9 11 12 22 28 14 20 20 9 22
BEL-C05B 91
305 132 135 186 86 70 103 137 147 97 53 63 69 64 53 80 91 86 97 128
165 126 164 147 153 83 89 92 70 92 91 84 102 75 81 114 141 110 125 141
115 103 98 100 107 99 82 90 111 118 119 123 82 51 42 30 49 71 101 87
110 104 98 107 68 46 39 45 48 52 49 51 58 96 90 154 131 111 111 84
67 64 55 42 54 52 56 47 27 21 12
BEL-C07A 62
321 340 287 267 227 180 194 156 217 231 263 237 286 392 333 325 282 165 180 162
272 258 202 292 387 425 384 276 453 537 485 394 246 120 241 320 344 306 211 258
134 121 133 212 227 192 249 133 96 147 108 138 70 66 87 104 97 87 114 119
144 144
BEL-C07B 62
289 336 279 274 222 180 186 162 223 229 262 253 279 390 337 314 284 167 178 163
274 248 209 294 383 438 393 304 459 559 494 411 264 119 218 321 349 298 197 228
132 103 151 216 227 188 252 125 104 146 99 135 82 60 87 114 97 83 111 133
129 150
BEL-C08A 60
251 173 166 111 156 168 192 205 202 185 133 173 331 324 232 197 206 244 318 240
178 138 141 167 140 111 145 134 191 111 179 194 263 196 188 245 139 130 194 28
39 37 40 50 49 36 41 52 73 52 54 42 28 30 34 40 29 42 23 22
BEL-C08B 60
260 188 185 116 126 159 186 189 188 185 138 203 353 312 239 197 203 256 340 244
182 145 136 158 144 111 150 131 184 102 170 176 252 170 180 231 138 115 185 43
42 36 36 54 50 39 37 68 70 45 60 41 30 27 38 42 31 43 18 25
BEL-C09A 175
97 129 109 120 152 110 105 134 143 126 87 89 77 80 76 69 67 63 45 64
85 67 74 92 103 74 61 79 105 73 97 138 194 107 106 120 121 129 133 146
109 103 152 153 123 143 126 139 132 138 113 102 170 187 187 181 202 179 185 116
77 127 159 186 118 137 192 258 245 157 145 142 190 232 238 179 167 141 194 257
182 194 127 132 114 158 189 143 116 155 175 177 125 100 120 146 125 130 149 146
145 134 114 94 114 83 94 124 114 97 69 96 94 75 104 91 83 98 122 86
51 51 46 57 58 45 38 44 62 41 34 33 41 45 53 40 43 40 56 60
57 62 60 64 62 53 63 70 72 51 53 45 55 52 58 46 44 51 46 62
49 32 33 41 45 50 50 43 41 35 40 36 49 32 40
BEL-C09B 175
103 126 114 121 151 112 107 131 140 121 93 88 79 81 75 69 64 65 54 56
87 69 70 96 96 71 65 78 98 80 91 137 197 108 119 114 121 128 137 136
118 109 149 158 124 120 146 148 133 134 112 99 171 188 188 175 212 186 197 115
81 122 154 169 128 146 202 269 245 167 137 147 192 221 243 183 169 141 200 259
186 203 133 123 126 149 191 139 116 160 166 171 135 96 122 154 121 128 149 146
146 132 125 91 115 89 92 122 112 98 73 97 98 75 98 97 81 98 127 86
50 48 47 61 50 51 38 40 67 39 39 29 38 45 55 43 38 38 55 62
63 62 59 65 57 52 63 75 78 55 47 47 48 60 54 45 47 48 47 59
55 33 45 30 43 49 53 45 45 33 37 37 47 27 36
BEL-C10A 56
182 216 249 252 218 203 221 207 232 197 197 207 230 180 146 156 134 133 127 166
137 157 149 175 158 118 131 112 100 105 89 109 155 169 160 148 109 100 103 168
123 108 105 140 126 136 123 96 130 112 109 93 80 72 85 100
BEL-C10B 56
175 209 243 254 217 202 220 213 228 199 193 171 272 186 145 159 134 127 126 174
137 159 147 177 156 112 130 112 98 113 83 106 160 164 170 147 102 102 100 168
126 116 105 152 138 129 121 97 112 118 106 92 82 70 83 94
BEL-C12A 73
129 135 155 162 143 113 115 172 172 130 138 175 191 152 129 101 176 166 222 119
133 98 135 112 86 121 157 81 112 146 142 124 150 117 151 128 141 144 162 92
151 110 97 110 108 117 109 161 125 110 129 118 142 117 178 154 142 149 173 130
90 120 100 91 84 104 101 106 98 117 90 123 135
BEL-C12B 66

118 97 157 150 168 176 262 288 218 210 185 257 215 224 149 185 149 214 158 114
123 162 78 123 123 104 104 148 111 125 128 127 136 159 98 122 73 74 98 105
152 122 184 126 116 102 87 122 105 142 136 158 141 159 132 99 86 56 89 64
85 70 82 87 114 112
BEL-C13A 74
218 253 236 239 195 163 160 285 253 301 215 314 242 269 260 249 143 169 199 201
235 272 248 212 183 252 202 197 200 194 210 199 186 113 154 187 142 154 150 195
145 119 96 127 106 87 73 74 75 111 90 129 121 75 85 72 71 61 90 101
110 113 108 93 97 101 86 89 83 78 107 110 138 140
BEL-C13B 74
228 241 223 248 196 166 157 271 249 297 217 302 248 262 262 238 146 165 193 203
241 259 261 202 178 246 202 199 198 191 209 208 186 112 155 188 148 157 146 186
138 109 97 146 104 84 78 79 71 116 90 141 113 73 84 77 67 60 89 91
118 112 109 102 96 104 90 89 79 81 106 120 149 154
BEL-C14A 91
200 260 250 231 254 229 194 202 245 236 195 228 300 286 238 202 164 140 168 185
201 223 230 186 211 167 124 156 142 132 156 119 111 98 160 144 140 148 154 144
151 75 69 55 53 55 67 71 67 84 117 81 92 81 107 82 92 138 86 72
118 89 70 71 75 98 83 80 95 85 78 76 70 66 76 71 58 55 41 56
64 76 71 59 47 41 53 64 61 57 51
BEL-C14B 91
200 259 238 244 256 217 209 218 264 236 203 227 289 276 234 206 163 139 162 187
209 218 212 200 203 172 125 160 141 132 156 122 110 99 163 142 124 152 155 141
140 79 73 46 52 61 70 77 73 88 129 83 88 79 118 80 87 121 97 69
129 105 62 79 81 105 84 87 110 75 70 68 55 62 79 76 55 59 39 60
60 85 63 63 51 51 47 64 58 60 45
BEL-C15A 112
55 41 114 54 77 106 144 89 109 74 145 77 69 57 45 35 40 31 28 52
62 70 82 80 100 96 51 49 60 81 98 122 128 149 143 118 100 133 120 129
65 65 82 104 81 82 105 128 93 123 56 62 90 80 95 96 114 94 76 102
46 53 43 66 74 81 103 75 69 58 56 58 61 55 48 51 50 62 43 67
60 75 69 87 66 87 82 88 64 72 84 84 89 99 105 79 90 121 108 98
111 76 61 52 73 99 74 73 93 59 37 44
BEL-C15B 112
47 41 113 51 83 109 140 91 109 76 146 75 68 62 42 37 37 42 24 53
66 70 86 78 111 90 56 47 66 94 96 123 120 160 140 116 116 134 109 136
68 64 79 118 77 87 105 118 96 117 62 61 81 86 92 95 119 96 81 102
53 55 43 58 77 81 97 81 75 55 52 63 60 61 50 44 54 59 46 65
63 78 66 83 67 98 83 79 62 68 89 72 78 126 108 82 83 121 109 104
100 82 62 59 80 100 72 77 80 63 43 44
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43 48 62 41 46 27 41 34 35 64 85 78 63 173 456 265 257 159 117 95
127 126 140 177 175 165 240 77 105 93 119 106 145 122 115 149 165 164 167 121
81 135 125 147 109 104 104 178 125 108 165 138 131 170
BEL-C16B 54
41 46 59 40 52 24 37 34 34 69 83 84 65 134 481 264 239 160 102 91
109 113 142 189 187 167 212 76 104 104 115 114 150 127 108 138 170 170 164 122
79 141 126 144 116 101 106 168 130 108 172 132 139 163
BEL-C17A 84
327 510 519 582 838 516 646 564 608 654 394 631 599 390 517 417 374 267 405 290
428 442 435 231 325 232 289 394 345 342 431 360 341 302 335 268 289 314 307 264
203 272 261 276 210 157 217 219 328 264 217 255 236 212 200 269 184 169 246 198
184 168 222 199 295 170 212 176 182 164 176 181 192 234 163 188 212 233 261 249
215 163 173 143
BEL-C17B 84
330 500 475 592 807 503 631 546 607 647 396 644 600 377 519 411 376 262 403 295
423 441 434 234 322 231 286 395 349 340 430 362 340 307 334 275 292 315 293 267
213 281 264 285 208 166 219 230 335 276 213 253 241 211 204 270 184 178 240 198
173 168 217 200 295 166 214 179 180 184 177 179 194 233 164 192 203 228 259 253

219 164 165 143
BEL-C18A 93
137 149 109 132 153 168 82 100 143 126 137 165 106 102 139 185 185 158 177 196
225 309 457 319 261 248 319 284 177 270 297 324 476 280 217 136 135 120 155 173
229 267 366 373 338 264 189 176 287 205 202 207 308 375 460 455 487 314 179 260
278 268 278 228 378 432 656 436 281 333 295 321 293 321 299 276 436 290 262 353
409 381 386 251 369 296 328 394 369 286 351 392 233
BEL-C18B 93
127 143 117 119 154 138 109 105 137 133 144 161 115 111 120 188 192 166 180 199
221 311 444 325 267 244 316 293 174 268 290 322 475 305 228 132 135 125 160 172
213 229 378 391 338 255 191 183 295 212 194 207 311 386 459 466 501 318 179 247
265 237 266 233 361 438 622 410 290 345 285 309 280 321 304 283 427 288 263 343
399 379 378 237 351 293 364 359 361 279 358 369 216
BEL-C19A 49
470 427 315 199 197 230 157 179 184 140 131 140 150 148 202 243 272 345 346 364
434 405 424 406 456 386 362 356 362 410 302 314 389 277 413 399 302 396 416 435
461 457 562 552 371 538 616 560 543
BEL-C19B 49
464 431 308 202 194 221 162 176 186 139 135 137 147 143 210 242 267 348 329 354
382 371 429 408 456 387 364 345 361 417 302 314 391 277 416 396 299 388 431 436
471 467 571 559 383 539 617 565 559
BEL-C21A 64
263 171 220 229 388 381 362 239 178 183 141 150 133 149 187 130 178 147 161 184
146 140 159 158 129 159 214 249 233 270 198 215 206 197 197 146 146 171 147 157
119 110 137 121 102 81 131 107 110 134 123 136 152 127 106 121 148 141 121 122
136 149 138 177
BEL-C21B 64
256 176 213 232 365 364 356 225 184 184 135 145 119 153 185 125 162 136 154 176
151 161 165 175 125 160 219 242 237 275 208 213 217 197 208 160 156 176 139 166
130 118 137 119 98 84 122 114 105 134 126 136 150 130 103 118 162 136 119 109
140 146 134 167

APPENDIX TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1998). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

If the bark is still on the sample, as in Figure A1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction or soon after. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

The Practice of Tree-Ring Dating at the Nottingham Tree-Ring Dating Laboratory

1. **Inspecting the Building and Sampling the Timbers**. Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample in situ timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are

sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

To ensure that we are getting the date of the building as a whole, or the whole of a phase of construction if there is more than one, about 8–10 samples per phase are usually taken. Sometimes we take many more, especially if the construction is complicated. One reason for taking so many samples is that, in general, some will fail to give a date. There may be many reasons why a particular sequence of ring widths from a sample of timber fails to give a date even though others from the same building do. For example, a particular tree may have grown in an odd ecological niche, so odd indeed that the widths of its rings were determined by factors other than the local climate! In such circumstances it will be impossible to date a timber from this tree using the master sequence whose widths, we can assume, were predominantly determined by the local climate at the time.

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure A2; it is about 150mm long and 10mm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost in coring. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

During the initial inspection of the building and its timbers the dendrochronologist may come to the conclusion that, as far as can be judged, none of the timbers have sufficient rings in them for dating purposes and may advise against sampling to save further unwarranted expense.

All sampling by the Laboratory is undertaken according to current Health and Safety Standards. The Laboratory's dendrochronologists are insured.

Figure A1: A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting

Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

Figure A3: Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measured twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis

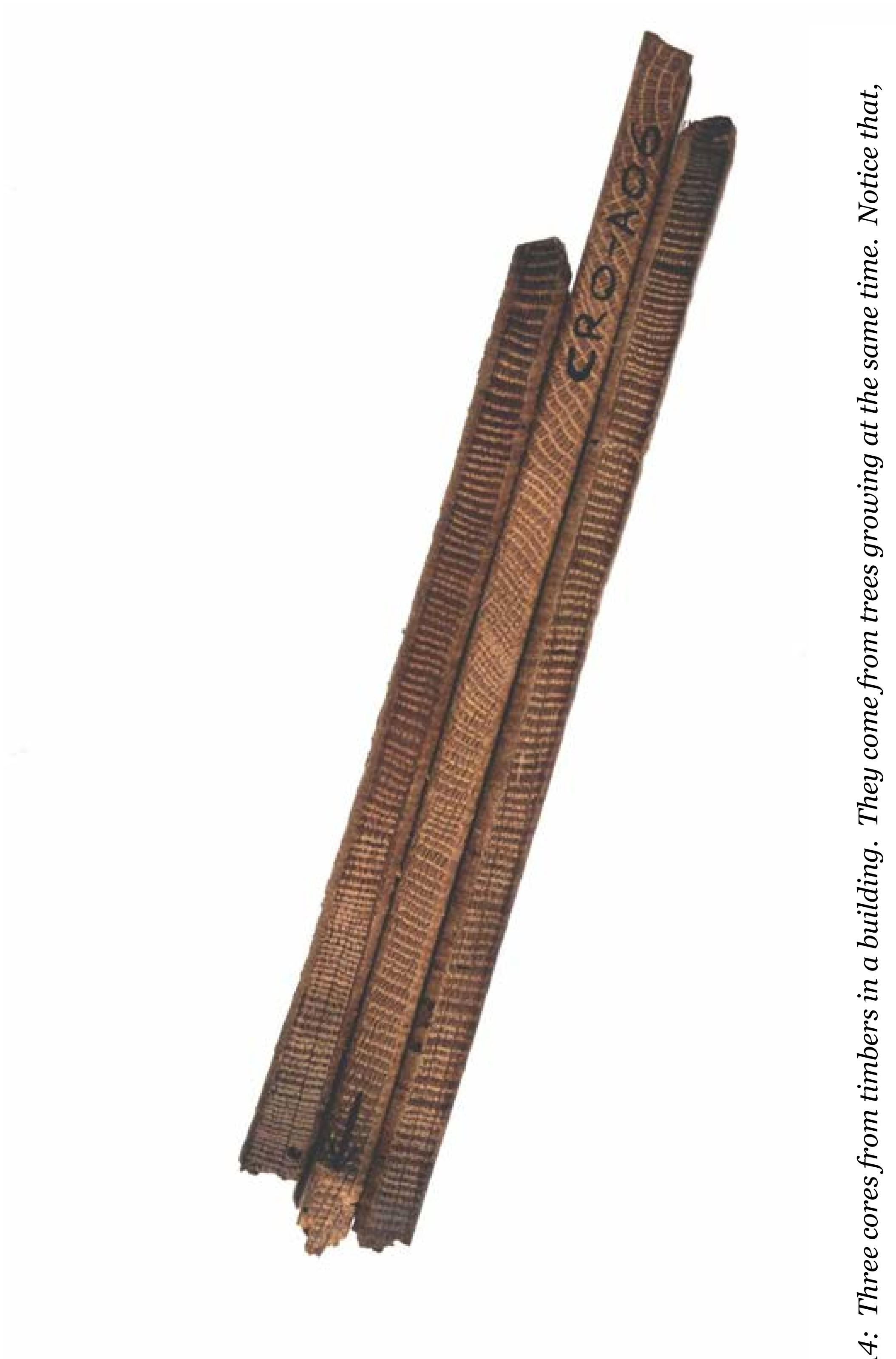


Figure A4: Three cores from timbers in a building. They come from trees growing at the same time. Notice that,

2. **Measuring Ring Widths**. Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure A2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig A3).

3. **Cross-Matching and Dating the Samples**. Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig A4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t*-value (defined in almost any introductory book on statistics). That offset with the maximum *t*-value among the *t*-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a *t*-value of at least 4.5, and preferably at least 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton and Litton 1988; Laxton *et al* 1988; Howard *et al* 1984–1995).

This is illustrated in Figure A5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN-C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the bar diagram, as is usual, but the offsets at which they best cross-match each other are shown; eg the sequence of ring widths of C08 matches the sequence of ring widths of C45 best when it is at a position starting 20 rings after the first ring of C45, and similarly for the others. The actual *t*-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the *t*-value between C45 and C08 is 5.6 and is the maximum found between these two among all the positions of one sequence relative to the other.

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

The straightforward method of cross-matching several sample sequences with each other one at a time is called the 'maximal *t*-value' method. The actual method of cross-matching a group of sequences of ring-widths used in the Laboratory involves grouping and averaging the ring-width sequences and is called the 'Litton-Zainodin Grouping Procedure'. It is a modification of the straightforward method and was successfully developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988).

4. Estimating the Felling Date. As mentioned above, if the bark is present on a sample, then the date of its last ring is the date of the felling of its tree (or the last full year before felling, if it was felled in the first three months of the following calendar year, before any new growth had started, but this is not too important a consideration in most cases). The actual bark may not be present on a timber in a building, though the dendrochronologist who is sampling can often see from its surface that only the bark is missing. In these cases the date of the last ring is still the date of felling.

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called sapwood rings, are usually lighter than the inner rings, the heartwood, and so are relatively easy to identify. For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure A2, both indicated by arrows. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling.

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. Oak boards quite often come from the Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure A2 was taken still had complete sapwood but that some of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 20mm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

Even if all the sapwood rings are missing on a sample, but none of the heartwood rings are, then an estimate of the felling-date range is possible by adding on the full compliment of, say, 15 to 35 years to the date of the last heartwood ring (called the heartwood/ sapwood boundary or transition ring and denoted H/S). Fortunately it is often easy for a trained dendrochronologist to identify this boundary on a timber. If a timber does not have its heartwood/sapwood boundary, then only a post quem date for felling is possible.

5. Estimating the Date of Construction. There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998; Miles 1997, 50–5). Hence, provided that all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after (Laxton *et al* 2001, fig 8; 34–5, where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storage before use, or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

6. Master Chronological Sequences. Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Figure A6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Figure A6. We have a

master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. Ring-Width Indices. Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Figure A7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

t-value/offset Matrix

	C45	C08	C05	C04
C45		+20	+37	+47
C08	5.6		+17	+27
C05	5.2	10.4		+10
C04	5.9	3.7	5.1	

Bar Diagram

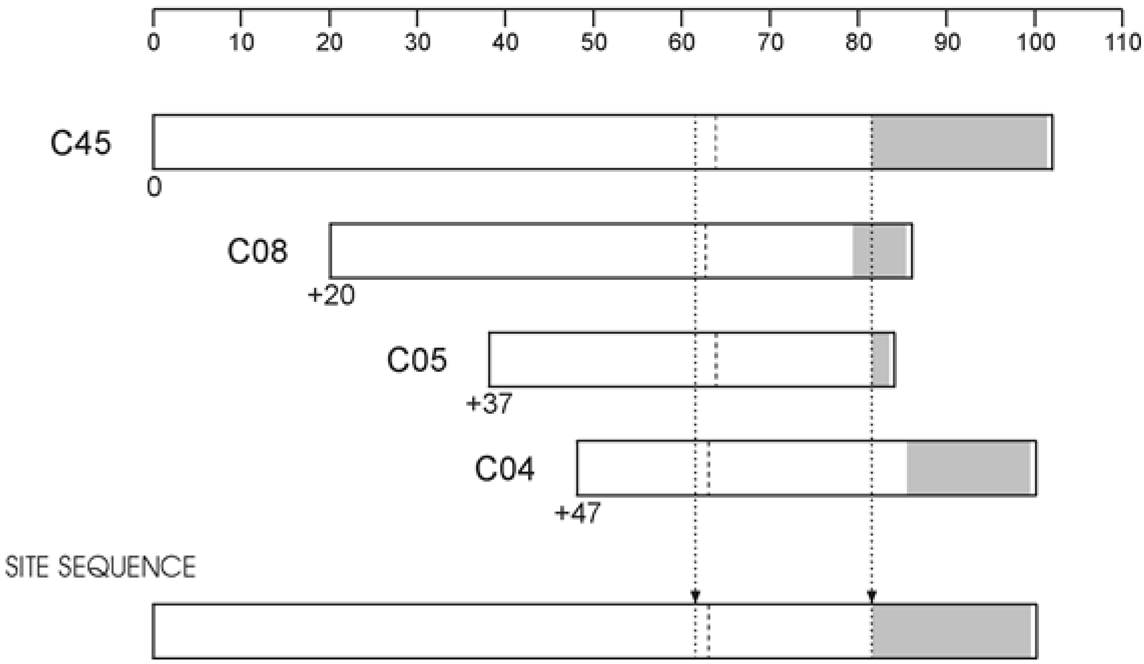


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

The bar diagram represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (offsets) to each other at which they have maximum correlation as measured by the *t*-values. The *t*-value/offset matrix contains the maximum *t*-values below the diagonal and the offsets above it. Thus, the maximum *t*-value between C08 and C45 occurs at the offset of +20 rings and the *t*-value is then 5.6. The site sequence is composed of the average of the corresponding widths, as illustrated with one width.

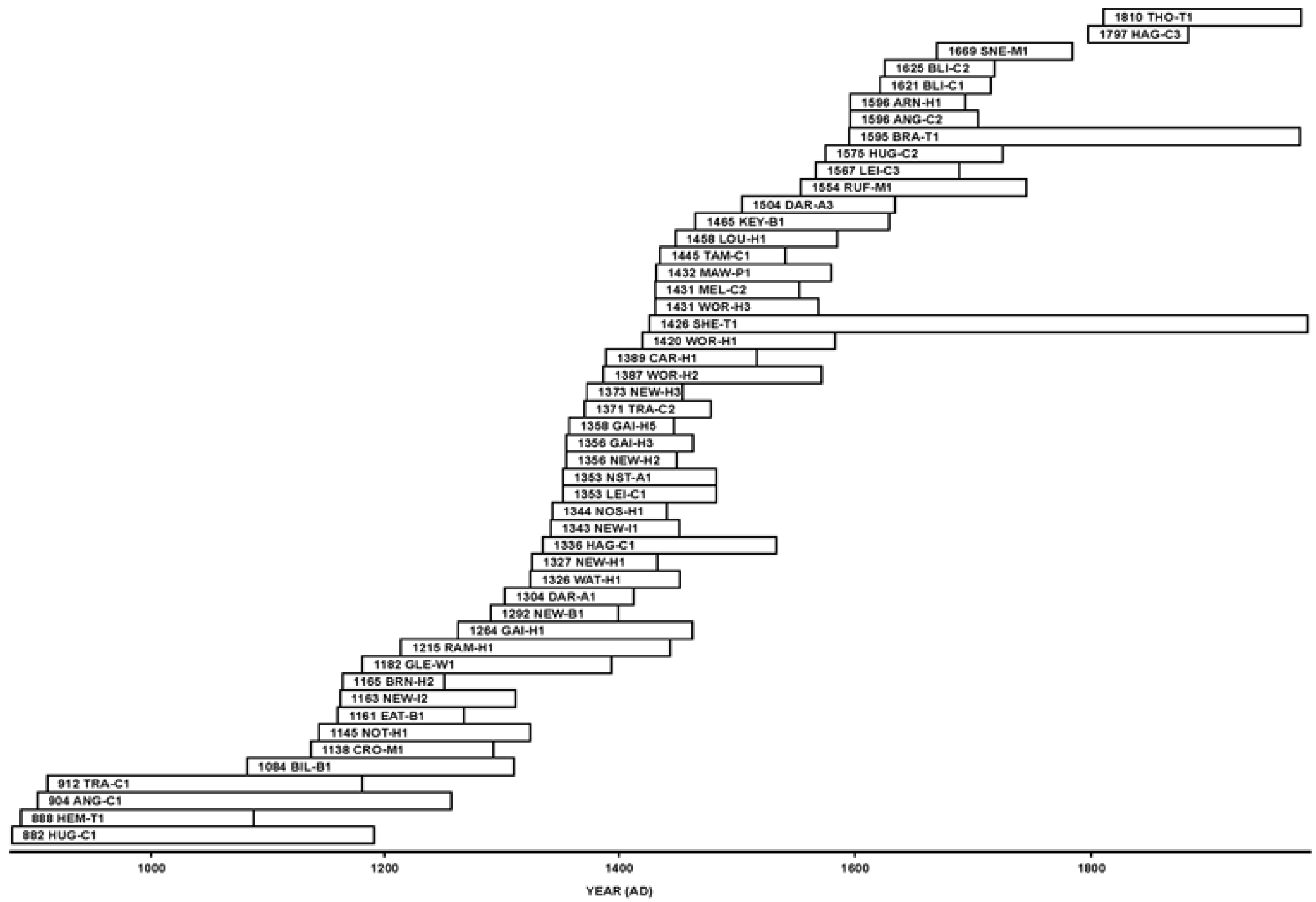
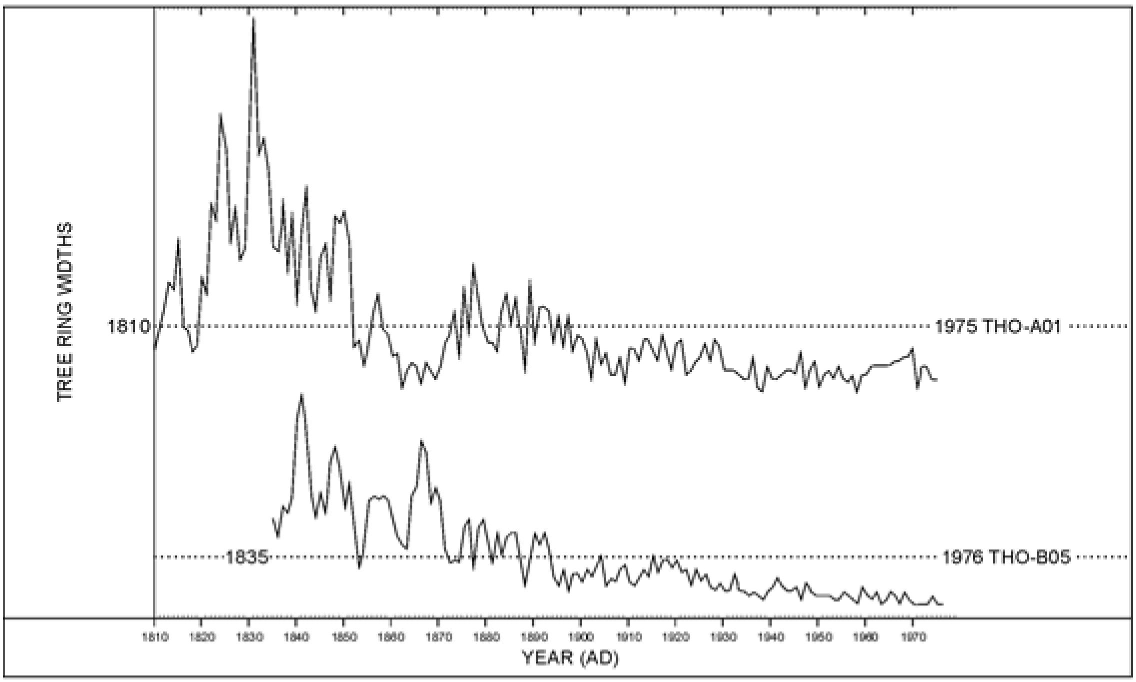


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

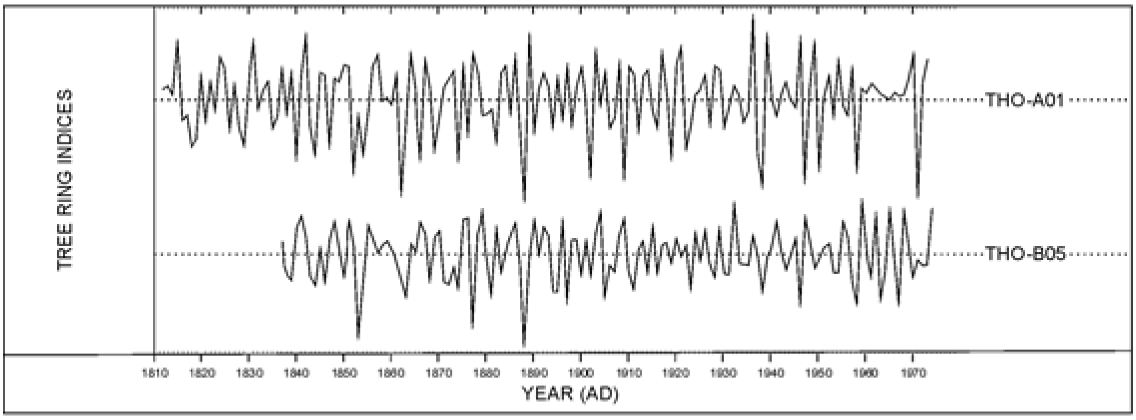


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences

Figure A7 (b): The Baillie-Pilcher indices of the above widths

The growth trends have been removed completely

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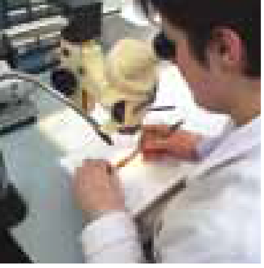
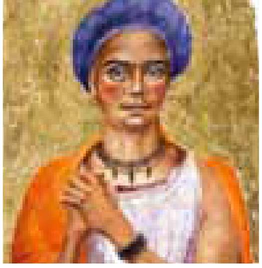


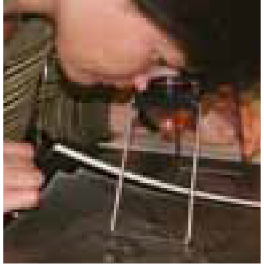


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