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The Shambles 6 Market Street North Walsham Norfolk

Tree-ring Dating of Oak Timbers

Alison Arnold, Robert Howard, and Cathy Tyers

Discovery, Innovation and Science in the Historic Environment

Research Report Series no. 3-2022

Front Cover: The Shambles in North Walsham. Photograph: Alison Arnold

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THE SHAMBLES
6 MARKET STREET
NORTH WALSHAM
NORFOLK

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SUMMARY

Tree-ring analysis was undertaken on timbers from two roofs, a first-floor ceiling, and an *ex situ* cellar joist, resulting in the successful dating of 29 samples. Analysis has shown that timbers from all areas of the building were felled in the winter of AD 1599/1600 and the winter of AD 1600/01, with no discernible difference in date between the two roof ranges or any part of the ceiling. It appears, therefore, that the extant timber work in this building dates to after the great fire that occurred in June AD 1600.

CONTRIBUTORS

Alison Arnold, Robert Howard, and Cathy Tyers

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INTRODUCTION

North Walsham High Street Heritage Action Zone

North Walsham, located some 24km north of Norwich (Fig 1), has just over 100 listed buildings, which is the highest number of any town in North Norfolk, with most of these thought to date from the eighteenth and early nineteenth century. The town was badly damaged by a fire on 25 June AD 1600, but fabric pre-dating this event is believed to survive, possibly in cellars and around the Market Place. The town is one of the 69 successful (HSEE014) High Street Heritage Action Zones bids (HSHAZ) selected in 2019, which is being delivered by Historic England to unlock the potential of high streets across England, fuelling economic, social and cultural recovery. Dendrochronology is one of the supporting elements to the HSHAZ programme in North Walsham, improving the understanding of the town centre area to inform and support future planning and improvement decisions. The centre of North Walsham was designated as a conservation area in 1972, with the area extended in 2009.

The Shambles

This Grade II listed building (List Entry Number 1039524), is located on Market Street (Fig 1). It is of two-storeys plus attics and is of L-shaped plan, consisting of an east–west aligned front range and a north–south aligned rear range, which is thought to date to the seventeenth century.

Front range

The roof over this part of the building has three principal-rafter and slightly cranked collar trusses, between which are two sets of purlins, windbraces, and common rafters; the truss in the gable end also has a tiebeam (Fig 2).

Rear range

The roof over this part of the building consists of six principal-rafter and collar trusses, between which are two sets of purlins, windbraces, and common rafters (Fig 3). At first-floor level there is an exposed ceiling frame with main beams and common joists (Fig 4); those in bays 3 and 4 are chamfered and stopped (Fig 5), whilst those in bays 1 and 2 are plain. During renovation works some of the cellar ceiling timbers were removed.

SAMPLING

Forty oak timbers (*Quercus* spp), from the front- and rear-range roofs and from the exposed first-floor ceiling frame of the rear range were sampled by coring; additionally, a cross-sectional slice was taken from an *ex situ* joist, also of oak, which has been removed from the ceiling of the rear-range cellar during renovations. Each sample was given the code NHW-A and numbered 01–41. Further details relating to all samples can be found in Table 1. The location of all *in* *situ* sampled timbers are indicated on Figure 6. Sampled trusses and main beams/bays have been numbered from east to west (front range) and north to south (rear range).

ANALYSIS AND RESULTS

Several of the samples broke during coring and those where the break was clean were glued back together using Evostick interior wood adhesive. Seven samples were found to have less than 40 growth rings and so were deemed unlikely to produce secure dating and rejected prior to measurement. The remaining 34 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. All measurements were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), resulting in 29 samples matching at the minimum value of *t*=4.4, to form a single group.

These 29 samples were combined at the relevant offset positions to form NHWASQ01, a site sequence of 138 rings (Fig 7). Attempts to date this site sequence against a series of relevant chronologies for oak resulted in it matching securely and consistently at a first-ring date of AD 1463 and a last-measured ring date of AD 1600. The evidence for this dating is given by the *t*-values in Table 2.

Attempts were then made to individually date the remaining ungrouped samples by comparing them against the reference chronologies, but these were unsuccessful, and they remain undated.

INTERPRETATION

Tree-ring analysis has resulted in the successful dating of 29 samples from the roofs of both the front and rear ranges, the first-floor ceiling frame to the rear range, and a sample taken from an *ex situ* joist from the rear-range cellar. To aid interpretation, these samples have been considered by area below. Where complete sapwood does not survive, the estimate that oak trees in this area had 15–40 sapwood rings (95% probability) has been used.

Front range

Roof
Seven of the samples from this roof have been dated. Two of these, NHW-A10 and NHW-A11, were taken from timbers with complete sapwood but *c* 10mm and *c* 5mm, respectively, of the friable outer rings were lost from the cores during the sampling process. By looking at how many rings there are in the surviving outer 10mm and 5mm on the respective samples it is possible to estimate that *c* 8 and *c* 4 rings, respectively, were lost. With last-measured ring dates of AD 1592 (NHW-A10) and AD 1595 (NHW-A11), this would give felling dates for the timbers

represented of *c* AD 1600 and *c* AD 1599. Three of the other dated samples have the heartwood/sapwood boundary ring, which in all cases is broadly contemporary, and suggestive of a single felling. The average heartwood/sapwood boundary ring date is AD 1585, giving an estimated felling date for the timbers represented to within the range AD 1600–25, consistent with these having also been felled in *c* AD 1599–1600.

Two other samples do not have the heartwood/sapwood boundary and so an estimated felling date cannot be calculated for them, except to say that with last-measured ring dates of AD 1548 (NHW-A12) and AD 1576 (NHW-A07) this would be estimated to be, at the earliest, after AD 1563 and after AD 1591, making it possible that both of these timbers were also felled in *c* AD 1599 or *c* AD 1600. Sample NHW-A12 matches NHW-A09 at t = 11.6, a value high enough to suggest that both timbers were cut from the same tree and hence felled at the same time (AD 1600–25). Additionally, sample NHW-A07 matches NHW-A09 at a value of t = 8.6 which, although not high enough to suggest a same-tree derivation, it does lend support to the likelihood that this sample was part of the same felling episode as the rest of the roof timbers.

Rear range

Roof

Nine of the samples taken from this roof have been dated. Two of these, NHW-A24 and NHW-A25, retain complete sapwood and the last-measured ring date of AD 1600, the felling date of the timbers represented. Five of the other samples have the heartwood/sapwood boundary ring, which is broadly contemporary and suggestive of a single felling. The average heartwood/sapwood boundary date for these samples is AD 1566. Allowing for sample NHW-A16 having a last-measured ring date of AD 1586 with incomplete sapwood, this gives an estimated felling date for the timbers represented within the range AD 1587–1606, consistent with them having also been felled in AD 1600. Two other samples do not have the heartwood/sapwood boundary ring but with last-measured ring dates of AD 1524 (NHW-A21) and AD 1570 (NHW-A14) this would give the timbers represented *termini post quem* for felling dates of AD 1539 and AD 1585, again making it possible that these two timbers were also felled at the same time as the other dated roof timbers.

Ceiling

Twelve of the samples taken from first-floor ceiling frame have been dated. One of these, NHW-A34, has complete sapwood and the last-measured ring date of AD 1599. Both the spring and summer growth cells are present for this last ring demonstrating that felling occurred in winter AD 1599/1600. A second sample, NHW-A29, was taken from a timber with complete sapwood, but the sapwood part of the core detached and could not be confidently re-attached and measured, although it is thought likely that no rings were lost at this break. The last-measured ring on this sample of AD 1585 is the heartwood/sapwood boundary which, with 14 rings on the detached portion, gives it a felling date of *c* AD 1599.

Six other samples have the heartwood/sapwood boundary ring which range between AD 1560 (NHW-A33) and AD 1579 (NHW-A40). This is perhaps slightly more than one would usually expect between a group of timbers felled at precisely the same time. These last-measured ring dates give a series of estimated felling date ranges from AD 1575–1600 at the earliest, to AD 1594–1619 at the latest. Thus, all samples can be seen to have a felling date range which encompasses AD 1599 and thus may be part of a single felling, although it remains possible that they were felled over a period spanning a small number of years.

Four samples do not have the heartwood/sapwood boundary and so estimated felling dates cannot be calculated for them. With last-measured ring dates of AD 1524 (NHW-A36), AD 1539 (NHW-A32), AD 1541 (NHW-A31), and AD 1542 (NHW-A37), these would give *terminus post quem* dates for felling of AD 1539, AD 1554, AD 1556, and AD 1557, respectively. Thus, it is possible that these four timbers were also felled at the same time as the other dated roof timbers and had simply been more heavily trimmed during conversion from tree to joist.

Cellar

Sample NHW-A41 was taken from a joist removed from the cellar ceiling during renovations. It has the heartwood/sapwood boundary ring date of AD 1575 allowing an estimated felling date to be calculated for the timber represented to within the range AD 1590–1615.

DISCUSSION

The tree-ring dating has demonstrated that the two roofs and first-floor ceiling frame are coeval, all being constructed with timber felled in, or around, AD 1599 and AD 1600; the *ex situ* joist from the cellar is also likely to have been felled at this time. The two samples (NHW-A24, NHW-A25) with absolute felling dates of AD 1600 can be seen to have both the spring and summer growth cells for this year, thus demonstrating that the trees represented were felled after the tree had stopped growing that year, ie in the winter of AD 1600/01 and the same can be said for NHW-A34, hence indicating that the tree represented was felled in the winter of AD 1599/1600. With the fire, which devastated the town, being known to have occurred in June AD 1600, it can now be said that, although it contains some timber felled possibly a year earlier, the dated extant timber in this building appears to be a product of re-building after the fire.

It had been speculated that the first-floor ceiling of the rear range was the result to two separate building phases but there is no discernible difference in date of these timbers regardless of which part of the ceiling they came from. It may be that the two bays with chamfered and stopped joists were a room of higher status than those served by the other two bays.

Although it is not possible to identify from where the timber was sourced, it can be seen that, with the exception of Alcester Town Hall in the West Midlands and Hays Wharf in London, the reference chronologies against which site sequence

NHWASQ01 matches most highly are located in East Anglia and the East Midlands. This is something one would expect to see if a relatively local woodland source had been used for the timber, and it should be noted that the timber for Hays Wharf is likely to have been derived from a wider area around London and, combining the data from 85 timbers, is very well replicated.

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TABLES

Table 1: Details of tree-ring series from The Shambles, 6 Market Street, North Walsham, Norfolk

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
FRONT RANGE						
Roof						
NHW-A01	North principal rafter, truss 1	44	01	1543	1585	1586
NHW-A02	Collar, truss 1	NM (29)	15	----	----	----
NHW-A03	North lower purlin, truss 1–2	NM (25)	--	----	----	----
NHW-A04	South common rafter 4, bay 1	46	04	----	----	----
NHW-A05	North principal rafter, truss 2	52	09	1544	1586	1595
NHW-A06	Collar, truss 2	70	01	----	----	----
NHW-A07	South common rafter 4, bay 2	43	--	1534	----	1576
NHW-A08	North lower purlin, truss 2–3	NM (30)	--	----	----	----
NHW-A09	North principal rafter, truss 3	108	11	1488	1584	1595
NHW-A10	Collar, truss 3	55	09+*c* 8 lost	1538	1583	1592
NHW-A11	North lower purlin, truss 3–4	66	22+*c* 4 lost	1530	1573	1595
NHW-A12	North principal rafter, truss 4	81	--	1468	----	1548
NHW-A13	South principal rafter, truss 4	NM (17)	--	----	----	----
REAR RANGE						
Roof						
NHW-A14	East principal rafter, truss 3	78	--	1493	----	1570
NHW-A15	West upper purlin, truss 3–4	74	h/s	1489	1562	1562
NHW-A16	West principal rafter, truss 4	88	02	1499	1584	1586
NHW-A17	East upper purlin, truss 4–5	64	h/s	1494	1557	1557
NHW-A18	West upper purlin, truss 4–5	84	h/s	1474	1557	1557
NHW-A19	East common rafter 2, truss 4–5	53	10	----	----	----
NHW-A20	East principal rafter, truss 5	NM (24)	h/s	----	----	----
NHW-A21	West principal rafter, truss 5	51	--	1474	----	1524
NHW-A22	Collar, truss 5	NM (38)	--	----	----	----

NHW-A23	West common rafter 4, truss 5®6	113	03	1463	1572	1575
NHW-A24	East principal rafter, truss 6	124	24C	1477	1576	1600
NHW-A25	West principal rafter, truss 6	126	18C	1475	1582	1600
First-floor ceiling frame						
NHW-A26	Joist 6, bay 1	87	h/s	1475	1561	1561
NHW-A27	Joist 10, bay 1	67	20	1528	1574	1594
NHW-A28	Main beam 2	68	02	----	----	----
NHW-A29	Main beam 3	103	h/s+14 detached	1483	1585	1585
NHW-A30	Joist 2, bay 3	48	13	1534	1568	1581
NHW-A31	Joist 5, bay 3	70	--	1472	----	1541
NHW-A32	Joist 6, bay 3	46	--	1494	----	1539
NHW-A33	Joist 10, bay 3	73	14	1502	1560	1574
NHW-A34	Joist 15, bay 3	59	34C	1541	1565	1599
NHW-A35	Main beam 4	54	h/s	----	----	----
NHW-A36	Joist 4, bay 4	53	--	1472	----	1524
NHW-A37	Joist 7, bay 4	63	--	1480	----	1542
NHW-A38	Joist 12, bay 4	73	35	1522	1559	1594
NHW-A39	Joist 13, bay 4	NM (39)	--	----	----	----
NHW-A40	Joist 14, bay 4	60	h/s	1520	1579	1579
Cellar ceiling						
NHW-A41	*Ex situ* joist	72	h/s	1502	1573	1573

h/s = the heartwood/sapwood boundary is the last ring on the sample
C = complete sapwood retained on sample; last-measured ring is the felling date
+*nn* = number of rings lost during coring or rings present in a detached section of core

Table 2: Results of the cross-matching of site sequence NHWASQ01 and example reference chronologies when the first ring date is AD 1463 and the last-measured ring date is AD 1600

Site reference	*t* – value	Span of chronology AD	Reference
Church of St Thomas A Becket, Tugby, Leicestershire	8.6	1440–1620	Arnold and Howard 2021
Powcher's Hall (east roof), Ely Cathedral, Ely, Cambridgeshire	7.8	1457–1609	Arnold *et al* 2004
Hays Wharf, Southwark, London	7.4	1248–1647	Tyers 1996a; Tyers 1996b
Church of St Catherine, Cossall, Nottinghamshire	7.3	1461–1619	Arnold and Howard 2016
Alcester Town Hall, Alcester, Warwickshire	7.3	1374–1625	Arnold and Howard 2020
Apethorpe Hall, Northamptonshire	6.9	1292–1639	Arnold and Howard 2008
Marriot's warehouse, King's Lynn, Norfolk	6.9	1310–1583	Tyers 1999
Manor House, Alford, Lincolnshire	6.8	1500–1668	Arnold *et al* 2003
Godwick Great Barn, Godwick, Tittleshall, Norfolk	6.8	1406–1597	Arnold and Howard 2013
Kirby Hall, Northamptonshire	6.7	1418–1597	Arnold *et al* Howard forthcoming

FIGURES

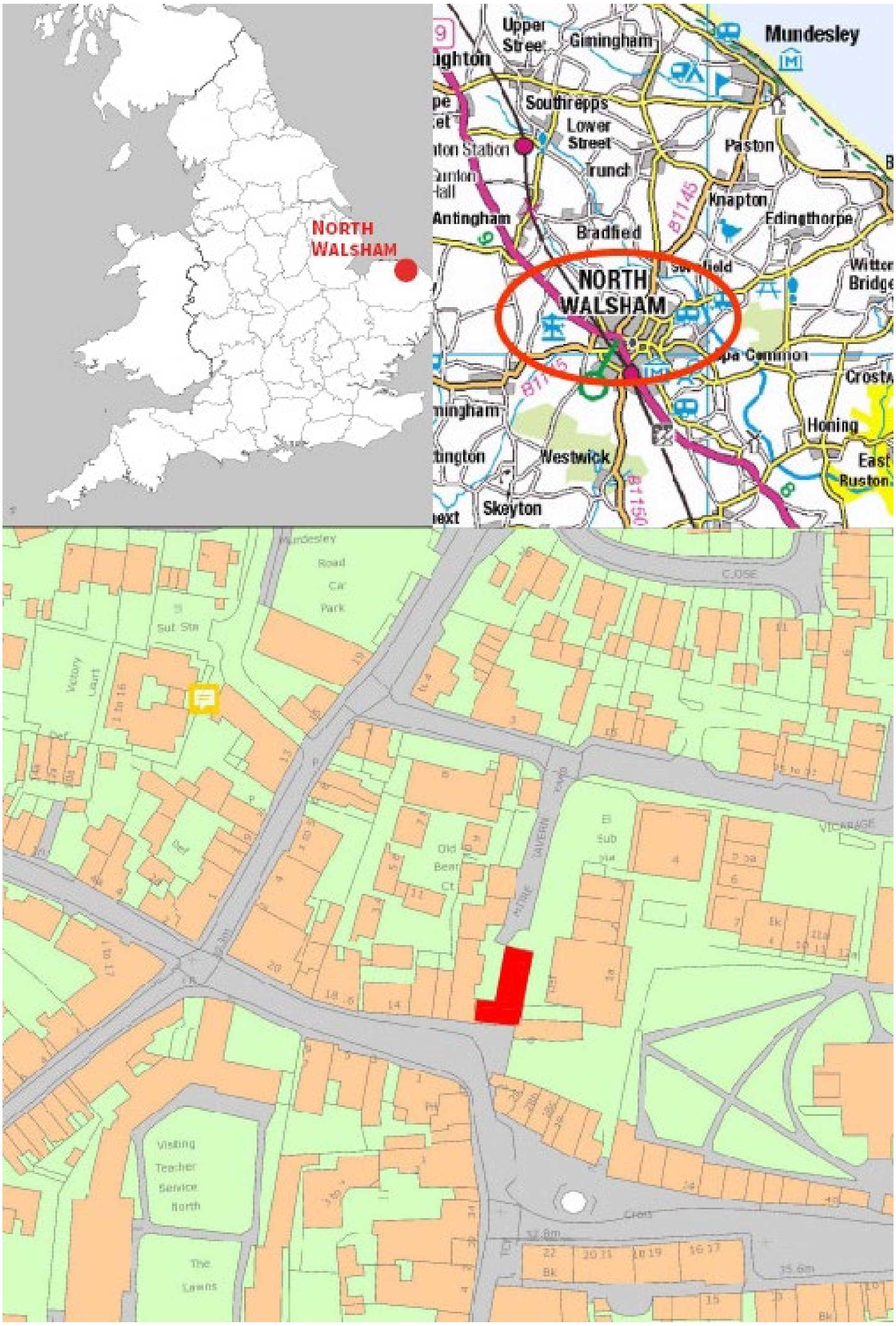


Figure 1: Map to show the location of The Shambles in North Walsham marked in red. Scale: top right 1:120000, bottom 1:1250. © Crown Copyright and database right 2020. All rights reserved. Ordnance Survey Licence number 100024900.

Figure 2: Truss 3, photograph taken from the east (Alison Arnold)

Figure 3: Rear range; truss 3, photograph taken from the north (Alison Arnold)

Figure 4: Rear range; ceiling structure, photograph taken from the south (Alison Arnold)

Figure 5: Chamfered and stopped joists in bay 3, photograph taken from the east (Alison Arnold)

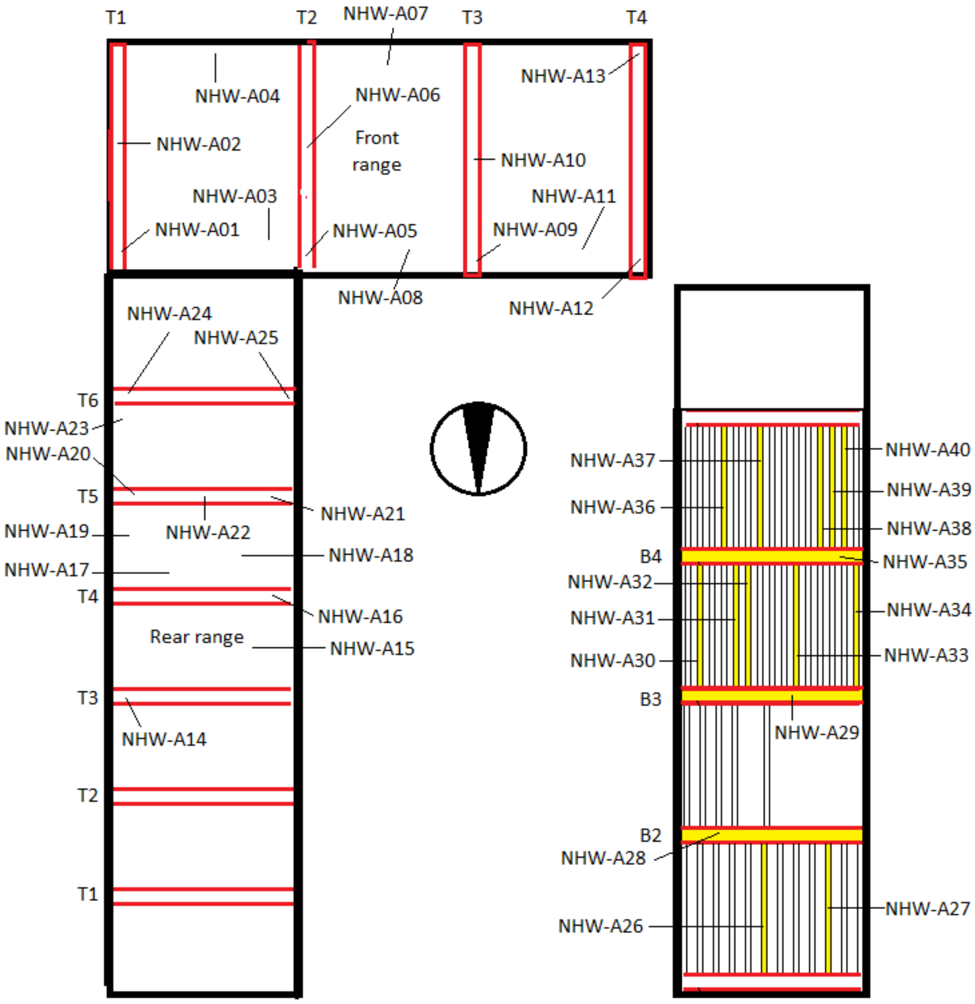
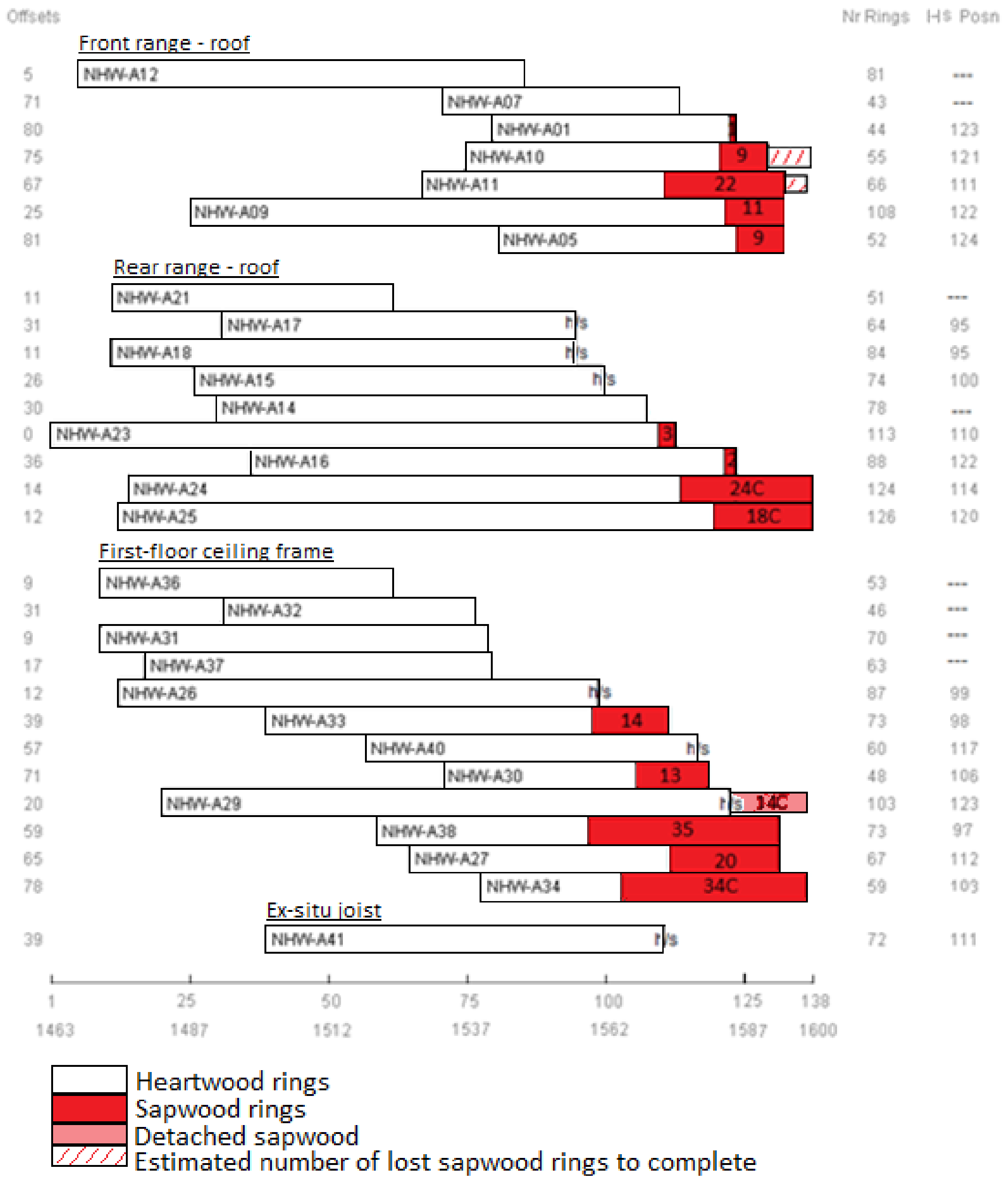


Figure 6: Sketch plan at roof and first-floor level (rear range), showing the location of sampled timbers



h/s = the heartwood/sapwood boundary ring is the last-measured ring

C = complete sapwood retained on sample; last-measured ring is the felling date.

Figure 7: Bar diagram of samples in site sequence NHWASQ01, sorted by area

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

NHW-A01A 44
189 213 161 79 108 183 237 209 197 188 181 148 208 174 185 185 112 184 166 228
199 159 168 174 206 223 212 244 187 139 168 234 247 142 152 186 185 198 134 138
125 169 204 144
NHW-A01B 44
183 209 171 85 105 178 244 199 198 203 181 151 193 144 186 195 117 207 187 229
197 146 175 186 211 238 198 219 176 140 174 239 243 172 140 195 178 193 137 121
130 196 229 148
NHW-A04A 46
257 210 200 254 205 221 159 205 161 211 168 249 221 183 129 145 179 172 283 179
172 192 193 173 329 161 179 260 180 228 184 161 150 107 94 142 187 189 208 218
157 163 150 152 146 92
NHW-A04B 46
256 208 210 255 206 210 154 209 175 223 166 245 223 186 126 147 178 182 277 176
157 190 182 173 329 153 186 219 174 211 183 157 144 113 94 144 171 190 219 223
160 153 153 152 136 99
NHW-A05A 50
530 433 409 358 501 588 502 502 417 361 210 394 378 312 394 384 412 407 482 467
468 329 445 404 450 412 452 266 190 121 200 150 143 127 203 131 209 153 251 150
311 256 386 257 353 216 275 230 245 206
NHW-A05B 31
355 483 428 477 385 454 235 159 103 178 142 125 149 183 127 211 150 228 158 280
272 385 234 309 226 277 221 234 323 313 274
NHW-A06A 70
129 124 183 152 150 79 88 233 223 260 350 280 223 192 253 368 319 231 175 164
127 151 162 239 78 109 76 71 65 74 105 134 121 91 103 105 80 190 442 278
204 304 190 149 95 124 97 233 254 264 252 214 237 287 245 219 183 166 145 194
149 234 177 142 200 215 264 181 140 125
NHW-A06B 70
141 126 185 145 157 82 84 164 217 266 358 263 220 202 254 409 319 229 161 164
122 153 139 226 86 97 81 67 64 77 110 124 126 93 102 108 71 194 447 279
210 308 182 146 88 129 97 242 251 256 270 210 226 280 241 214 186 141 145 187
148 253 194 161 216 210 244 181 144 142
NHW-A07A 43
173 158 141 189 313 299 278 132 165 120 209 226 205 326 305 317 157 151 93 117
123 180 110 152 203 140 225 114 153 231 183 166 224 205 195 235 179 171 150 199
206 132 155
NHW-A07B 43
147 156 145 191 323 351 311 128 167 117 214 229 193 332 306 342 186 154 88 114
109 190 108 162 200 146 213 128 182 216 178 174 228 214 196 236 181 176 144 213
200 130 167
NHW-A09A 108
181 192 130 96 85 153 112 192 156 107 57 50 61 59 71 78 86 49 98 40
73 67 126 96 109 91 57 127 164 131 208 98 88 64 63 141 76 135 200 201
101 97 86 146 99 133 150 169 232 257 301 297 279 119 188 94 178 210 192 407
283 295 180 175 124 108 126 195 115 155 176 146 170 112 174 244 160 117 145 174
193 235 180 138 112 194 204 137 205 108 178 257 443 87 204 106 136 147 164 119
140 142 217 159 171 162 158 169
NHW-A09B 108
155 197 110 97 81 141 111 196 144 107 65 51 57 46 75 75 99 51 94 45
60 78 114 106 89 97 62 122 157 136 208 101 83 70 57 145 82 135 191 201
118 81 92 140 102 135 145 171 230 259 312 300 280 124 187 97 180 200 193 438
307 285 183 167 127 102 114 206 116 156 175 144 174 111 185 258 159 121 145 168
194 235 178 137 123 185 204 153 197 107 179 259 434 95 212 103 131 150 162 116

140 140 217 157 189 159 172 165
NHW-A10A 55
459 426 452 411 285 341 469 466 293 257 300 350 253 260 225 245 178 290 199 235
184 147 249 230 229 238 214 184 213 248 232 241 238 192 159 196 194 265 127 123
179 126 187 112 114 161 122 114 169 152 117 213 93 95 68
NHW-A10B 55
420 428 464 402 289 343 488 454 302 268 305 339 256 259 236 218 173 283 194 242
195 145 237 222 238 248 189 182 205 247 245 239 228 192 156 205 193 259 123 125
188 134 181 111 112 160 118 119 166 158 122 206 98 89 73
NHW-A11A 66
300 399 344 315 348 459 377 332 342 329 349 280 209 292 297 347 238 190 251 280
143 156 124 164 111 191 169 145 123 100 107 103 113 103 89 68 59 52 63 87
84 97 101 120 137 169 135 89 102 109 129 68 80 87 86 112 146 112 115 127
83 112 110 143 154 106
NHW-A11B 66
303 417 353 328 341 463 365 356 352 308 337 302 206 274 289 327 232 192 250 284
138 157 117 163 108 188 167 130 122 87 111 96 115 101 83 65 54 45 74 73
90 105 103 109 140 179 128 86 101 113 131 69 73 86 94 111 152 114 112 130
83 117 99 141 160 110
NHW-A12A 81
300 505 511 441 297 278 225 383 294 141 248 154 299 138 142 82 183 108 243 280
213 209 158 82 71 142 89 215 138 63 42 46 50 34 67 58 73 43 79 35
59 73 71 88 61 69 45 65 94 116 164 86 64 49 56 72 43 61 113 125
67 48 61 114 97 116 131 132 127 203 303 288 317 123 235 131 238 207 222 446
384
NHW-A12B 81
272 484 490 447 291 280 220 386 292 137 245 158 298 139 141 81 181 111 244 283
215 212 162 79 67 142 93 215 135 70 42 42 50 36 62 63 74 42 76 39
48 80 69 86 63 68 46 81 82 117 161 82 64 46 54 74 42 69 104 129
70 47 60 105 106 120 132 132 141 183 313 290 316 118 228 133 237 207 233 453
371
NHW-A14A 78
180 245 256 261 197 181 218 194 230 154 197 171 163 166 258 163 213 232 232 238
198 136 154 182 178 249 168 150 163 109 137 328 194 159 109 118 88 70 56 57
53 76 70 94 116 112 160 235 119 135 137 113 211 206 153 128 200 132 166 173
174 185 342 189 117 125 158 154 140 102 153 187 163 130 142 130 262 165
NHW-A14B 78
170 235 262 257 202 183 189 183 228 161 182 170 170 169 255 166 205 249 206 213
200 137 160 192 183 236 170 155 151 116 124 326 184 163 115 128 84 71 57 52
53 73 74 82 133 91 177 212 128 132 140 109 245 193 152 118 213 131 189 156
183 189 322 195 120 123 155 167 157 110 154 189 157 125 145 126 227 168
NHW-A15A 74
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88 74 110 98 95 74 114 130 79 150 128 100 99 106 71 87 101 64 82 55
74 79 105 86 83 79 83 73 88 103 106 116 84 88 85 94 103 103 91 127
138 91 93 49 62 48 46 61 51 55 42 55 37 43
NHW-A15B 74
227 199 141 103 187 148 163 158 88 94 77 104 92 110 100 106 95 100 68 88
92 69 110 100 86 82 117 136 87 146 132 111 97 93 72 86 92 82 90 64
75 75 110 81 86 81 81 82 84 101 104 123 84 89 80 102 109 92 97 135
138 86 87 48 67 49 54 57 44 54 50 50 35 37
NHW-A16A 88
102 134 130 182 162 209 101 159 148 127 217 192 167 179 203 175 175 166 166 203
157 172 130 186 87 152 131 121 82 58 58 47 62 94 74 145 181 152 189 102
202 284 197 144 191 179 223 181 182 267 295 177 195 161 242 282 298 312 155 167
251 218 170 160 185 302 198 188 196 201 244 160 188 137 111 148 224 138 162 164
132 193 172 142 135 280 261 159
NHW-A16B 88
118 131 126 177 164 211 101 154 148 133 214 189 171 176 201 172 167 169 169 196

163 169 132 181 89 145 128 130 73 63 44 46 71 87 88 128 183 150 197 102
221 275 175 135 185 180 214 175 177 256 335 172 198 157 249 282 296 307 163 160
246 219 166 159 178 268 187 185 201 202 244 161 191 139 110 138 232 138 155 160
132 194 172 148 130 294 276 173
NHW-A17A 64
180 246 211 179 173 145 134 129 121 151 114 93 91 77 85 115 108 142 121 137
110 120 149 116 150 124 114 107 87 107 105 77 137 144 133 128 85 151 116 130
118 102 104 102 119 175 167 92 77 61 71 63 81 82 82 86 74 51 37 49
52 72 51 64
NHW-A17B 64
194 250 211 183 182 147 142 130 118 134 122 91 87 79 85 114 107 151 113 137
104 116 136 114 152 119 120 102 85 104 108 78 137 146 126 132 80 148 116 136
116 105 92 96 100 166 156 92 84 62 61 70 89 76 88 90 73 54 31 45
45 72 51 61
NHW-A18A 84
205 273 164 185 224 173 193 150 144 160 194 172 190 291 173 144 142 144 116 149
124 127 132 105 107 82 113 111 169 163 144 100 92 73 96 137 92 138 106 136
102 105 126 108 133 106 108 105 77 86 78 76 104 109 103 102 72 111 99 85
101 88 105 101 105 176 173 92 75 73 98 83 103 100 123 136 99 90 50 72
59 88 84 76
NHW-A18B 84
195 273 163 185 228 169 190 150 143 162 189 180 189 265 179 150 143 156 121 150
119 130 121 100 104 81 102 123 163 164 148 98 93 79 95 139 96 132 111 133
101 110 124 106 138 100 109 116 76 80 77 89 94 111 102 102 67 115 95 93
94 91 104 103 100 179 171 91 75 69 102 88 99 101 132 122 99 86 53 76
57 86 86 82
NHW-A19A 40
208 205 251 238 218 174 145 75 195 122 129 116 145 168 179 189 165 110 124 100
106 113 109 98 80 97 106 103 92 110 88 103 93 101 78 72 64 57 77 101
NHW-A19B 43
182 217 156 192 171 252 301 185 206 184 200 218 244 241 213 245 229 233 191 140
82 198 132 121 127 142 179 172 206 171 105 124 108 112 107 119 97 73 94 105
117 96 137
NHW-A21A 51
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183 138 209 153 139 165 115 148 135 141 195 113 105 111 123 211 190 171 144 156
132 125 176 176 225 128 170 179 161 89 99
NHW-A21B 51
359 524 509 339 402 450 359 319 291 354 344 279 318 358 193 270 240 129 109 130
176 147 191 150 140 167 109 153 132 133 195 116 102 116 144 216 181 174 154 152
131 135 173 174 227 125 174 178 159 89 100
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256 390 346 277 275 241 321 395 292 357 199 118 131 91 80 89 96 93 89 96
89 101 97 107 147 112 121 117 85 61 91 120 84 112 59 58 41 30 23 32
48 88 48 53 53 28 54 39 61 50 49 43 32 28 26 50 33 17 28 34
27 36 22 23 26 16 18 22 19 18 27 27 19 19 21 21 40 40 35 15
24 39 50 67 67 93 76 35 32 28 40 35 50 57 43 67 35 77 51 43
74 64 74 87 88 97 122 129 108 131 150 128 137
NHW-A23B 113
259 368 329 282 266 236 311 381 276 359 199 122 117 94 93 91 114 100 82 104
86 96 96 103 145 109 122 111 69 55 96 122 73 107 55 50 46 27 23 27
50 86 49 52 47 29 53 35 62 50 44 44 37 24 27 43 36 18 28 31
29 30 22 25 22 14 17 22 15 20 25 27 22 24 17 21 40 42 32 17
24 37 44 79 68 91 61 37 31 25 35 31 55 56 43 62 40 74 49 54
74 61 76 73 85 97 115 125 100 129 149 126 137
NHW-A24A 124
282 374 420 451 330 379 337 330 225 199 240 133 189 227 153 181 112 117 174 185
107 103 113 82 107 87 91 85 62 74 83 127 134 132 136 118 103 99 104 93
91 118 103 78 59 127 64 83 71 86 121 111 130 107 142 143 102 83 168 113

144 111 103 112 105 65 74 67 110 80 68 79 99 65 82 62 44 43 65 68
79 67 74 59 70 67 66 89 61 57 49 71 82 86 82 73 49 79 63 52
45 47 66 61 66 56 66 64 62 89 60 57 106 72 90 103 97 113 104 120
78 60 52 67
NHW-A24B 124
278 372 418 452 326 385 343 321 235 196 250 126 184 228 159 173 107 114 171 188
101 107 115 84 118 78 94 79 70 72 85 129 132 115 130 105 90 96 103 98
93 109 113 73 67 121 70 79 66 84 125 112 139 96 146 143 101 90 166 104
140 119 96 120 98 68 78 71 119 83 75 67 92 62 74 61 46 50 58 67
74 64 85 63 56 81 56 104 61 51 61 63 89 76 77 80 65 68 66 47
46 47 69 55 69 64 67 59 68 78 67 53 109 81 95 87 115 91 112 117
67 54 53 65
NHW-A25A 126
473 364 321 340 503 450 323 410 316 305 229 258 334 197 235 259 159 179 150 144
202 269 169 143 151 186 175 171 128 139 84 130 125 141 210 215 168 170 132 104
108 109 92 174 98 88 84 107 71 112 82 105 151 173 130 122 217 196 126 107
206 167 169 171 197 228 192 119 103 144 180 164 141 137 184 132 131 78 77 89
95 67 93 72 100 75 87 96 69 63 46 47 52 68 93 70 93 100 91 107
77 64 58 71 73 75 72 83 83 85 85 73 65 82 123 60 108 127 219 175
111 89 71 67 59 80
NHW-A25B 126
438 361 313 337 503 455 318 406 320 297 227 260 324 203 240 261 161 169 155 145
204 271 168 134 159 200 182 161 141 141 91 148 135 141 230 220 170 168 127 109
102 108 86 172 105 86 86 114 65 110 83 113 151 159 140 122 230 208 128 106
208 168 175 172 186 237 187 116 114 122 163 167 141 126 186 135 130 82 75 80
103 74 85 80 92 80 88 88 70 65 52 43 54 76 90 76 83 105 99 106
77 71 57 61 75 72 72 76 78 88 88 77 72 105 96 70 103 132 215 170
119 84 84 58 66 59
NHW-A26A 87
236 307 232 287 221 187 185 167 195 172 177 161 202 180 164 157 134 102 120 113
102 99 68 45 53 55 50 58 65 49 49 47 37 73 68 59 65 68 68 49
66 71 90 109 87 62 76 65 82 79 62 105 123 93 85 68 123 93 77 85
98 88 95 102 141 153 85 90 75 100 100 123 117 127 196 110 121 61 92 50
109 85 73 73 71 70 66
NHW-A26B 87
240 300 234 281 228 190 187 161 195 181 178 160 195 175 150 153 133 81 121 113
102 94 54 49 58 54 54 50 60 71 63 39 38 69 67 55 69 69 69 51
57 88 89 103 76 73 69 71 77 84 60 101 140 89 76 66 114 82 84 83
92 87 90 110 145 154 80 90 86 97 103 125 114 120 176 116 118 57 84 59
110 82 70 74 75 66 69
NHW-A27A 67
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158 179 116 124 73 101 83 112 92 107 93 96 117 91 111 134 122 118 119 129
116 134 98 134 133 132 82 105 105 134 147 143 160 102 80 63 81 68 97 79
110 103 92 76 103 92 103
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46 72 75 87 86 83 94 113 109 122 117 168 196 147 102 121 151 159 166 123
156 171 116 117 78 95 79 119 95 109 104 88 113 85 120 132 124 110 116 125
130 126 108 126 125 126 85 113 112 119 158 143 153 99 80 67 81 78 89 76
109 106 92 77 104 87 103
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101 178 152 196 294 256 289 338 284 387 367 342 409 451 371 377 319 390 325 287
260 212 214 193 164 172 200 165 98 125 119 99 93 83 86 84 79 73 190 199
128 199 130 124 118 107 128 122 86 88 77 59 96 79 101 82 95 61 51 71
86 89 80 69 80 79 79 106
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266 209 218 190 169 166 194 155 105 120 127 108 106 72 82 77 78 72 195 198
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86 94 78 72 80 69 91 91
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225 251 175 153 164 149 266 199 219 212 229 199 194 220 160 173 156 165 144 120
120 158 113 184 138 183 163 155 220 217 203 148 172 176 157 131 165 148 149 133
161 159 180 164 156 189 237 204 209 180 208 177 248 237 196 205 255 202 164 142
152 182 193 184 188 139 235 172 258 175 164 160 157 189 182 184 159 202 153 170
149 238 282
NHW-A29B 103
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226 252 161 159 171 146 268 202 227 206 225 203 194 213 161 172 161 171 143 116
121 155 119 187 151 178 159 157 214 224 206 141 173 173 168 118 157 153 150 130
163 160 179 163 153 203 237 203 210 184 202 177 256 235 198 195 259 195 181 145
164 197 180 179 189 144 235 187 275 171 170 160 155 185 180 192 157 209 154 161
157 232 314
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141 181 148 262 172 271 299 288 298 339 241 339 379 260 322 365 252 287 185 194
231 279 235 176 171 224 194 161 193 178 216 210 217 214 192 210 206 159 168 176
131 120 107 99 106 126 130 123
NHW-A30B 48
137 179 147 250 181 251 290 276 294 330 243 327 360 264 318 385 245 285 191 206
225 254 238 188 175 210 190 155 204 175 193 192 200 207 182 215 195 148 159 167
125 137 109 93 89 120 134 117
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236 157 156 314 270 127 130 135 107 151 155 166 212 165 120 128 137 123 341 300
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115 158 172 137 164 247 240 268 476 287
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236 159 164 316 257 109 138 135 105 148 159 167 201 139 124 124 133 142 334 265
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100 156 169 136 168 250 229 264 470 302
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273 292 378 571 452 334
NHW-A32B 46
698 416 358 463 312 335 301 258 233 356 476 560 419 285 177 176 181 133 165 133
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279 298 374 579 464 346
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209 273 281 369 271 225 154 141 173 159 331 238 191 120 123 119 194 119 89 96
201 151 409 201 213 174 130 127 115 140 110 191 200 161 159 217 211 248 371 306
374 280 207 189 180 148 117 180 135 168 154 159 158 174 104 114 122 107 102 83
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NHW-A33B 73
208 275 283 364 271 228 151 143 178 149 329 247 181 128 121 118 191 119 87 97
201 153 411 202 221 186 125 131 119 125 110 196 192 159 162 217 210 248 367 303
376 272 196 193 186 143 120 174 132 162 142 157 153 170 104 113 111 108 104 88
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104 121 93 129 101 92 94 87 85 113 119 109 93 76 59 60 50 56 69
NHW-A34B 59
194 208 201 212 265 280 247 253 323 233 263 204 309 359 312 229 177 175 180 188
150 140 113 123 137 126 119 120 121 145 99 93 144 111 117 90 70 107 128 105
101 112 92 125 106 99 89 79 97 108 117 114 89 80 60 60 50 47 65

NHW-A35A 54
115 191 316 408 389 290 460 478 583 398 326 161 192 271 306 274 327 266 286 232
333 355 262 134 103 104 82 99 163 272 298 229 175 175 139 173 173 206 274 239
290 190 141 161 159 145 125 155 156 235 135 191 245 246
NHW-A35B 54
109 194 256 405 402 299 534 629 579 401 325 188 201 261 280 267 311 268 283 235
328 345 258 136 104 100 97 109 182 258 305 244 176 187 141 166 182 199 288 252
280 180 147 147 159 147 124 158 156 234 143 200 252 217
NHW-A36A 53
183 188 161 347 369 181 108 168 144 112 137 164 197 175 176 160 162 180 160 121
119 163 133 115 131 101 129 160 121 135 134 116 162 154 133 131 98 157 100 103
101 76 107 76 89 93 143 79 81 84 87 75 176
NHW-A36B 53
188 198 145 357 368 175 113 159 146 111 141 150 204 170 166 168 157 191 161 122
115 168 137 119 133 115 133 167 116 145 134 105 150 158 130 125 92 164 97 102
108 70 118 69 90 97 137 89 78 88 87 67 185
NHW-A37A 63
252 243 301 411 372 287 338 395 304 267 246 153 179 201 218 208 257 235 235 295
243 367 327 293 250 234 209 168 134 185 126 128 132 111 125 85 118 131 205 118
117 113 145 104 273 154 142 131 117 130 115 146 118 163 129 127 103 176 201 204
265 238 229
NHW-A37B 63
291 247 292 403 379 286 339 385 306 265 253 158 180 205 217 211 256 232 237 290
253 367 321 292 253 229 207 171 147 186 135 124 135 112 127 83 115 136 184 129
115 103 143 110 267 139 142 121 118 132 116 140 122 162 140 119 105 174 189 209
273 234 231
NHW-A38A 73
119 123 352 153 207 186 122 118 101 139 137 185 178 169 148 244 236 277 394 273
403 369 306 331 340 247 259 431 329 377 234 280 258 270 216 184 169 201 171 145
76 71 78 101 91 89 92 111 127 156 106 126 123 100 78 91 104 124 98 103
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NHW-A38B 73
142 116 361 145 210 185 129 131 109 132 143 187 180 174 139 232 241 272 378 275
408 365 330 305 337 250 258 431 325 383 223 264 262 288 226 182 166 200 170 152
66 62 71 99 85 85 101 116 123 140 102 130 121 103 75 87 97 123 91 105
87 73 102 99 96 84 76 91 112 88 82 64 67
NHW-A40A 60
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207 99 109 129 160 160 158 125 143 149 112 100 72 51 33 107 125 117 105 87
119 124 102 96 73 62 99 115 122 123 171 84 70 116 192 197 170 130 139 132
NHW-A40B 60
238 353 210 217 186 147 107 130 126 117 108 131 115 123 102 151 136 124 159 229
199 100 107 136 158 160 155 126 140 153 109 97 72 52 32 112 123 113 110 84
123 125 98 97 74 66 95 122 114 126 167 87 72 110 192 200 167 128 137 135
NHW-A41A 71
273 192 231 195 199 190 157 233 207 150 126 103 122 80 124 98 198 179 172 132
187 105 253 192 195 178 220 128 108 159 146 151 113 169 140 125 131 177 155 121
91 132 128 152 125 80 116 148 123 97 57 79 64 82 99 64 63 68 114 113
83 90 56 63 59 50 80 77 99 92 74
NHW-A41B 72
259 200 232 145 165 167 148 211 221 158 161 130 135 81 132 92 218 215 193 125
184 103 229 173 170 187 215 131 104 157 148 146 114 173 127 138 123 180 151 123
92 123 129 155 129 87 112 146 129 101 64 73 63 86 88 67 62 70 113 106
87 98 64 52 60 46 77 77 87 89 72 69

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	

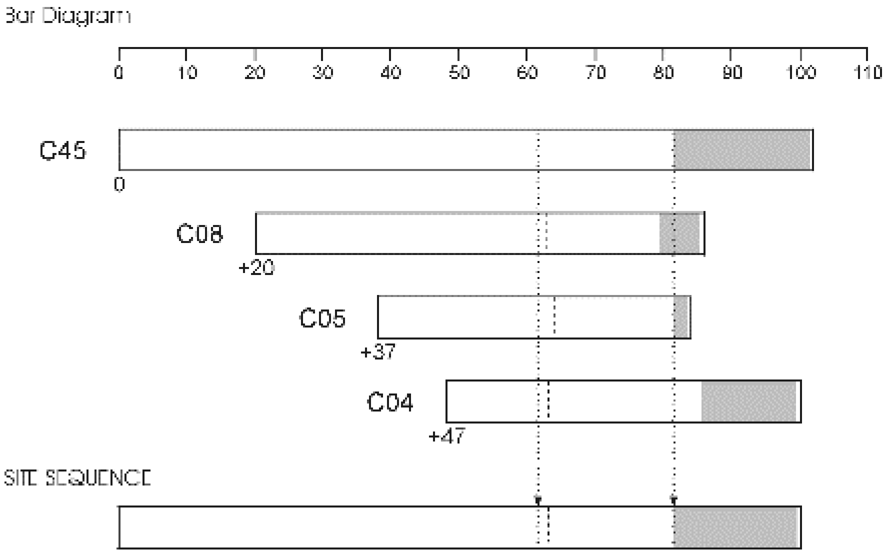


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

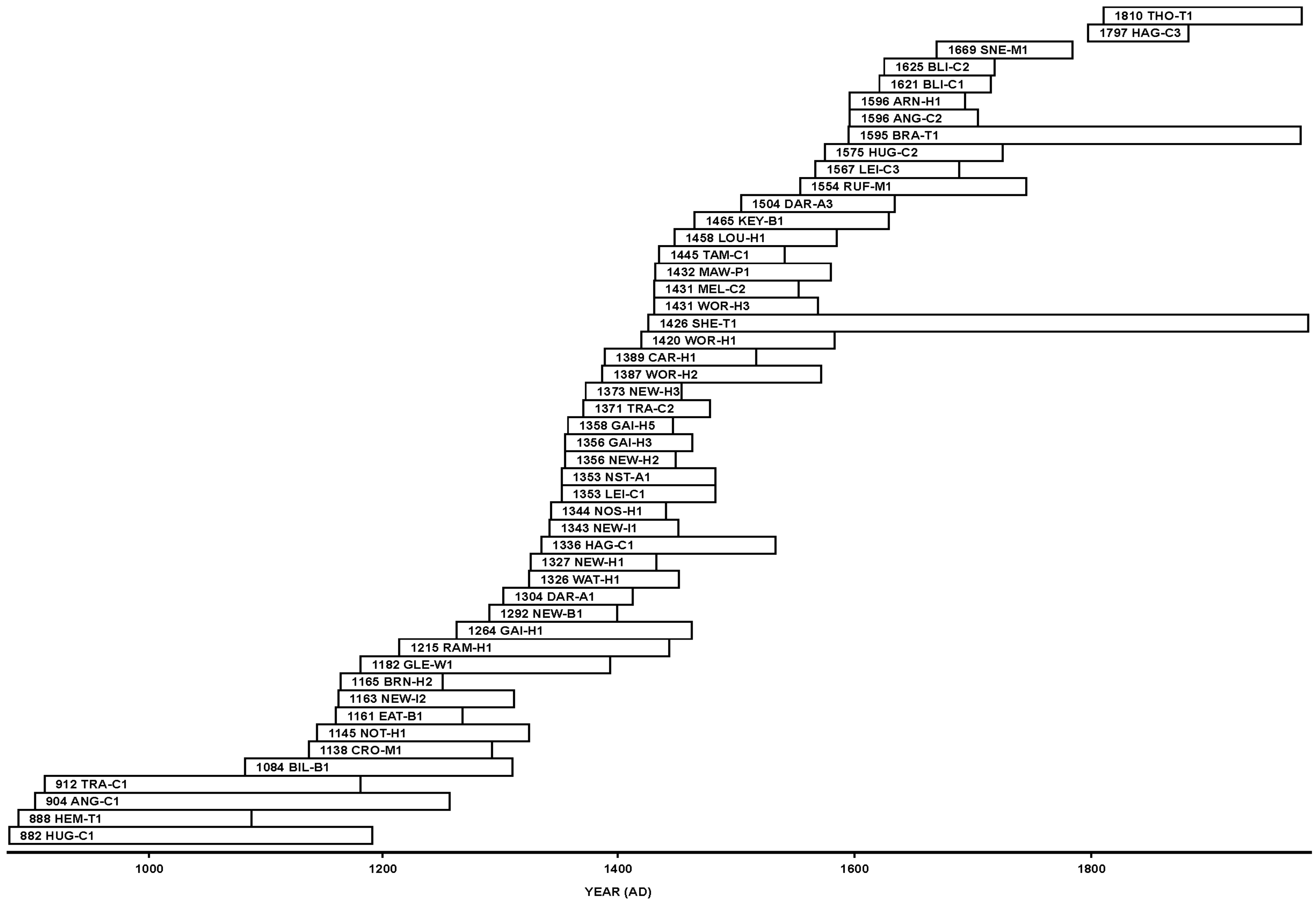
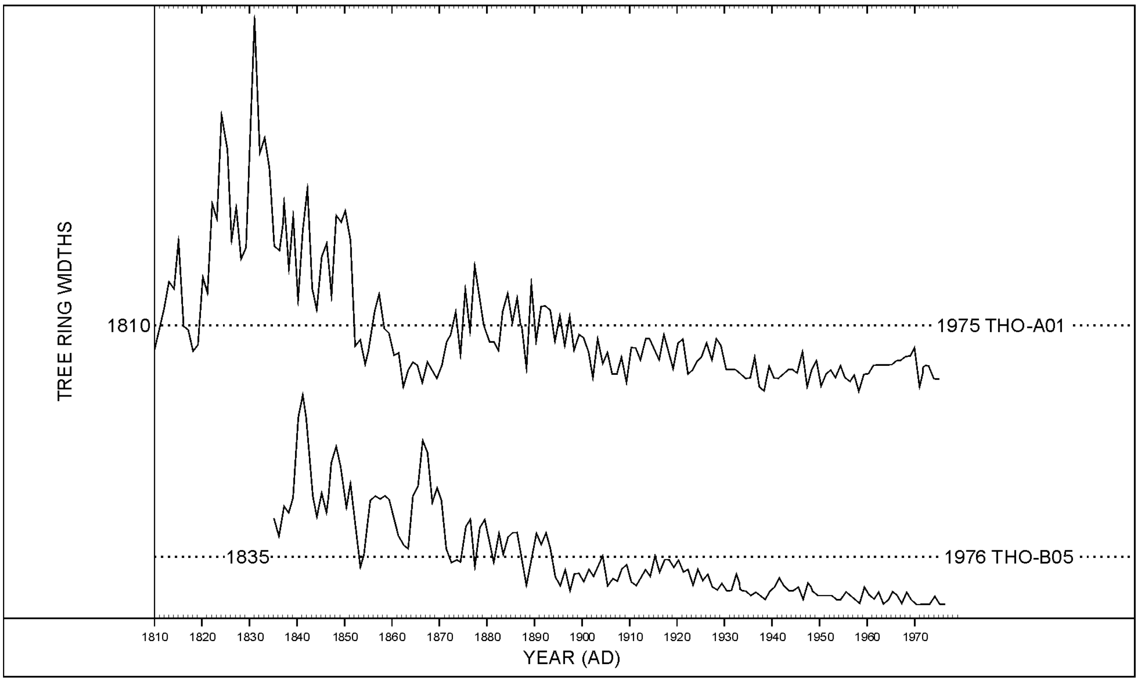


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

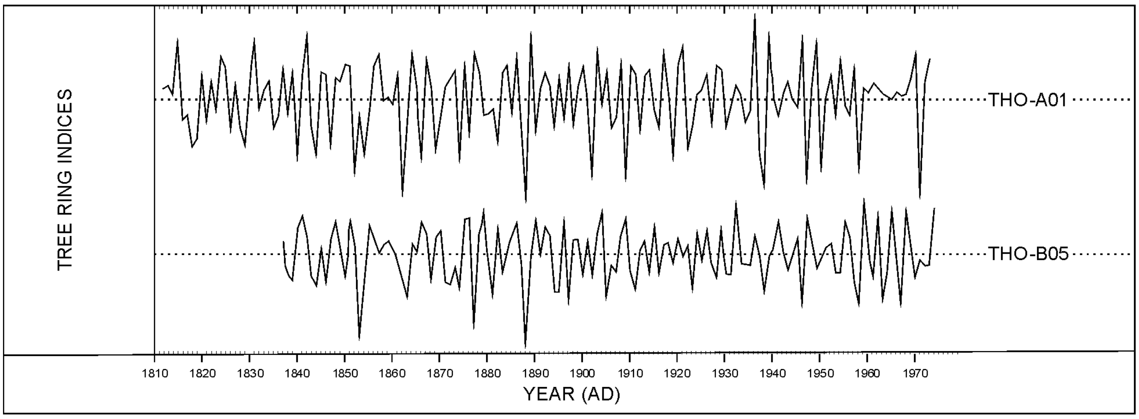


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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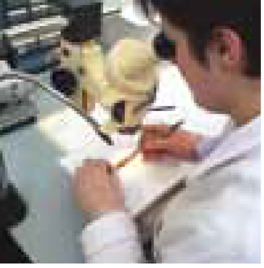
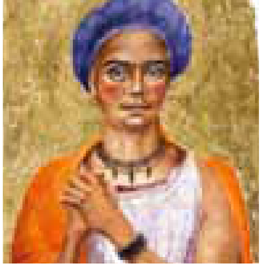


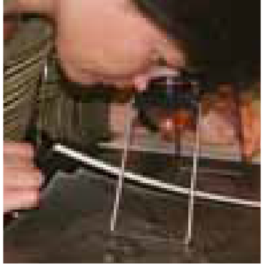


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