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Abbots Staith Buildings
Water Lane, Selby
North Yorkshire

Tree-ring Analysis of Timbers

Alison Arnold, Robert Howard, and Cathy Tyers

Discovery, Innovation and Science in the Historic Environment

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Front Cover: View of the north side of the Abbots Staith buildings from the east (DP311967) © Historic England Archive.

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SUMMARY
Dendrochronological analysis was undertaken on samples from 24 of the 27 timbers sampled in this building, the samples from the remaining timbers being unsuitable for reliable analysis. This analysis produced four oak site chronologies comprising series from seven, two, two, and three timbers respectively. Three of these oak chronologies were dated, spanning AD 1501–1576, AD 1416–1582, and AD 1555–1682. A further site chronology comprised two conifer samples but this, along with the fourth oak chronology, remains undated as do the remaining measured but ungrouped timber series.

Nine dated timbers, six joists, a trimmer beam, a door lintel and an *ex situ* timber, from the south wing are now known to have been felled in AD 1582, suggesting a programme of building works in the last decades of the sixteenth century. In addition, two ground-floor ceiling beams from the central range have been dated, probably having been felled in the spring of AD 1683, indicating a programme of building works occurring in the central wing a century later than that identified in the south wing.

CONTRIBUTORS
Alison Arnold, Robert Howard, and Cathy Tyers

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INTRODUCTION

The Scheduled Monument and Grade II* listed Abbots Staith Buildings (List Entry Number 1167663 here) is located in the Yorkshire town of Selby, close to the River Ouse (Fig 1). Originally, a two storey 'H-plan' structure, its original footprint has since been obscured by later buildings to the south and west. The doors all face the river, which would have provided the main access route from the river to the monastic complex, with the exception of that in bay 3, which faced the town. The upper storey of the South Wing was rebuilt in brick in the nineteenth century, whilst the upper storey of the North Wing no longer survives.

Where exposed, the ground-floor ceiling frame throughout the building is a mixture of historic beams, relatively modern looking timber beams, and steel joists. Within the South Wing there is a surviving section of historic ceiling frame which appears to be *in situ,* although other main beams and joists within this part of the building have been replaced (Fig 2). In the adjacent Central Range (bay 5) there is an *ex situ* main beam which is thought to have come from the South Wing (Fig 3). A single common joist within bay 3 of the Central Range also appears to fit in the original soffit of the main beam (Fig 4), and may be primary.

The main, external doorway into the South Wing is believed to be primary and retains its heavy timber lintel (Fig 5). The lintels over the rest of the external doorways have been replaced, or are inaccessible but those over the doorways, between bays and wings, do appear to be historic and potentially primary (Fig 6).

The building is thought to have been built by Selby Abbey in the fifteenth or early sixteenth century, possibly as warehousing and it is known to have had this function from the seventeenth century. The building is currently on the Heritage at Risk register because of its overall poor condition and slow decay.

SAMPLING

In 1997 sampling at the building was undertaken by the Sheffield University Dendrochronology Laboratory as a student training project, resulting in the removal of cores from 10 timbers and the removal of a cross-sectional slice from the *ex situ* timber; nine of these were oak (*Quercus* spp) and two were conifer. These were given the code SELBY and numbered 01–11. Four of the samples were rejected prior to measurement with either too few rings for dating purposes or the core had fragmented. No secure dating was obtained for any of the measured series at the time of the original analysis.

In 2018 further dendrochronological survey was requested by Nicky Brown (Historic England) in order to attempt to provide at least some independent dating evidence to inform decisions on appropriate interventions for repair and long-term care. Sampling was undertaken under the provision of Scheduled Monument Consent S17. Samples were obtained from 20 timbers (18 oak and two conifer) of which some had been sampled in 1997 but were re-sampled in an attempt to obtain longer ring sequences. Each of these samples were given the code ABB-T and numbered 01–20. In total samples were obtained from 27 timbers. Further details of all of the samples can be found in Table 1. The locations of samples from both phases of sampling have been marked on Figure 7. The central range is aligned north-west to south-east but for the purposes of this report is deemed to be aligned north to south (Fig 7). Bays have been numbered from north to south in the central range with bays and beams being numbered from east to west in the wings.

ANALYSIS AND RESULTS

One of the newly obtained samples taken from the floor-frame in the South Wing (ABB-T03) was found to have too few rings for secure dating purposes and so was rejected prior to measurement. The remaining 19 samples were prepared by sanding and polishing, and their growth-ring widths measured. The ring-width series from the two timbers that were both sampled and measured in 1997 and 2018 were compared and then combined to form single ring-width series for each timber (ABB-T10 v SELBY01, t = 19.0 at relative years 16–102; ABB-T11 v SELBY03, t = 8.8 at relative years 62–135). The ring-width series from each measured timber were then compared with each other by the Litton/Zainodin grouping programme (see Appendix). This resulted in 16 samples matching to form five groups. The data of all measurements are given at the end of the report.

Firstly, seven oak samples matched each other at a minimum t-value of 5.1 and were combined at the relevant offset positions to form ABBTSQ01, a site sequence of 76 rings (Fig 8). This site sequence was compared against a series of relevant reference chronologies for oak where it was found to match consistently and securely at a first-ring date of AD 1501 and a last-measured ring date of AD 1576. The evidence for this dating is given in Table 2.

Two oak samples also matched each other (t=7.3) and were again combined at the relative offset positions to form ABBTSQ02, a site sequence of 167 rings (Fig 9). This site sequence was found to span the period AD 1416–1582 (Table 3).

Two further oak samples also grouped (t=7.2) and were again combined at the relevant offset positions to form ABBTSQ03, a site sequence of 128 rings (Fig 10). Comparison against the reference chronologies found this site sequence spanned the period AD 1555–1682 (Table 4).

Three more oak samples were grouped at a minimum t-value of 9.9 and combined to form ABBTSQ04, a site sequence of 92 rings (Fig 11). Finally, two conifer samples matched each other (t=12.6) and were combined to form ABBTSQ05, a site sequence of 146 rings (Fig 12). Attempts to match these two site sequences and the remaining ungrouped samples against relevant reference chronologies for oak and conifer were unsuccessful and all remain undated, although some tenuous dating evidence was noted that will be rechecked as the reference database is further enhanced.

INTERPRETATION

Analysis has resulted in the successful dating of ring-width series from 11 timbers. Felling date ranges and *terminus post quem* for felling dates have been calculated, where appropriate, using the estimate that 95% of mature oak trees from this area have between 15 and 40 sapwood rings (Fig 13).

In the South Wing nine timbers; six joists and a trimmer from the bay 2 ceiling; a door lintel, and the *ex situ* timber, have been successfully dated. One of these, ABB-T13, has complete sapwood and the last-measured ring date of AD 1582, the felling date of the timber represented. Seven of the other samples have the heartwood/sapwood boundary, the dates of which are broadly contemporary and suggestive of a single felling ranging from AD 1559 (ABB-T06) to AD 1571 (ABB-T01). The average heartwood/sapwood boundary ring date of these seven samples is AD 1567, allowing an estimated felling date to be calculated for the timbers represented to within the range of AD 1582–1607, consistent with these timbers also having been felled in, or around, AD 1582. The final dated sample from the South Wing (ABB-T09), does not have the heartwood/sapwood boundary and so an estimated felling date cannot be calculated, except to say that with a last-measured heartwood ring date of AD 1545, this would be estimated to be after AD 1560 at the earliest. However, the high level of similarity between ABB-T09 and ABB-T13 is suggestive of it also being felled in, or around, AD 1582.

Two timbers from bay 5 of the Central Range have also been dated. One of these, SELBY06, was thought to probably retain complete sapwood. The last-measured complete ring dates to AD 1682. However, the spring vessels of the following year are present, giving this timber a probable felling date of spring AD 1683. The second sample, SELBY07, has the heartwood/sapwood boundary ring date of AD 1668, allowing an estimated felling date to be calculated for the timber represented to within the range of AD 1683–1708, consistent with it also being felled in, or around, the spring of AD 1683, particularly with the high level of similarity between these two dated ring-width series.

DISCUSSION

A section of ground-floor frame and the lintel over the external door of the South Wing, as well as an *ex situ* main ceiling-beam that is thought to have come from the South Wing, are clearly coeval, all being felled in, or around, AD 1582. These results, from timbers considered to be potentially associated with the primary construction phase, suggest building works in the South Wing occurred in the last decades of the sixteenth century, somewhat later than the fifteenth- or early sixteenth-century date attributed on stylistic grounds, thus raising questions as to the historic development of Abbots Staith buildings.

Only two other timbers have been dated from the rest of the building. Two main beams in bay 5 of the Central Range have now been dated as having been probably felled in, or around, the spring of AD 1683, again somewhat later than the expected origins of these buildings. However, the dating of only two timbers from this range requires careful interpretation with respect to the development of these historic buildings.

It is unfortunate that two of the site sequences constructed from the timbers of this site remain undated as these may have provided valuable further evidence in understanding the Abbots Staith Buildings. Site sequence ABBTSQ05 contains two conifer samples and due to the great variation in sapwood numbers conifer timbers may have, little can be deduced from these samples, apart from to say that these two ceiling beams from bay 2 in the central range appear likely to be coeval. However, it is possible to say, by looking at the relative heartwood/sapwood positions of the samples in undated site sequence ABBTSQ04 (Fig 11), that the three lintels represented (over doorways which link bays 3, 4, and 5 to each other and to the South Wing), are likely to have been felled at the same time. This suggests that these doorways are of the same date, although whether primary, or a later insertion, remains unknown.

Secure dating may have been hindered in the case of some of these samples by the presence of recurring bands of very narrow rings in their growth patterns. These may have been caused by certain regional woodland management practices rather than environmental influences and as such mask the climatic signal necessary for successful matching against the reference chronologies. Additionally, this part of the country often proves challenging when attempting tree-ring dating as demonstrated by the recent project in Beverley (Cook and Neave 2018). It is considered likely that very specific environmental factors are influencing the growth patterns of the trees making it especially important to have highly regional reference chronologies against which to match site sequences. Our databank of reference chronologies from Yorkshire is being strengthened and improved constantly and it is hoped that at some point in the future some presently undated sequences will be successfully matched.

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TABLES

Table 1: Details of samples taken from Abbots Staith Buildings, Water Lane, Selby, Yorkshire. Samples prefixed 'ABB-T' were taken in 2018. Samples prefixed 'SELBY' were taken in 1997.

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
South wing						
ABB-T01	Joist 3, bay 2	49	h/s	1523	1571	1571
ABB-T02	Joist 4, bay 2	50	05	1520	1564	1569
ABB-T03	Joist 5, bay 2	NM	--	----	----	----
ABB-T04	Joist 6, bay 2	67	08	1510	1568	1576
ABB-T05	Joist 10, bay 2	72	07	1503	1567	1574
ABB-T06	Joist 11, bay 2	73	14	1501	1559	1573
ABB-T07	Joist 13, bay 2	68	02	1505	1570	1572
ABB-T08	Trimmer, joists 5–7, bay 2	53	03	1521	1570	1573
ABB-T09	Main door lintel	130	--	1416	----	1545
ABB-T13	*Ex-situ* beam	117	17C	1466	1565	1582
SELBY11	*Ditto*	NM	--	----	----	----
Central range						
ABBT10S01	Beam 1, bay 3	120	20			
ABB-T10	*Ditto*	120	14	----	----	----
SELBY01	*Ditto*	87	2	----	----	----
ABBT11S03	Beam 3, bay 3	135	24C			
ABB-T11	*Ditto*	135	17C	----	----	----
SELBY03	*Ditto*	74	24C?	----	----	----
ABB-T12	Beam 3, bay 4	104	h/s	----	----	----
SELBY04	*Ditto*	NM	--	----	----	----
ABB-T14	Door lintel, bay ¾	74	14	----	----	----
ABB-T15	Door lintel. bay 4/5	86	30C	----	----	----
ABB-T16	Door lintel, bay 5/south wing	59	h/s	----	----	----

ABB-T17	Joist 12, east bay, bay 3	68	08	----	----	----
ABB-T18	Beam 3, bay 2 – conifer	146	17	----	----	----
ABB-T19	Beam 4, bay 2 – conifer	124	13	----	----	----
SELBY08	Beam 5, bay 2	NM	--	----	----	----
SELBY02	Beam 2, bay 3	142	--	----	----	----
SELBY05	Beam 1, bay 4 – conifer	NM	--	----	----	----
SELBY06	Beam 3, bay 5	128	21¼C?	1555	1661	1682
SELBY07	Beam 2, bay 5	107	h/s	1562	1668	1668
SELBY09	Beam 2, bay 2	84	16	----	----	----
SELBY10	Beam 1, bay 5 – conifer	147	----	----	----	----
North wing						
ABB-T20	Beam 3	108	05	----	----	----

NM = not measured
h/s = the heartwood/sapwood boundary is the last-measured ring;
C = complete sapwood retained on sample, last-measured ring is the felling date
¼C = complete sapwood retained on sample, a partial ring is formed following the last-measured ring, felling date is the following spring

Table 2: Results of the cross-matching of site sequence ABBTSQ01 and relevant reference chronologies when the first-ring date is AD 1501 and the last-measured ring date is AD 1576

Reference chronology	*t*-value	Span of chronology	Reference
Nun Appleton, Tadcaster, West Yorkshire	6.6	AD 1478–1657	Arnold *et al* 2008a
Kings Manor. York, North Yorkshire	6.1	AD 1361–1667	King pers comm
Clumpcliff, Wakefield, West Yorkshire	5.7	AD 1452–1613	Howard *et al* 2000
3 & 11–13 Cornmarket, Pontefract, West Yorkshire	5.4	AD 1471–1587	Arnold and Howard 2015
7–9 Northbar Within, Beverley, East Yorkshire	5.4	AD 1537–1674	Arnold *et al* 2021
Manor House, Donington-le-Heath, Leicestershire	5.3	AD 1411–1618	Esling *et al* 1989
Priory Barn, Little Wymondley, Hertfordshire	5.0	AD 1452–1531	Bridge 2001
Upper Hall, Hartshorne, Derbyshire	4.9	AD 1448–1611	Arnold *et al* 2008b
Moor Farm Cottage, Shardlow, Derbyshire	4.9	AD 1437–1616	Howard *et al* 1994
Bolsover Castle (Riding House), Derbyshire	4.8	AD 1494–1744	Howard *et al* 2005

Table 3: Results of the cross-matching of site sequence ABBTSQ02 and relevant reference chronologies when the first-ring date is AD 1416 and the last-measured ring date is AD 1582

Reference chronology	*t*-value	Span of chronology	Reference
Bishopsthorpe Palace, Bishopsthorpe, York, North Yorkshire	6.4	AD 1360–1527	Arnold *et al* 2008c
Ulverscroft Priory, Ulverscroft, Leicestershire	5.8	AD 1388–1533	Arnold *et al* 2008d
Church of St Mary bell tower, Pembridge, Herefordshre	5.8	AD 1382–1471	Tyers 2004
Scargill Castle Gatehouse, Barnard Castle, County Durham	5.3	AD 1432–1540	Howard *et al* 2002
Kepier Farm Hospital, Durham	5.3	AD 1304–1522	Howard *et al* 1996
Littlebourne Barn, near Canterbury, Kent	5.2	AD 1382–1582	Arnold *et al* 2003
Hunwick Hall Farm, Hunwick, County Durham	5.2	AD 1402–1497	Arnold *et al* 2004
104 Kirkgate, Leeds, Yorkshire	5.2	AD 1329–1628	Arnold *et al* 2020a
Wigmore moulded beam, Herefordshire	5.2	AD 1404–1480	Tyers 1999 unpubl
Kenilworth Castle (Leicester's Buildings), Warwickshire	5.0	AD 1423–1550	Arnold *et al* 2022

Table 4: Results of the cross-matching of site sequence ABBTSQ03 and relevant reference chronologies when the first-ring date is AD 1555 and the last-measured ring date is AD 1682

Reference chronology	*t*-value	Span of chronology	Reference
The Minster choir roof, Beverley, East Yorkshire	6.4	AD 1573–1736	Arnold *et al* 2020b
10 High Street, Stourbridge, West Midlands	6.3	AD 1534–1661	Howard *et al* 1993
Castle House, Melbourne, Derbyshire	5.5	AD 1583–1720	Arnold and Howard 2009 unpubl
St Hugh's Choir, Lincoln Cathedral, Lincolnshire	5.5	AD 1575–1724	Laxton *et al* 1984
Wednesbury Forge, Sandwell, West Midlands	5.5	AD 1322–1616	Tyers 2007
Middleton Hall, Warwickshire	5.3	AD 1593–1718	Arnold *et al* 2006
Bretby Hall, Derbyshire	5.1	AD 1494-1719	Howard *et al* 1999
All Saints Church (bellframe), North Scarle, Lincolnshire	5.0	AD 1602-1716	Arnold and Howard 2010
Brocklesbury Hall, near Caister, Lincolnshire	5.0	AD 1607–1701	Arnold *et al* 2007
Pitchforks, Norwell, Nottinghamshire	4.8	AD 1624–1747	Hurford *et al* 2010

FIGURES

Figure 1: Maps to show the location of Abbots Staith Buildings in Selby, North Yorkshire, marked in red. Scale: top right 1:10,000, bottom 1:1250 © Crown Copyright and database right 2022. All rights reserved. Ordnance Survey Licence number 100024900.

Figure 2: South Wing with section of surviving floor frame, photograph taken from the east (Photograph: Alison Arnold)

Figure 3: Ex situ *main beam thought to have come from the South Wing, photograph taken from the east (Photograph: Alison Arnold)*


Figure 4: A single common joist sits in its original soffit in bay 3, photograph taken from the south-east (Photograph: Alison Arnold)


Figure 5: The doorway into the South Wing, with sampled lintel above, photograph taken from the east (Photograph: Alison Arnold)

Figure 6: Lintel over doorway between bays 3 and 4, photograph taken from the north (Photograph: Alison Arnold)

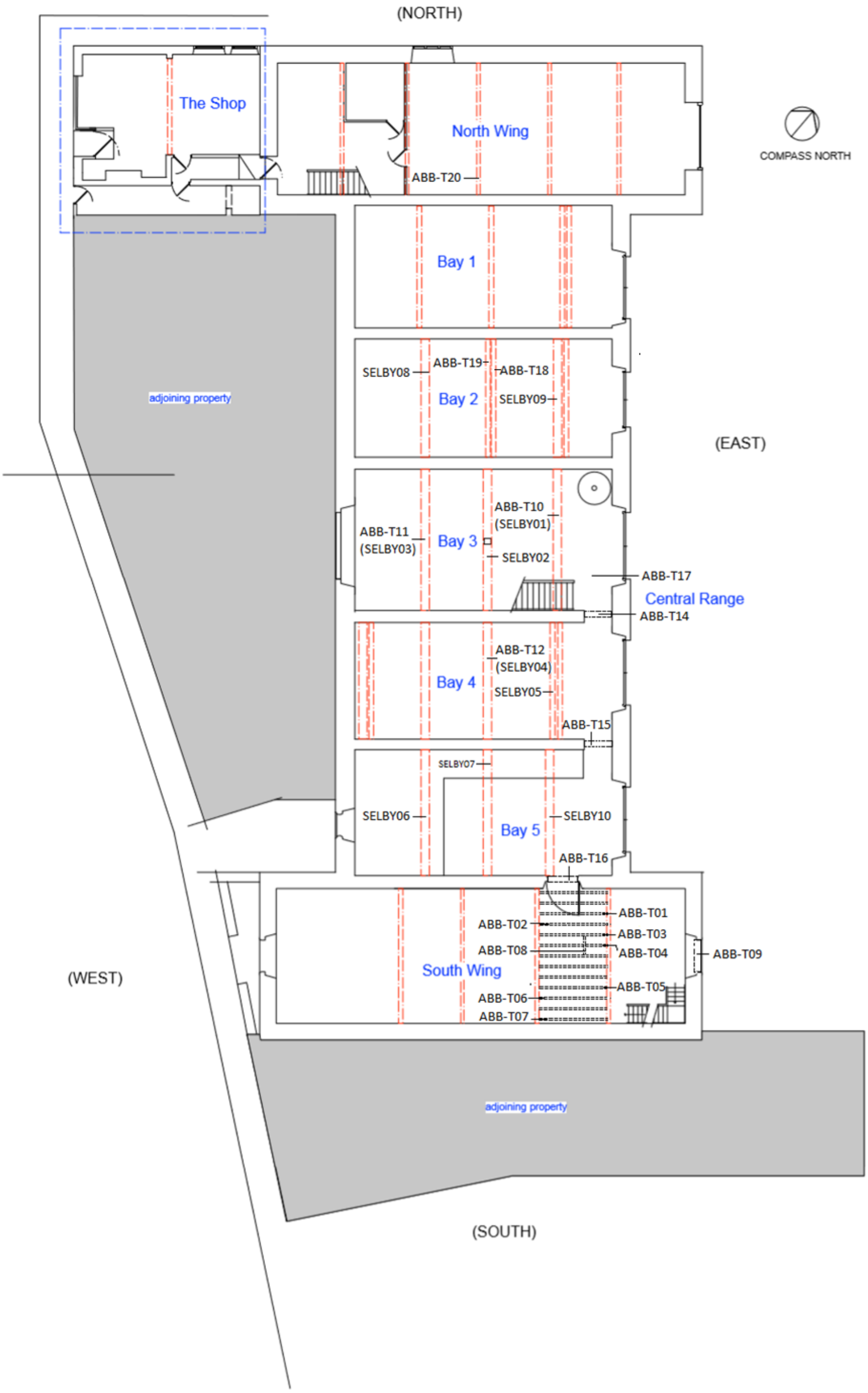

Figure 7: Ground-floor plan, showing sampled timbers, with exception of ex situ *beam ABB-T13/SELBY11 (after Wiles & Maguire)*

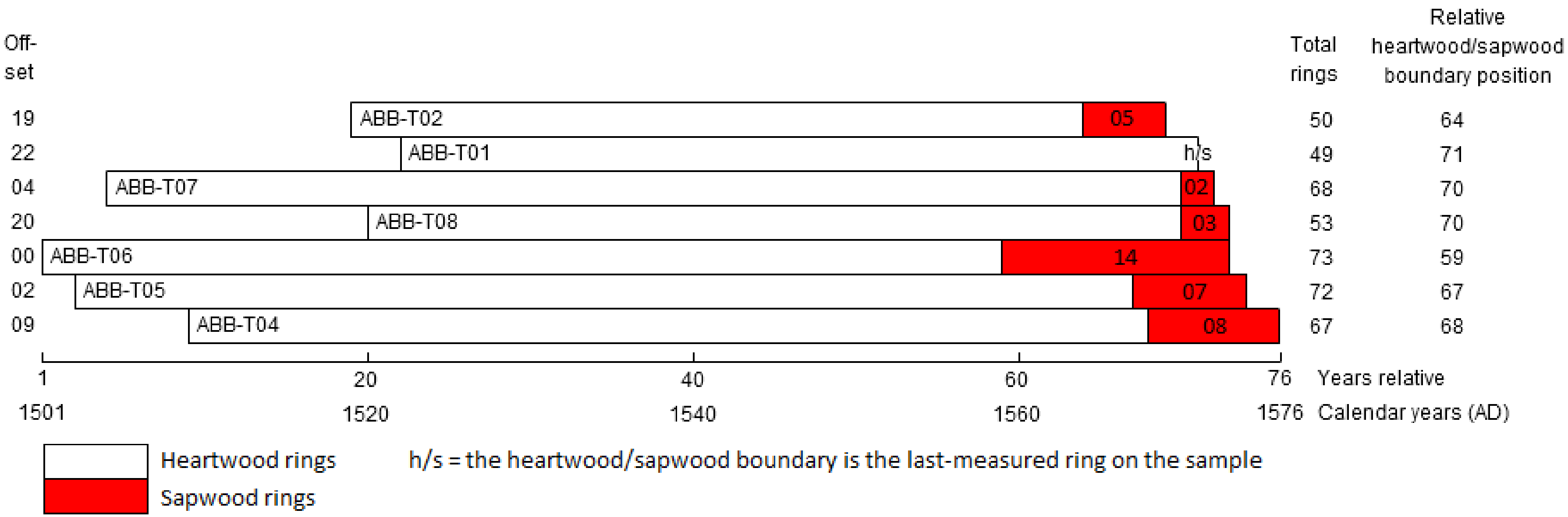

Figure 8: Bar diagram to show the relative position of samples in site sequence ABBTSQ01

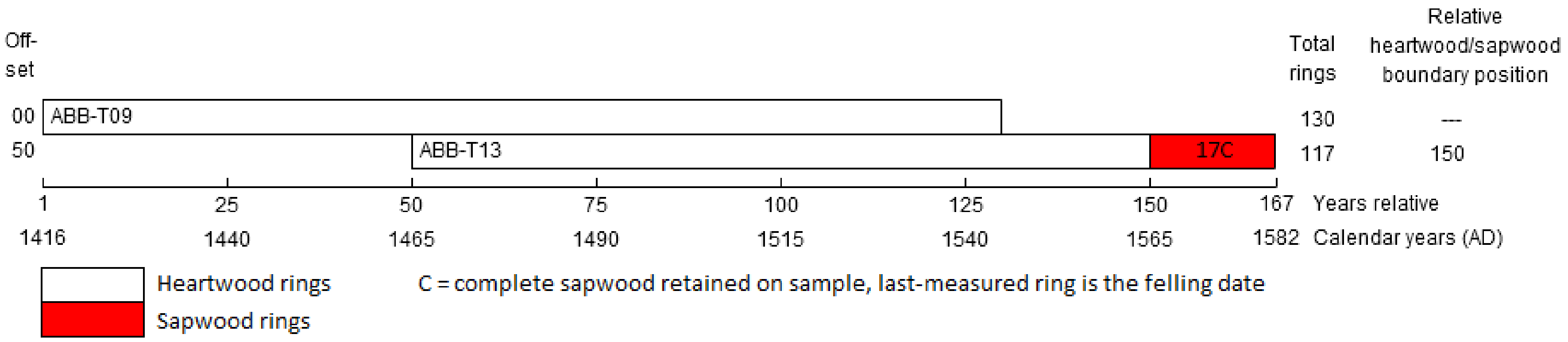

Figure 9: Bar diagram to show the relative position of samples in site sequence ABBTSQ02

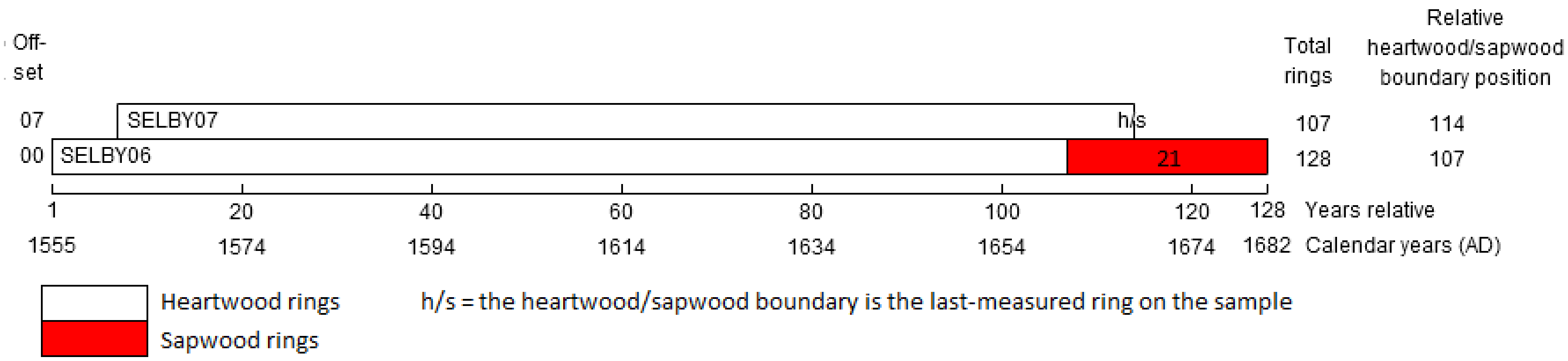

Figure 10: Bar diagram to show the relative position of samples in site sequence ABBTSQ03

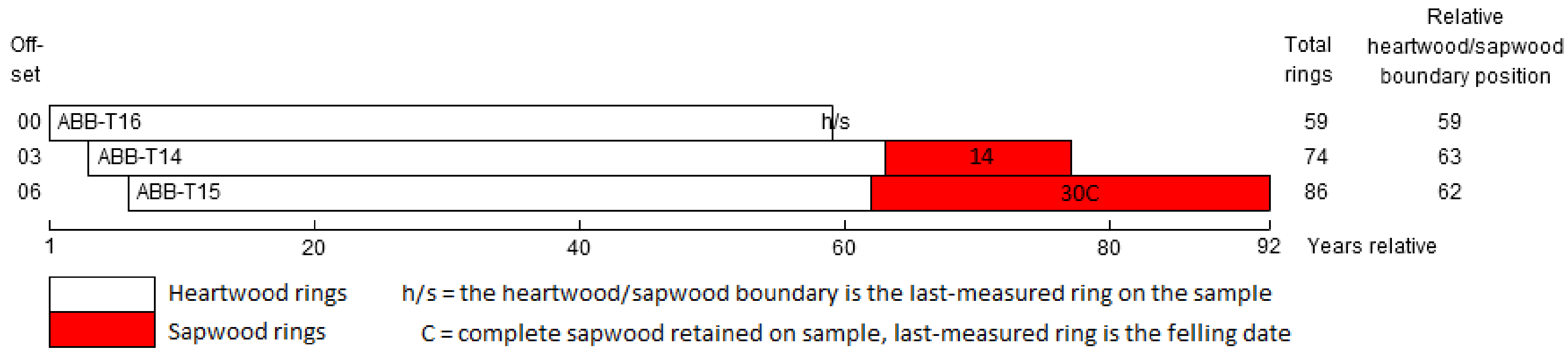

Figure 11: Bar diagram to show the relative position of samples in undated site sequence ABBTSQ04

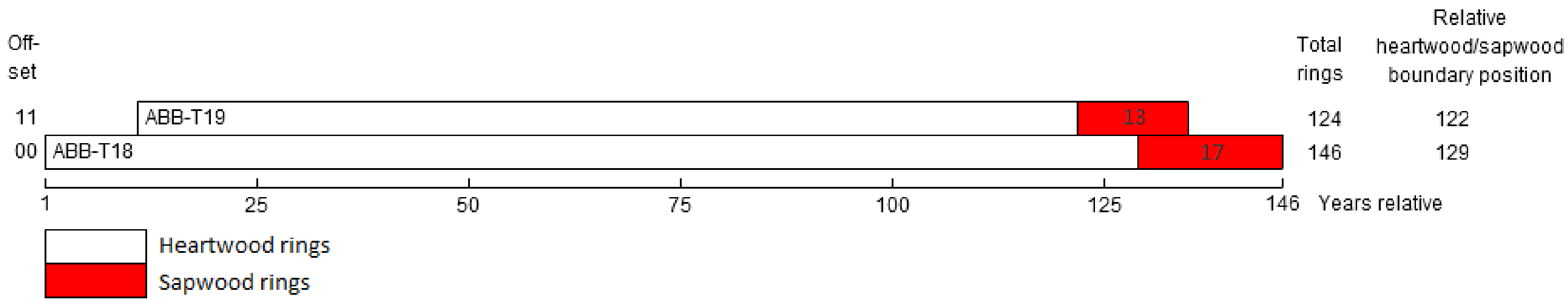

Figure 12: Bar diagram to show the relative position of samples in undated site sequence ABBTSQ05

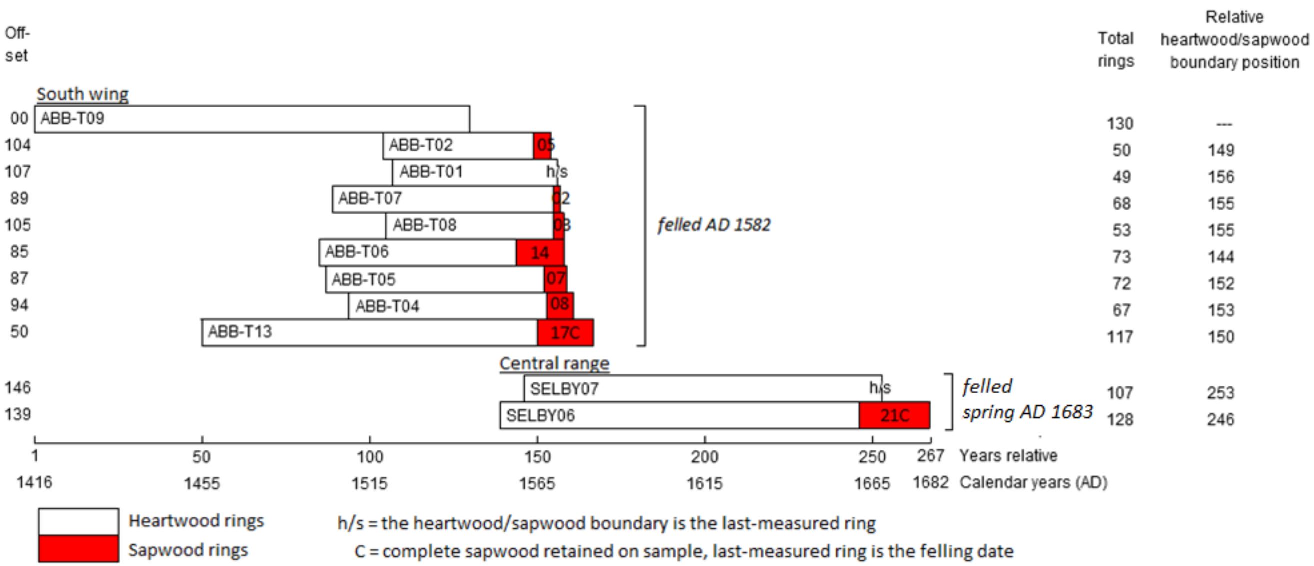

Figure 13: Bar diagram to show all dated samples and felling dates

DATA OF MEASURED SAMPLES

ABB-T01A 49
159 237 163 337 323 324 282 193 240 174 144 128 201 170 269 504 421 383 342 204
319 336 394 224 239 166 261 351 396 411 367 338 293 223 199 335 453 428 451 309
366 287 367 284 400 447 298 343 276
ABB-T01B 49
175 213 198 364 316 351 259 171 178 182 149 125 205 178 262 488 400 365 349 210
312 368 407 229 238 162 263 357 394 404 374 329 294 229 201 341 446 436 451 301
364 294 368 279 392 442 306 342 279
ABB-T02A 50
312 550 475 396 223 92 278 296 275 241 210 258 274 161 202 261 271 281 225 173
153 171 205 268 221 165 137 134 127 113 227 258 243 230 222 254 162 93 120 265
263 320 191 200 155 141 211 292 301 179
ABB-T02B 50
346 548 485 406 207 85 287 294 279 240 236 268 275 157 209 255 258 263 221 173
179 184 193 254 243 193 159 139 128 108 230 273 232 223 233 246 166 89 108 233
241 317 184 187 154 132 216 281 317 171
ABB-T04A 67
361 466 350 236 326 409 202 126 106 92 152 376 372 223 159 116 263 242 277 195
152 191 133 163 156 202 192 190 225 153 132 165 215 239 246 220 136 152 125 121
147 164 146 152 180 182 137 108 137 146 135 160 131 117 102 108 118 120 160 134
160 113 125 135 177 170 170
ABB-T04B 67
356 469 347 242 277 421 202 133 103 114 174 370 377 222 164 121 267 245 263 196
143 181 132 148 154 206 255 214 239 144 139 152 213 224 224 225 128 167 108 110
145 159 126 155 195 203 140 109 129 146 137 168 126 114 102 107 107 116 167 119
162 117 127 123 181 172 167
ABB-T05A 72
213 280 236 311 288 343 314 309 261 197 178 245 307 307 197 171 174 253 515 365
252 185 108 194 395 351 247 188 308 106 109 180 182 196 181 112 78 73 90 73
114 166 313 159 170 86 95 148 237 210 197 198 117 85 78 82 171 149 170 144
118 76 94 62 104 167 130 146 81 65 83 114
ABB-T05B 72
204 283 249 325 286 345 316 284 247 186 194 217 300 309 189 174 162 248 500 367
236 189 109 231 380 345 248 189 301 117 105 208 221 220 162 113 78 65 85 76
122 165 324 158 169 90 92 170 260 208 184 192 110 80 73 87 171 148 169 140
124 85 83 61 96 191 149 138 89 71 81 94
ABB-T06A 73
215 390 274 256 249 242 270 257 263 241 288 204 235 289 279 243 194 145 200 293
432 428 261 225 181 229 295 240 165 98 189 150 150 197 279 166 171 142 152 127
129 102 121 141 119 98 94 102 90 124 151 99 118 108 124 100 129 68 115 79
128 94 95 96 115 104 95 121 100 109 75 99 112
ABB-T06B 73
208 391 287 261 240 224 275 240 259 233 274 188 225 277 267 245 187 142 199 280
434 417 246 229 176 212 280 234 165 81 186 140 152 191 275 173 176 139 140 125
137 94 117 146 108 94 98 111 94 121 154 110 113 108 127 90 120 77 109 80
128 92 101 91 117 94 108 117 96 117 68 107 100
ABB-T07A 68
132 226 220 172 117 130 119 60 73 53 114 122 72 143 71 117 208 187 145 120
80 183 274 275 232 124 117 113 95 110 174 158 202 148 138 117 117 145 187 267
236 217 217 188 223 310 323 389 245 229 233 127 112 170 233 264 393 217 248 244

253 276 411 374 182 242 156 124
ABB-T07B 68
130 226 219 176 127 119 86 61 80 50 103 125 77 136 74 109 228 164 103 118
85 161 264 285 229 119 109 115 101 97 162 132 189 144 133 122 105 146 192 266
240 206 232 197 230 308 322 383 236 227 236 130 116 177 249 268 372 210 240 241
226 250 392 382 203 258 162 145
ABB-T08A 53
331 388 252 243 136 312 413 480 303 237 353 189 253 299 343 259 210 207 175 175
200 205 224 234 242 167 205 155 150 195 197 167 170 232 250 221 158 202 233 176
204 143 118 115 99 120 125 174 135 174 119 131 92
ABB-T08B 53
339 430 244 249 137 321 422 474 294 241 354 218 244 307 342 249 213 213 173 176
201 200 219 249 233 167 206 150 151 196 195 170 165 235 253 210 160 198 232 181
210 151 109 111 87 119 128 175 133 167 113 129 92
ABB-T09A 130
278 295 229 201 337 298 331 398 308 93 48 64 113 175 136 142 193 106 101 98
123 62 58 61 109 134 103 178 97 119 157 195 188 224 165 142 315 326 297 225
225 151 150 137 233 261 239 285 225 140 100 130 156 158 153 266 190 204 176 196
136 168 201 118 157 208 114 153 235 191 234 275 202 222 225 112 185 156 175 236
252 170 94 126 141 162 224 281 125 64 46 51 74 99 94 145 123 155 213 165
204 203 209 138 155 324 305 273 242 180 122 76 42 36 27 41 67 52 87 99
103 161 228 207 165 124 82 155 207 256
ABB-T09B 130
285 286 227 215 330 295 342 393 301 98 52 61 103 166 139 142 199 101 100 104
111 70 56 56 121 129 97 164 106 122 156 186 188 227 167 152 307 298 307 216
233 146 144 139 209 255 255 271 229 137 103 130 157 170 134 260 190 200 172 189
140 166 204 115 147 221 115 139 238 191 230 289 190 226 229 116 186 162 185 243
252 154 98 131 147 152 216 280 122 57 52 50 77 100 91 159 108 153 216 167
204 201 192 132 153 322 290 279 238 176 120 91 48 32 29 38 53 42 71 86
103 181 197 196 161 126 68 164 207 263
ABB-T10A 105
300 362 229 179 297 246 280 195 242 191 163 135 215 230 211 235 241 181 173 250
95 56 53 45 62 67 90 67 79 66 107 123 126 131 78 44 32 47 45 66
26 65 71 66 47 74 124 143 139 69 112 153 103 115 150 131 131 102 60 30
31 32 39 78 43 60 99 83 154 123 152 70 69 95 102 86 84 56 66 72
97 90 89 39 34 32 37 40 56 63 59 81 92 112 68 98 96 65 78 81
51 82 47 84 59
ABB-T10B 105
258 336 311 250 413 76 71 52 38 53 43 47 73 71 65 69 82 102 144 74
44 51 45 50 63 52 57 45 31 74 106 90 117 136 96 111 102 119 133 144
137 182 145 74 67 47 54 45 82 53 52 88 90 150 150 133 86 56 93 129
118 156 137 122 112 116 110 125 51 47 61 58 50 82 79 86 114 200 223 136
183 202 180 195 165 73 64 51 69 39 64 79 96 84 84 74 93 63 100 65
59 60 47 54 57
ABB-T11A 135
266 316 305 288 383 283 373 219 279 360 256 180 221 238 176 174 191 155 185 220
38 52 30 45 53 74 74 75 101 123 117 110 118 171 148 56 55 83 63 83
60 74 61 82 71 87 86 115 122 62 65 76 73 60 81 76 99 99 112 87
122 241 221 215 171 95 405 43 48 47 53 50 52 85 101 78 105 125 96 108
100 72 70 77 52 64 85 77 88 101 81 92 67 78 73 103 111 103 108 140
126 124 185 199 155 118 126 129 136 98 226 294 66 51 52 36 54 45 61 72
91 109 144 144 152 155 127 100 101 97 102 132 146 107 116
ABB-T11B 135

286 316 296 288 381 293 371 209 272 340 249 181 217 241 181 173 185 145 183 217
43 35 42 42 43 97 108 94 127 77 68 86 92 120 104 44 30 31 37 38
36 53 47 73 73 86 106 121 224 69 75 69 60 71 83 84 100 117 98 90
115 234 217 219 174 167 465 41 39 56 56 47 56 80 95 80 60 121 98 114
90 81 66 63 64 69 81 84 74 101 94 87 62 77 67 111 99 112 113 126
124 137 180 173 143 116 107 129 134 104 227 287 65 51 49 44 50 55 61 76
78 119 142 138 156 156 122 99 107 88 106 134 148 106 115
ABB-T12A 104
324 504 538 487 403 401 418 301 267 337 486 382 495 600 541 499 813 587 500 669
628 696 521 513 589 616 560 87 72 35 47 57 58 60 36 47 56 63 79 103
137 141 198 220 69 42 54 58 42 50 83 70 75 60 75 81 84 90 94 98
88 122 136 147 116 152 248 45 38 20 35 31 37 38 27 31 21 33 50 82
171 155 194 196 185 156 148 115 118 165 183 195 204 120 189 254 160 140 134 184
160 140 179 233
ABB-T12B 104
337 514 526 506 404 410 410 293 226 332 495 385 500 600 547 501 815 595 492 664
592 697 525 528 605 600 563 87 69 38 51 52 60 62 35 45 61 60 78 106
135 152 197 211 69 60 43 44 49 58 86 79 73 53 76 77 76 79 98 74
92 101 139 163 121 159 249 40 37 23 38 35 27 40 30 31 22 27 47 87
175 139 212 195 195 154 172 120 116 168 185 198 207 130 205 232 167 141 130 190
149 143 171 218
ABB-T13A 117
359 629 317 299 213 342 237 293 214 302 207 273 288 292 269 257 93 140 225 207
215 257 126 167 187 92 160 143 168 189 155 142 134 210 326 251 306 241 199 69
36 36 27 48 54 77 65 87 113 110 137 154 173 94 83 169 179 115 173 126
118 49 38 47 32 41 55 55 54 66 103 105 92 96 98 111 117 116 132 166
146 145 143 153 73 50 71 78 59 89 209 149 146 184 127 109 108 88 84 70
108 131 117 109 107 182 144 190 308 269 178 179 257 262 345 175 240
ABB-T13B 117
341 620 334 294 210 319 235 244 245 314 200 248 299 290 264 254 111 142 223 211
222 263 153 173 184 99 142 150 175 184 166 130 147 213 332 256 291 240 203 64
41 34 30 43 56 80 60 91 112 113 136 153 168 98 87 171 173 110 178 120
124 45 37 41 33 46 54 54 61 69 101 98 93 94 99 111 113 119 138 164
147 143 148 154 72 61 63 94 63 109 217 147 168 191 134 115 106 98 89 65
100 140 117 103 110 186 139 202 296 269 180 183 255 266 352 182 213
ABB-T14A 74
205 352 330 274 210 177 223 225 200 173 143 235 234 213 277 296 193 111 74 126
183 162 120 120 137 197 134 94 146 160 174 156 115 79 118 171 134 143 94 129
116 162 150 138 100 99 107 131 118 88 93 84 94 91 79 65 62 53 47 56
65 52 75 54 65 53 36 45 29 32 36 38 29 35
ABB-T14B 74
208 358 328 261 223 180 223 211 188 165 150 227 229 223 287 267 209 121 70 128
181 160 124 122 136 186 125 88 135 164 176 157 112 80 119 168 133 140 91 131
115 162 150 143 97 99 105 131 107 84 94 84 98 81 93 57 63 56 49 52
72 45 82 48 59 54 37 46 37 30 33 32 33 32
ABB-T15A 86
238 216 193 240 209 226 208 163 167 140 117 144 140 150 93 50 117 181 137 114
108 151 188 138 117 147 157 128 128 112 87 92 114 110 115 86 112 98 116 137
105 81 79 100 117 83 83 69 70 96 87 70 44 60 57 45 46 67 57 60
56 62 55 41 43 41 34 34 42 36 27 45 50 64 45 37 31 40 38 52
56 37 35 42 39 55
ABB-T15B 86
250 231 203 239 215 230 238 176 165 136 120 142 155 158 92 55 112 179 139 126

99 158 194 148 114 146 154 124 136 112 80 85 127 112 107 85 115 96 128 131
99 93 73 109 114 88 76 70 71 98 86 84 47 56 47 41 48 52 55 52
61 51 49 41 42 33 36 30 43 33 37 39 52 53 42 38 43 51 45 41
51 42 53 40 34 73
ABB-T16A 59
183 173 195 161 208 151 130 124 149 158 236 257 271 214 253 210 228 155 163 123
92 56 87 145 124 115 90 106 138 102 88 154 150 146 115 98 61 64 93 100
99 76 95 97 132 126 98 76 91 96 111 97 69 55 73 80 73 67 58
ABB-T16B 59
185 173 201 155 213 155 112 117 153 160 236 259 261 222 250 208 225 155 163 134
94 55 84 140 142 116 85 109 142 98 91 152 154 145 117 91 58 58 109 98
111 63 97 94 132 127 92 88 82 106 102 96 71 57 77 82 71 66 50
ABB-T17A 68
342 349 231 156 270 192 158 146 200 182 238 321 287 342 262 223 194 162 216 239
247 234 104 149 143 157 118 76 181 204 155 138 119 216 144 101 133 130 167 90
169 240 259 197 198 285 267 236 335 304 273 274 302 284 175 177 390 369 334 374
102 60 58 61 65 106 103 183
ABB-T17B 68
349 344 234 165 267 183 168 139 208 177 244 303 287 340 277 219 198 168 215 247
238 233 101 154 142 153 121 75 180 203 153 137 120 215 138 100 132 137 162 92
176 232 268 187 203 281 267 243 340 304 275 276 294 285 174 174 412 368 336 367
104 62 57 58 71 101 111 186
ABB-T18A 146
130 139 196 152 112 136 121 136 104 88 110 88 114 103 103 124 192 182 111 116
109 151 156 90 108 99 73 133 122 116 74 90 117 111 91 94 66 60 49 81
105 74 86 85 70 60 70 97 92 56 32 47 78 99 77 69 56 55 55 55
64 48 66 59 59 36 48 52 74 47 49 70 72 110 99 81 80 73 67 68
95 105 93 82 88 121 96 88 71 79 72 60 66 78 83 77 91 102 86 83
79 65 72 75 64 42 72 86 95 97 90 42 79 95 93 78 76 76 63 73
55 73 69 83 67 65 91 70 82 93 59 100 84 95 142 95 87 82 65 63
76 45 81 96 118 123
ABB-T18B 146
130 143 197 147 113 137 121 136 98 92 113 91 119 101 98 130 198 183 107 111
104 151 154 89 111 94 79 133 123 119 73 85 119 108 86 89 71 54 49 80
99 85 87 79 70 66 71 96 82 52 37 47 93 109 73 69 52 50 56 55
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89 103 90 81 99 119 105 89 65 83 77 57 67 75 79 68 84 97 87 81
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52 72 70 87 71 57 90 67 82 92 62 96 84 96 145 95 84 83 68 63
74 56 70 97 118 128
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159 178 161 140 185 204 195 124 135 141 187 195 122 147 135 143 238 223 182 105
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89 200 138 135 137 130 120 86 86 83 83 88 59 88 57 76 89 83 53 54
88 77 140 149 103 80 78 77 107 147 145 94 109 108 148 105 100 82 105 94
79 64 107 108 96 82 115 144 107 90 52 67 66 59 51 90 86 82 94 70
48 81 85 79 69 71 48 60 54 40 59 60 66 67 56 103 132 169 127 77
128 102 96 94
ABB-T19B 124
157 182 157 144 183 201 193 126 134 142 187 194 117 153 128 145 243 220 184 103
133 203 174 130 124 122 113 140 173 164 173 164 135 135 131 107 136 173 96 55
100 200 136 140 126 130 118 93 81 84 73 99 68 83 63 67 88 83 59 50
81 93 131 155 102 79 65 79 101 158 147 103 115 107 143 101 98 83 106 93

75 69 107 105 104 85 113 134 112 91 58 67 63 60 50 82 87 82 97 73
49 76 92 73 79 57 55 51 60 45 60 58 66 72 45 110 127 171 127 73
134 99 108 95
ABB-T20A 108
78 125 207 121 102 279 345 315 253 123 216 248 255 231 198 167 215 297 254 130
226 246 176 237 135 95 197 164 133 92 128 156 244 200 146 109 160 149 212 167
238 101 144 228 249 257 267 272 172 186 192 85 135 197 324 262 243 186 185 239
194 154 107 127 98 159 195 217 171 205 143 125 100 108 113 97 164 165 172 78
92 164 164 131 126 102 108 90 103 124 168 187 265 256 152 147 138 164 200 130
156 103 100 118 156 137 136 132
ABB-T20B 108
101 116 212 120 104 288 340 304 245 122 216 249 254 225 204 164 221 299 256 125
227 255 177 239 140 88 195 172 137 80 135 155 270 192 149 113 158 159 208 157
229 101 145 226 269 260 295 265 170 181 183 83 138 210 311 257 251 180 191 240
191 147 107 118 98 170 203 219 169 199 134 134 97 106 117 107 151 172 157 82
93 144 166 144 130 97 97 93 97 116 160 214 253 249 148 152 157 156 198 138
154 116 97 105 147 136 129 133
SELBY01 87
317 383 324 246 465 84 62 49 42 51 32 53 47 68 59 63 79 90 147 79
52 47 44 55 72 51 74 64 56 74 97 99 110 130 90 108 113 106 122 150
129 196 184 120 77 61 59 53 84 63 50 99 83 142 139 141 79 69 99 127
129 166 138 135 130 133 121 161 57 38 55 50 52 71 73 79 93 203 194 112
157 170 138 157 149 65 47
SELBY02 142
327 328 384 515 280 449 393 307 330 404 483 535 287 255 305 369 495 366 418 240
234 137 181 252 270 111 53 63 44 59 120 142 156 349 281 204 227 267 215 242
333 325 365 337 201 102 51 46 57 32 62 93 77 77 63 95 151 237 92 56
62 49 57 62 109 160 71 48 59 48 53 91 62 73 111 94 120 73 46 59
46 56 77 94 98 56 47 63 63 53 60 84 62 77 144 106 162 182 130 171
152 175 67 49 58 35 74 78 76 64 32 37 45 45 52 68 62 86 53 102
101 73 51 71 65 53 98 174 123 180 167 160 168 180 236 143 148 228 322 327
255 238
SELBY03 74
118 96 97 81 110 109 51 31 38 40 39 41 68 66 57 43 49 44 52 48
46 39 42 63 72 115 90 91 74 79 78 53 79 65 67 78 96 101 108 74
93 195 197 184 133 116 136 148 112 156 243 36 31 28 24 32 32 34 45 35
43 49 45 51 60 71 74 84 84 90 114 144 114 126
SELBY06 128
177 115 191 290 237 208 173 156 137 158 300 325 214 284 178 191 225 198 165 121
71 71 63 67 96 94 116 92 183 261 352 163 157 118 113 121 149 200 257 394
385 271 249 204 297 286 288 265 277 235 257 401 339 347 338 258 238 196 328 223
140 182 305 247 244 177 204 249 237 181 128 138 173 94 83 109 132 253 206 117
212 192 141 122 159 184 238 121 101 150 265 297 166 206 135 116 94 100 120 150
175 149 94 128 192 175 147 149 186 178 150 224 193 203 230 184 131 161 199 191
154 173 184 186 157 157 160 188
SELBY07 107
128 101 155 167 157 163 141 182 89 209 159 205 213 204 231 245 258 328 362 292
289 257 378 347 238 172 145 119 94 105 158 270 254 272 231 175 204 166 161 146
148 196 151 174 259 245 247 244 224 146 188 260 214 148 160 261 289 323 283 241
391 297 263 171 235 251 163 159 218 201 269 211 214 160 182 172 168 211 233 252
122 216 309 328 331 301 256 216 142 175 110 135 179 220 213 114 152 185 221 191
156 156 124 128 153 187 192
SELBY09 84

519 467 115 49 86 146 162 136 213 387 404 238 372 342 471 533 332 442 307 366
433 112 58 95 126 127 165 262 286 313 373 363 354 322 359 389 398 127 48 60
82 82 117 125 147 168 130 123 171 300 334 83 76 62 120 116 144 254 286 246
275 254 280 172 258 294 311 295 268 198 91 84 51 73 85 91 112 125 91 117
159 161 114 116
SELBY10 147
325 278 329 273 72 209 245 229 271 196 223 237 183 229 238 197 193 192 149 126
190 163 165 181 165 174 145 137 159 141 148 135 146 190 133 206 195 163 205 186
111 104 99 115 114 217 174 138 162 214 154 111 76 32 114 86 140 113 158 141
129 131 128 109 113 155 164 125 205 100 153 116 108 121 166 160 112 144 112 153
137 89 127 91 80 79 88 61 66 71 117 92 86 66 98 86 129 154 167 169
177 129 103 89 114 108 94 109 129 85 78 119 87 51 70 64 55 49 38 42
63 59 71 73 55 45 39 59 69 48 64 81 102 120 117 76 75 71 91 86
86 107 115 169 114 118 135

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 Nottingham Tree-ring Dating Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Buildings* (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 back from the outside ring, which grew in 1976

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, although the sequences of widths look similar, they are not identical. This is typical

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

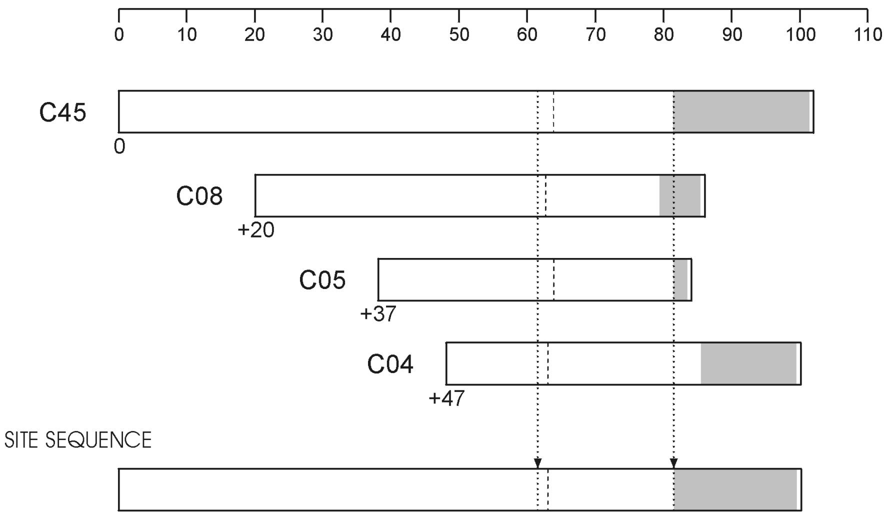


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

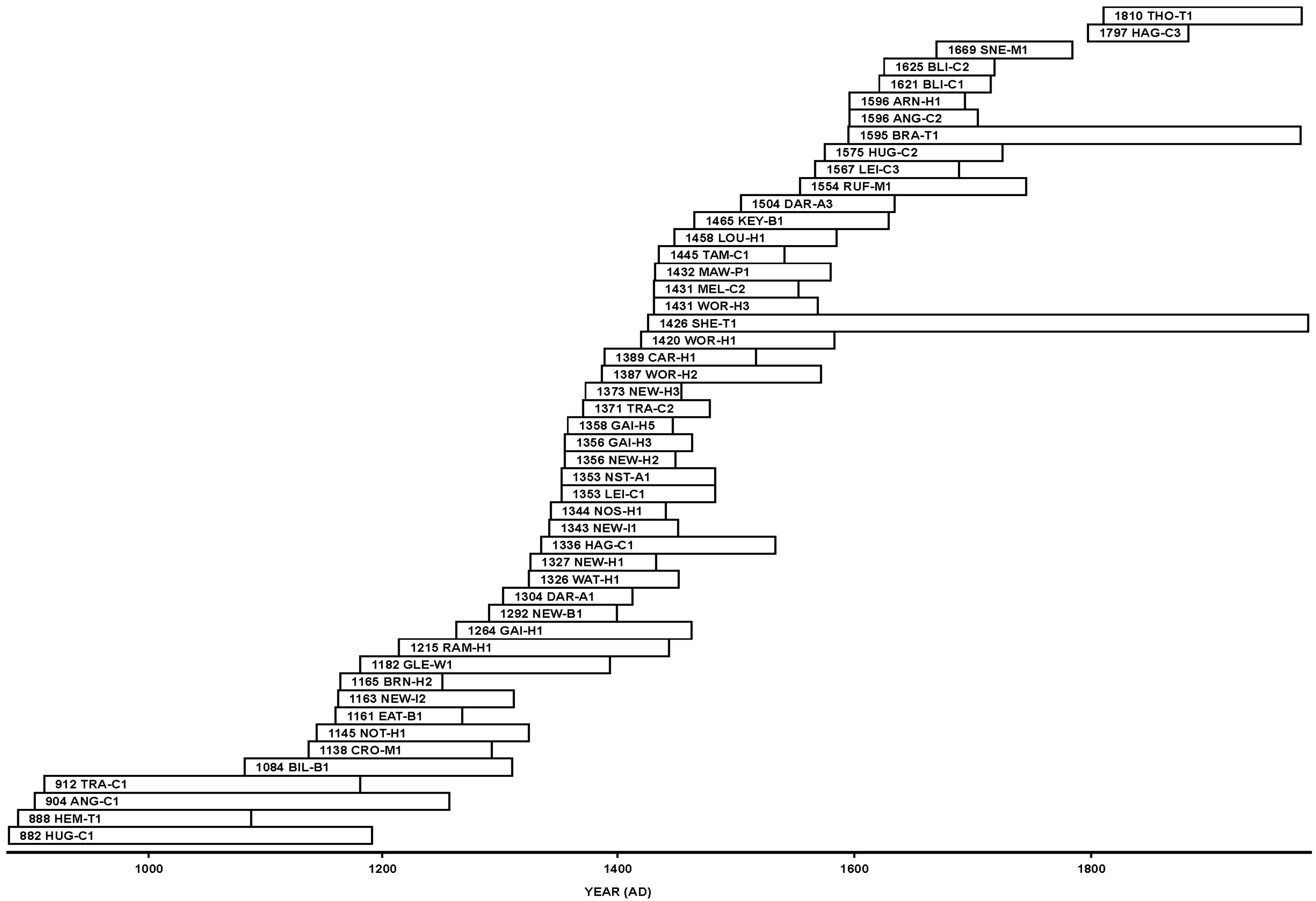
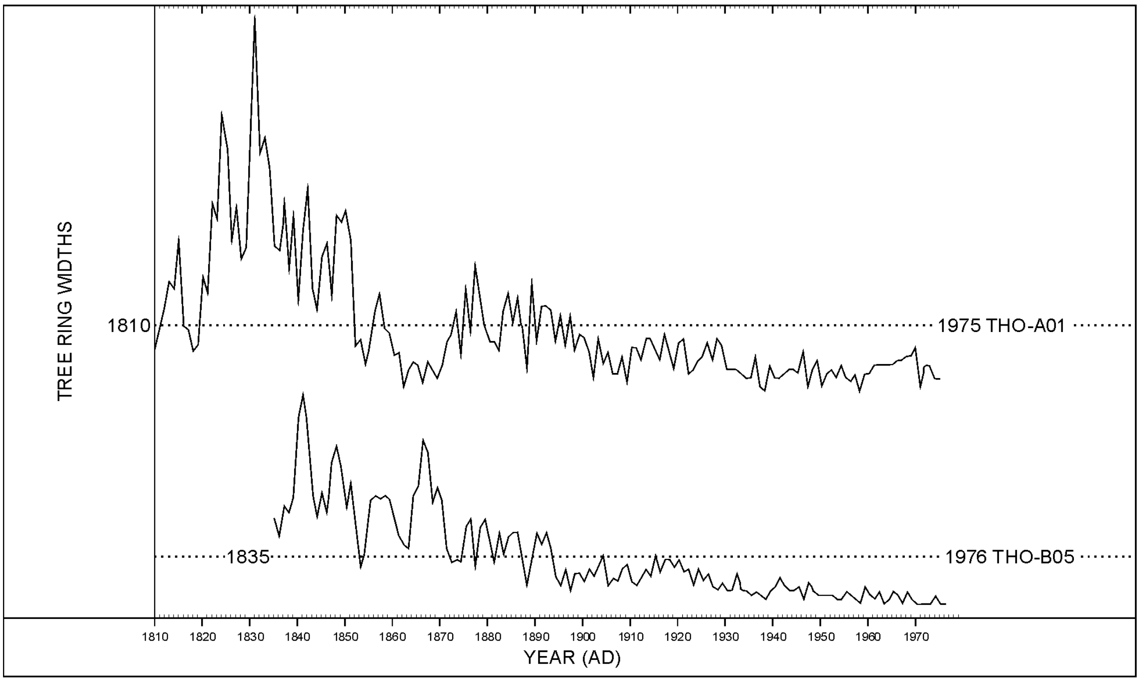


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

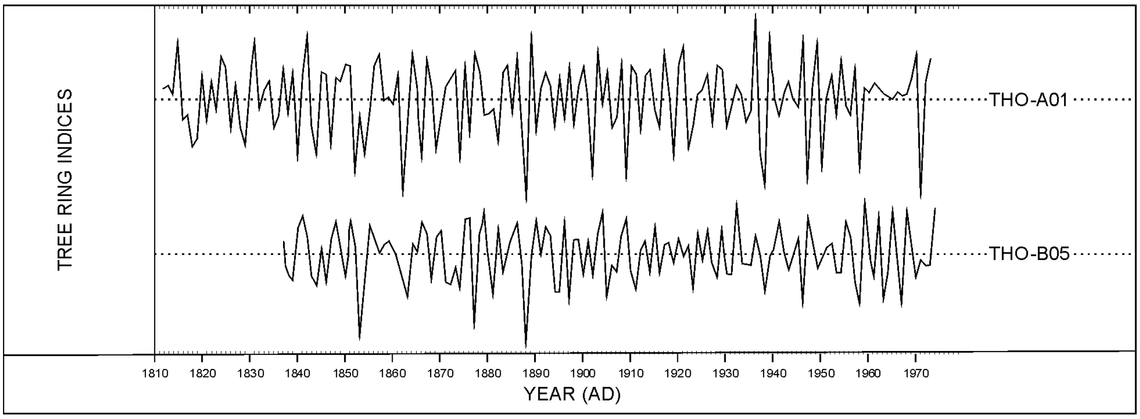


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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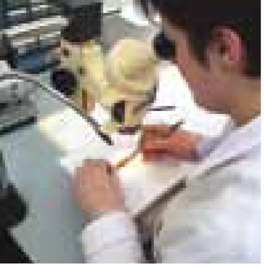
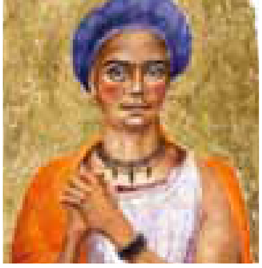


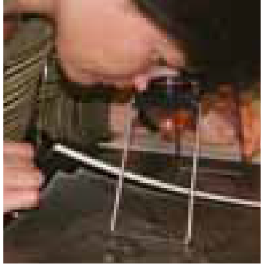


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