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Summary

Twenty-six samples from the roof of the west range of the cloister at Wells Cathedral were analysed by tree-ring dating. This analysis produced a single site chronology of twenty-three samples, having 147 rings and spanning the period AD 1319 to AD 1465. Interpretation of the sapwood on all the dated samples would suggest that the timber represented has an estimated felling date in the range AD 1475 - 80.

Keywords

Dendrochronology
Standing Building

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TREE-RING ANALYSIS OF TIMBERS FROM THE ROOF OF THE WEST RANGE OF THE CLOISTER, WELLS CATHEDRAL, SOMERSET

Introduction

Exactly when the construction of Wells Cathedral (ST 552459; Figs 1 and 2) was begun is not absolutely certain, but work was certainly in progress by AD 1186. It is one of the first truly English Gothic churches, using the pointed arch throughout rather than the earlier round-headed romanesque type. The main body of the church was largely complete by AD 1215, with the nave and the great west front, with its 400 niches, being finished thereafter; it was consecrated to St Andrew in AD 1239. The east end of the cathedral was remodeled in the fourteenth century and twin towers were added to the west front.

Of particular relevance to this report is the twenty-two bay roof of the west range of the cloister walk. Architectural and structural examination, undertaken by Dr Warwick Rodwell, shows that the present roof is clearly of one unified design and of a single build. Visible in the roof are a small number of timbers forming the ceilings of the rooms below which, on the basis of their moulding and some empty mortices, appear to be reused. These reused timbers are excluded from the present programme of analysis.

On stylistic grounds the roof of the west cloister is assigned to the late-fifteenth century, *c* AD 1460 – 90. On the basis of structural evidence the west cloister appears to be later than the east, the majority of timbers in which, on the basis of tree-ring dating, have a felling date of AD 1450 – 1 (Howard *et al* 2001), and earlier than the south cloister.

The Laboratory would like to take this opportunity to thank the Dean and Chapter of Wells Cathedral for allowing sampling. The Laboratory would also like to thank Dr Warwick Rodwell, consulting archaeologist, for advising on and assisting with the sampling, and for providing plans and other drawings. We would also like to thank Michael Hayecraft, Clerk of Works, for his invaluable cooperation and assistance during sampling. Finally, we would like to thank the roofing contractors of Ellis & Co, Restoration Ltd of Trowbridge, for their unstinting help in maintaining access to the roof space at all times during stormy conditions in late January.

Sampling

Sampling and analysis by tree-ring dating of the roof of the west range of the cloister were commissioned by English Heritage. The purpose of this was to establish a precise date for the main roof construction and help understand the chronological development of the cathedral complex. The results of this work would help inform grant-aided repairs to the roof of the cloister.

The roof consists of twenty-one principal rafter trusses with tie beams and collars. Between the principal trusses are sets of coupled common rafters. Together these carry single purlins supported by thin curved braces from the principal rafters. The roof has a ridge, though for the most part this appears to be a more recent replacement. The roof also has a wall plate, but this could not be accessed due to the curvature of the ceiling.

Thus, after discussion with Dr Rodwell and in conjunction with the English Heritage brief, a total of twenty-six core samples was obtained from the available timbers. All these samples were taken from timbers which were believed to be integral to the structure of the roof, these for the most part being principal rafters and collars. Each sample was given the code WLS-C, (for Wells, site "C") and numbered 20 – 45 (samples WLS-C01 – 19 having been obtained from the east cloister roof). The positions of these samples are marked on plans and drawings provided by Warwick Rodwell, reproduced here as Figure 3a/b. Details of the samples are given in Table 1. In this Table, as in Figure 3a/b, all trusses are numbered from north to south.

Analysis

Each of the twenty-six samples was prepared by sanding and polishing and the growth-ring widths of all were measured; the data of these measurements are given at the end of the report. The growth-ring widths of all twenty-six were compared with each other by the Litton/Zainodin grouping procedure (see appendix) and at a minimum t-value of 4.5 twenty-three of these grouped to form a single site chronology. The relative positions of these samples are shown in the bar diagram, Figure 4.

Because of the satisfactory cross-matching the samples were combined at these relative positions to form WLSCSQ04 (site chronologies WLSCSQ01 - 03 being produced of material from the east cloister), a site chronology of 147 rings. Site chronology WLSCSQ04 was compared with a series of relevant reference chronologies for oak, indicating a cross-match when the date of its first ring is AD 1319, and a last measured ring is AD 1465. Evidence for this dating is given in the t-values of Table 2.

Site chronology WLSCSQ04 was compared with the three remaining ungrouped samples, but there was no satisfactory cross-matching. Each of the three ungrouped samples was then compared individually with a full range of relevant reference chronologies. Again there was no satisfactory cross-matching

The material from both the east range roof (Howard *et al* 2001), and the west range roof were then analysed together. In the early stages of this analysis, at values down to t=5.5, two groups of samples formed, one made up only of material from the east range roof, and the other only of material from the west range roof. It is only at a value of t=5.4 that the material from the two roofs start to cross-match with each other. This analysis would tend to suggest that the timber for each of the two roofs came from different sources, though these two sources were perhaps not very far apart.

Interpretation

One of the samples in site chronology WLSCSQ04, WLS-C37, comes from a timber which retained complete sapwood. Unfortunately because of the fragile nature of the sapwood, about 1cm was lost from the outside of the core during sampling. Sample WLS-C37 retains 28 sapwood rings with a last measured ring date of AD 1465. This is the latest ring date of any sample in site chronology WLSCSQ04. On the basis of the sapwood remaining on this sample, and of observation and notes made at the time of coring, it is estimated that the 1cm loss from this core represents about 10 sapwood rings, certainly no more than 15. Such an estimate would indicate that the timber represented by sample WLS-C37 was felled about AD 1475, and almost certainly no later than AD 1480.

The relative position of the heartwood/sapwood boundaries on the other dated samples in site chronology WLSCSQ04 are generally indicative of timbers having the same, or at least a very similar, felling date. The earliest heartwood/sapwood boundary is at relative position 117, AD 1435, on sample WLS-C27. If it is accepted that the tree represented by this sample was also felled in AD 1475, it would have had 40 sapwood rings to the bark edge. This is not an unduly large number, the 95% confidence limit used by the Nottingham Laboratory for the amount of sapwood on mature oaks from this part of England being in the range 15 – 50 sapwood rings.

The sample with the latest heartwood/sapwood boundary is WLS-C45, at relative position 136, AD 1454. The tree represented by this sample would have had 21 sapwood rings to the bark edge if it too were felled in AD 1475. Such a figure is well within the 95% confidence limit.

Of course, it is not certain that all the trees used here were felled at exactly the same time. Given that this is a large 22-bay structure and part of an on-going complex of work, building may have taken some time and it is possible that timber was felled over a short period of a few years.

Conclusion

The analysis reported upon here has been able to address the questions posed by the English Heritage brief and provide a more reliable indication of the date of roof of the west cloister. It is estimated that all the timbers sampled and dated in site chronology WLSCSQ04 were probably felled in the period AD 1475 – 80. Such a date would accord well with that attributed to it on stylistic grounds, AD 1460 – 90, and show that it is indeed later than the roof of the east range by about twenty-five years. The dating of these two ranges may now help in attributing a more precise date to the roof of the south cloister, which is known to have followed on from that of the west range.

Although the timbers of the south range roof have not been inspected as to their suitability for tree-ring analysis it would certainly be worth doing so should circumstances permit. This, and the previous tree-ring analysis of the cloister roofs are helping in the understanding of the sequential development of the cathedral complex.

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Table 1: Details of samples from the west range of the cloister roof, Wells Cathedral

Sample no.	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
WLS-C20	West principal rafter, truss 3	117	h/s	AD 1321	AD 1437	AD 1437
WLS-C21	East principal rafter, truss 3	124	6	AD 1319	AD 1436	AD 1442
WLS-C22	East principal rafter, truss 4	84	h/s	AD 1364	AD 1447	AD 1447
WLS-C23	Collar, truss 4	98	no h/s	AD 1329	------	AD 1426
WLS-C24	East principal rafter, truss 5	80	h/s	AD 1372	AD 1451	AD 1451
WLS-C25	West principal rafter, truss 5	66	h/s	AD 1388	AD 1453	AD 1453
WLS-C26	East principal rafter, truss 6	111	h/s	AD 1329	AD 1439	AD 1439
WLS-C27	West principal rafter, truss 6	113	h/s	AD 1323	AD 1435	AD 1435
WLS-C28	Collar, truss 6	86	h/s	------	------	------
WLS-C29	Collar, truss 7	105	h/s	AD 1331	AD 1435	AD 1435
WLS-C30	East brace, truss 7	60	h/s	------	------	------
WLS-C31	West principal rafter, truss 7	119	h/s	AD 1330	AD 1448	AD 1448
WLS-C32	East principal rafter, truss 8	45	h/s	------	-----	------
WLS-C33	Collar, truss 8	85	h/s	AD 1366	AD 1450	AD 1450
WLS-C34	Collar, truss 9	71	2	AD 1381	AD 1449	AD 1451
WLS-C35	Collar, truss 10	73	h/s	AD 1374	AD 1446	AD 1446
WLS-C36	East principal rafter, truss 9	61	no h/s	AD 1368	------	AD 1428
WLS-C37	West principal rafter, truss 9	87	28c	AD 1379	AD 1437	AD 1465
WLS-C38	East principal rafter, truss 10	81	h/s	AD 1362	AD 1442	AD 1442
WLS-C39	West principal rafter, truss 10	74	h/s	AD 1372	AD 1445	AD 1445
WLS-C40	East principal rafter, truss 12	55	h/s	AD 1387	AD 1446	AD 1446
WLS-C41	West principal rafter, truss 12	72	h/s	AD 1371	AD 1442	AD 1442
WLS-C42	East principal rafter, truss 13	65	h/s	AD 1377	AD 1441	AD 1441
WLS-C43	West principal rafter, truss 13	54	h/s	AD 1391	AD 1444	AD 1444
WLS-C44	Collar, truss 14	57	no h/s	AD 1358	------	AD 1414
WLS-C45	Ridge beam, truss 13 – 14	60	h/s	AD 1395	AD 1454	AD 1454

*h/s = the heartwood/sapwood boundary is the last ring on the sample
c = complete sapwood retained on timber, all or part lost from core in sampling

Table 2: Results of the cross-matching of site chronology WLSCSQ04 and relevant reference chronologies when first ring date is AD 1319 and last ring date is AD 1465

Reference chronology	Span of chronology	*t*-value	
Bremhill Farm, Wilts	AD 1353 – 1484	8.0	(Alcock *et al* 1991)
England, London	AD 413 – 1728	6.5	(Tyers and Groves 1999 unpubl)
Lacock Abbey, Wilts	AD 1314 – 1448	5.9	(Esling *et al* 1990)
Rectory Park, Kent	AD 1313 – 1442	5.6	(Howard *et al* 1988)
Tusmore Park, Oxon	AD 1359 – 1545	5.0	(Howard *et al* 1992)
Southam, Warwicks	AD 1304 – 1418	5.0	(Alcock *et al* 1988 unpubl)
Chicksands Priory, Beds	AD 1200 – 1541	5.0	(Howard *et al* 1998)
Kent-88	AD 1158 – 1540	4.9	(Laxton and Litton 1989)
East Midlands	AD 882 – 1981	4.9	(Laxton and Litton 1988)
Southern England	AD 1083 – 1589	4.8	(Bridge 1988)

Figure 1: Map to show general location of Wells Cathedral

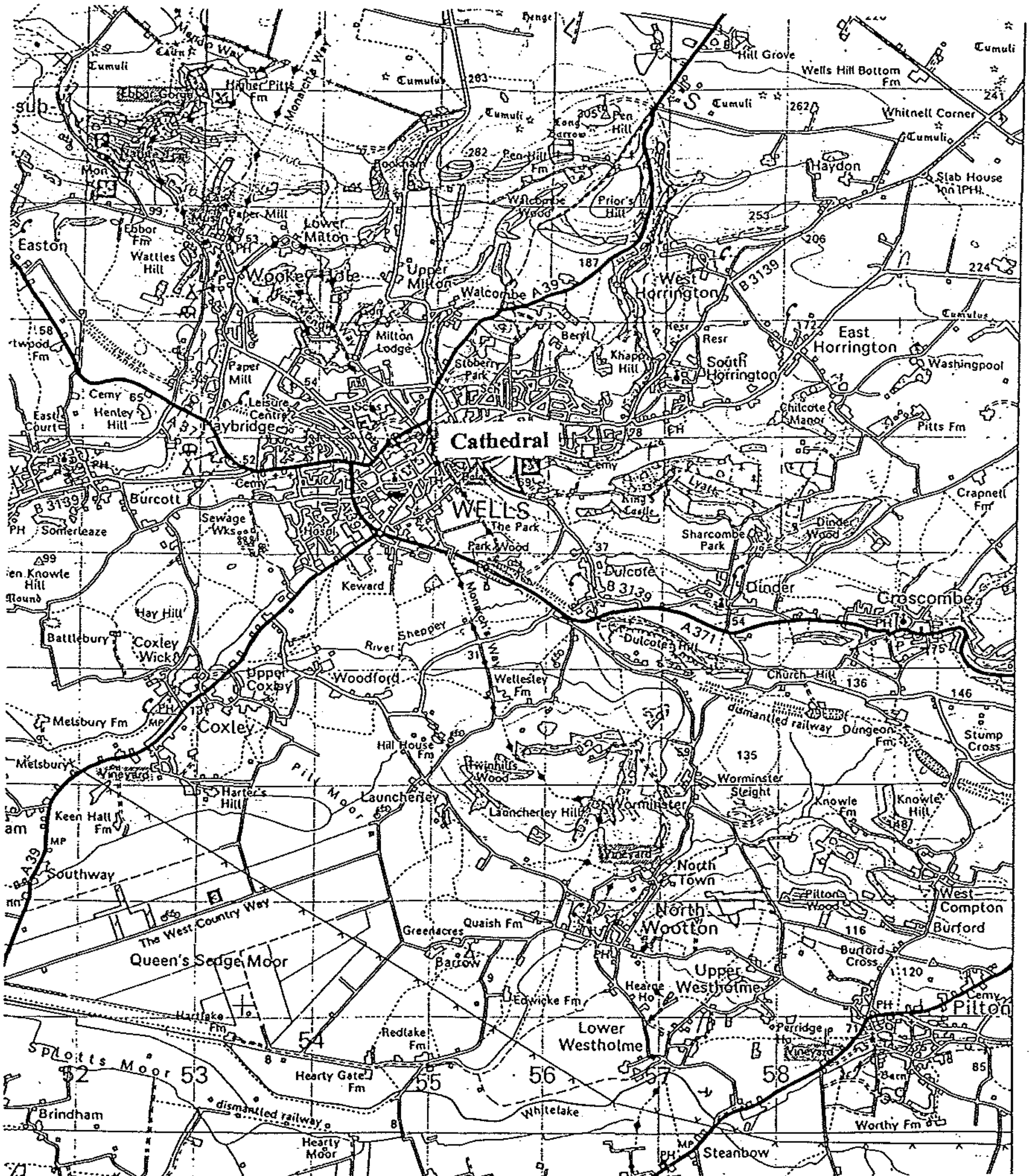
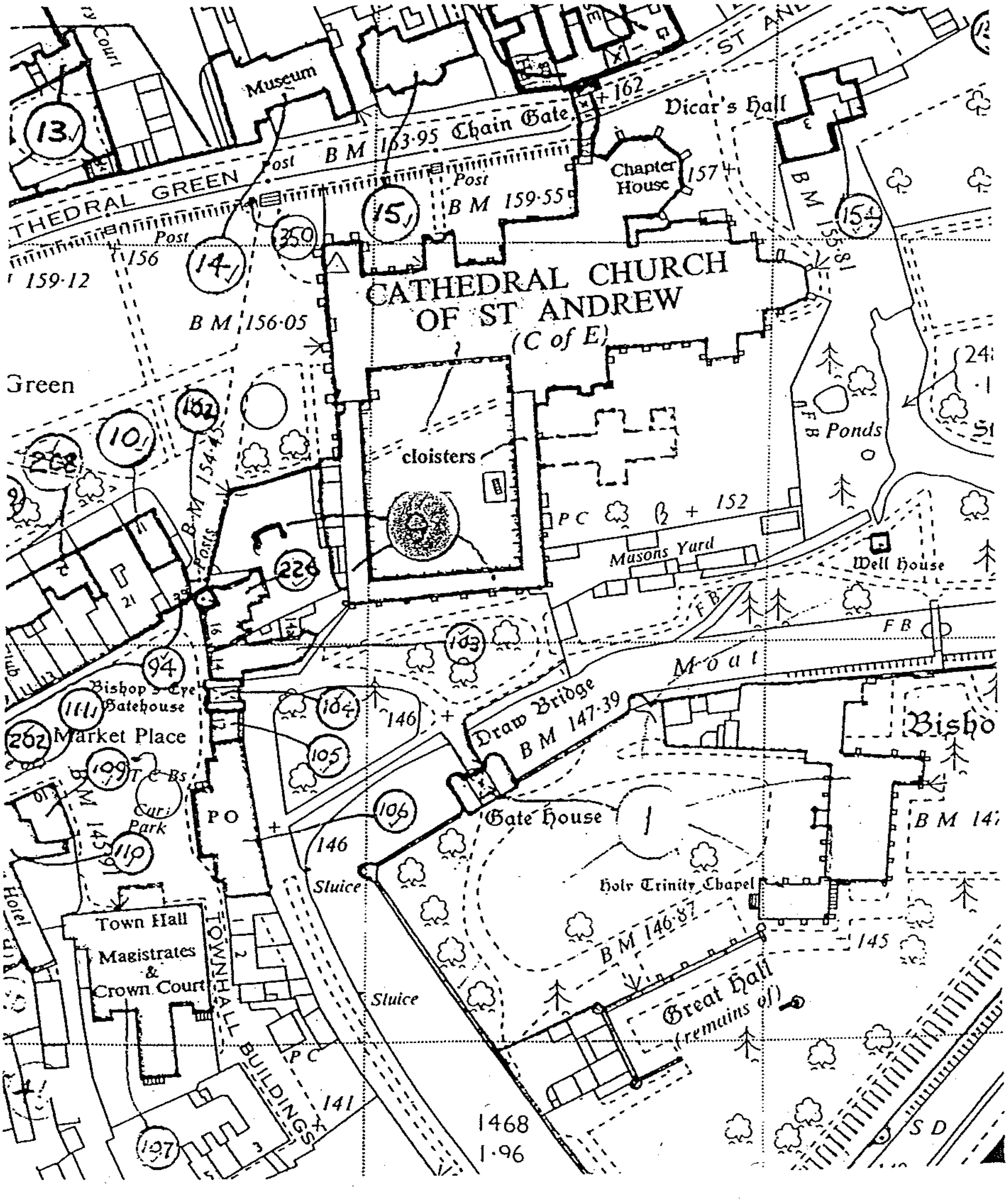


Figure 2: Plan to show location of cloisters in relation to the Cathedral



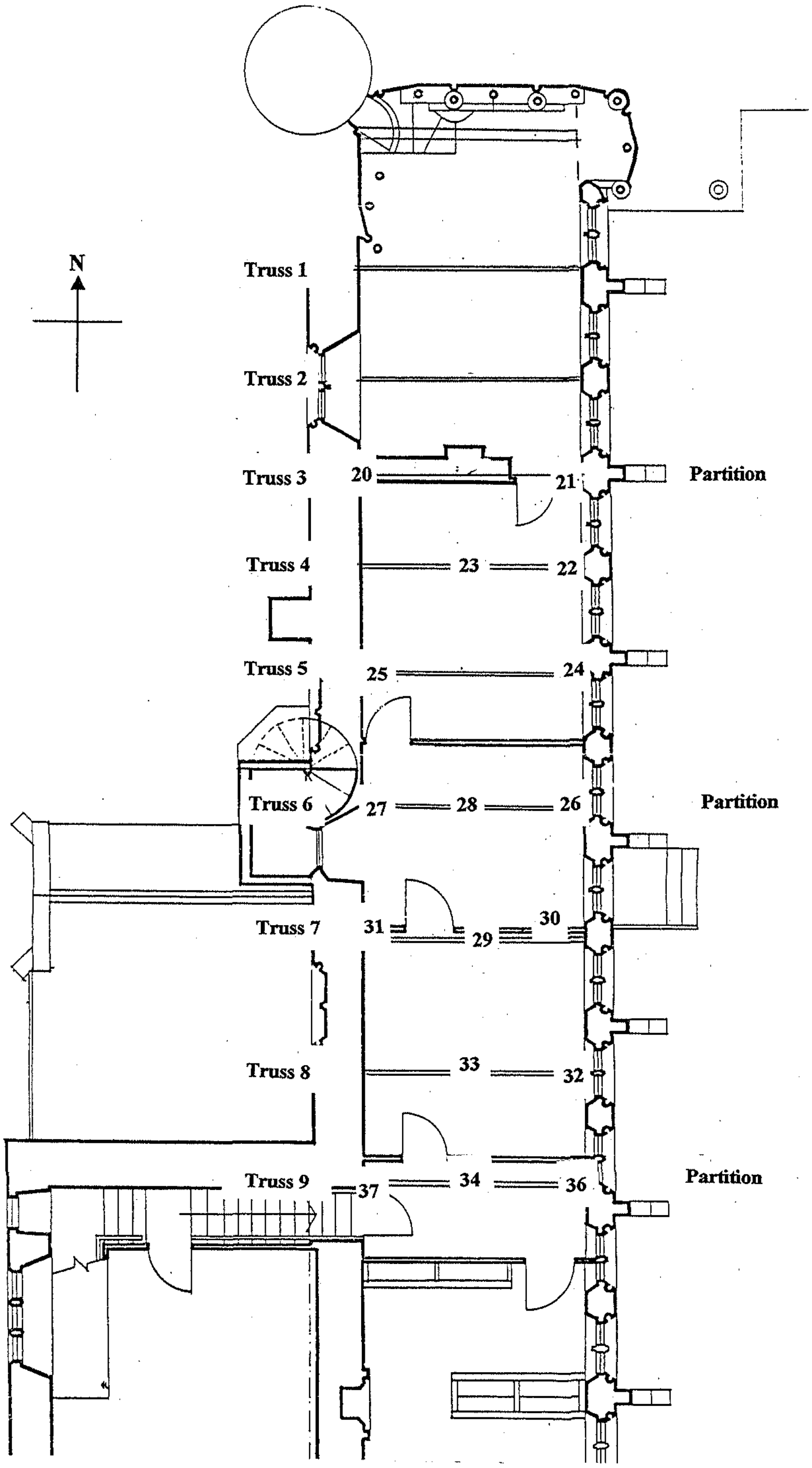


Figure 3a: Plan of the roof of the west cloister, trusses 1 – 9, to show sample locations

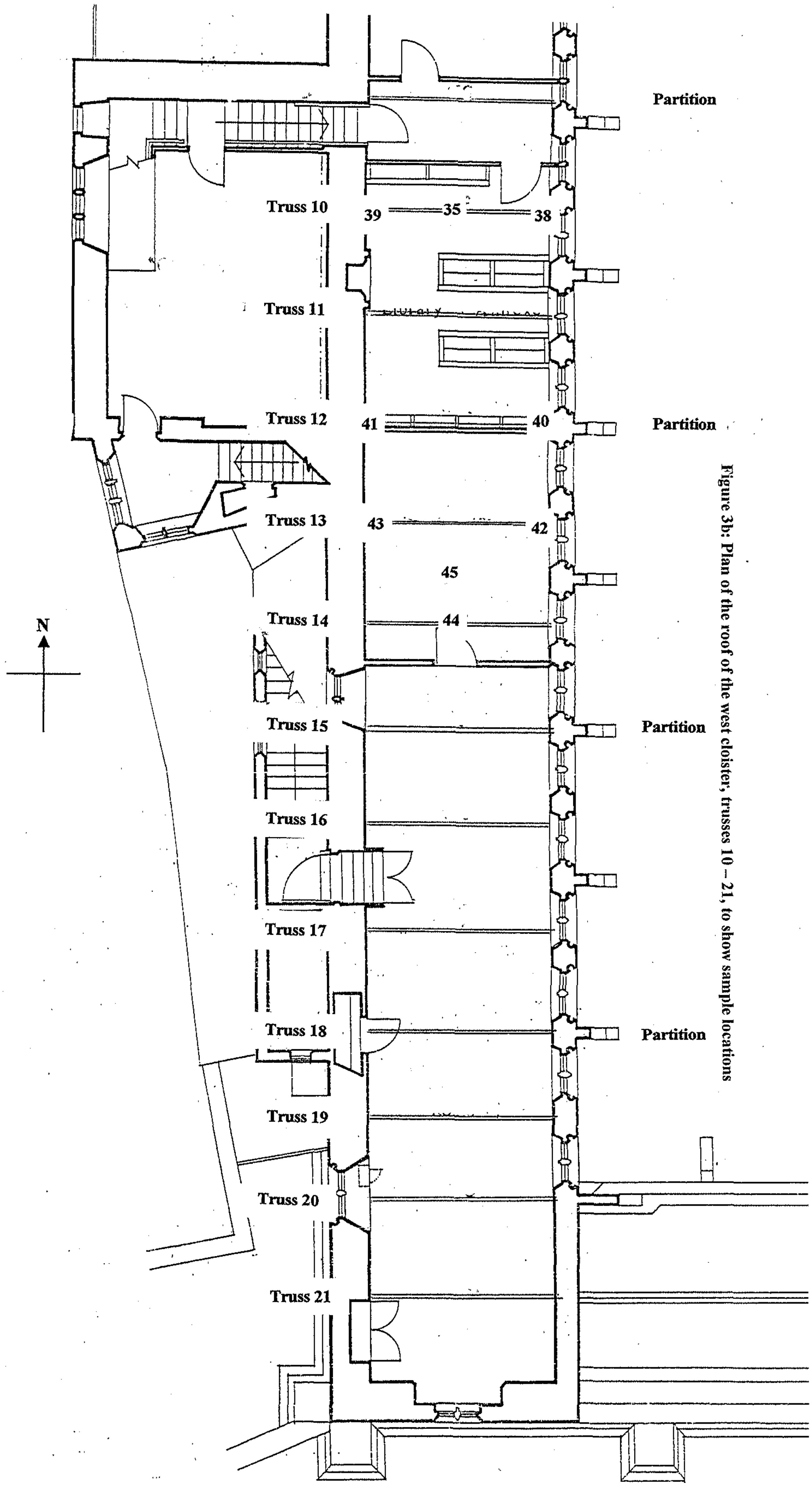
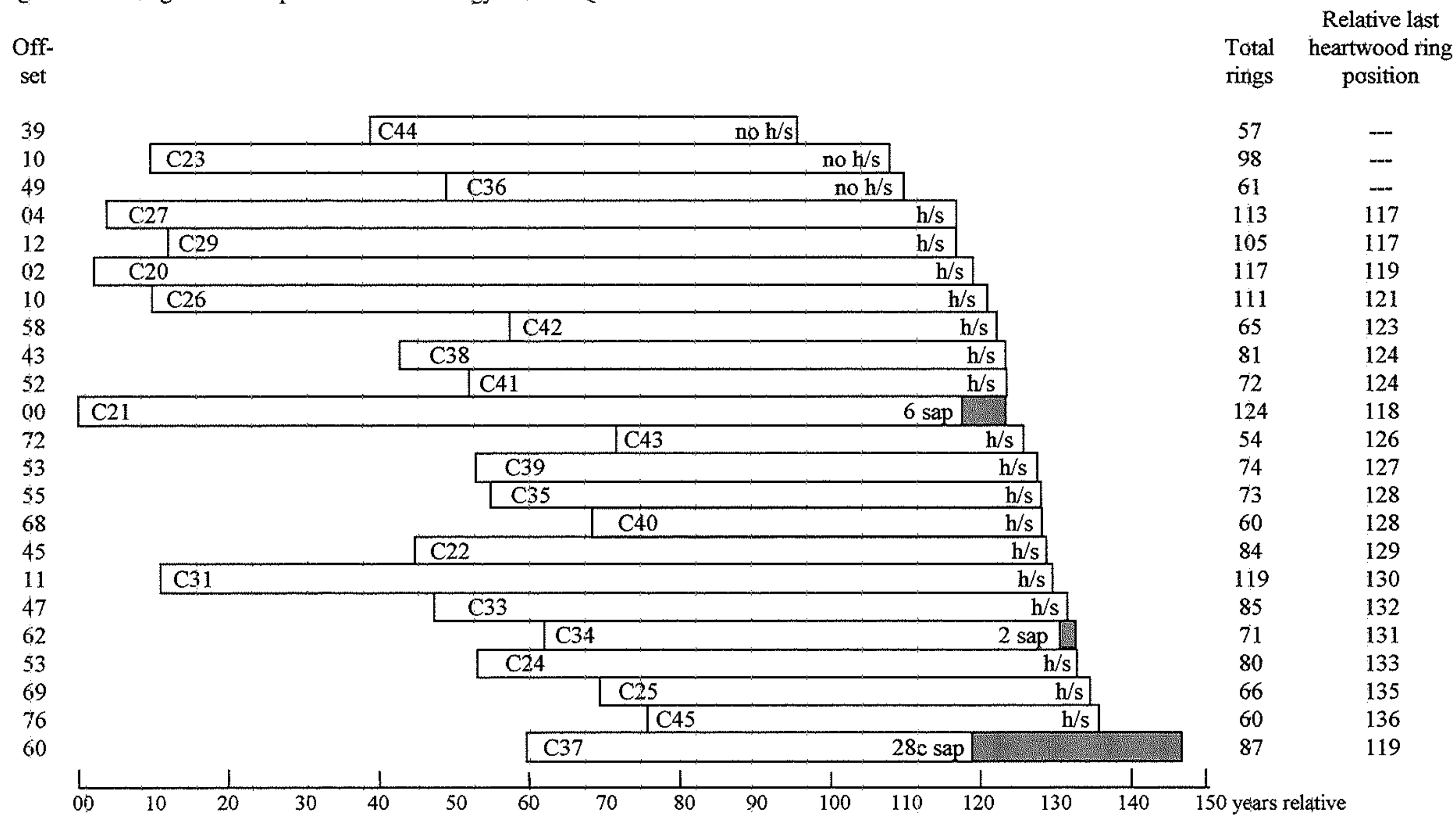


Figure 3b: Plan of the roof of the west cloister, trusses 10 – 21, to show sample locations

Figure 4: Bar diagram of samples in site chronology WLSCSQ04



White bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
c =complete sapwood on timber, all or part lost from core during sampling

Data of measured samples – measurements in 0.01mm units

WLS-C20A 117
88 83 100 66 101 107 168 140 111 86 52 62 55 87 102 87 83 95 105 62
88 99 127 200 180 202 113 85 84 195 230 167 152 175 153 234 209 222 180 160
150 241 279 351 204 198 156 268 278 233 158 129 118 128 147 179 174 170 187 166
131 129 157 152 116 153 169 155 97 76 107 106 53 37 42 53 60 43 44 64
61 50 68 106 92 122 121 102 120 153 104 90 81 70 80 64 75 94 83 109
108 88 102 120 79 66 71 101 109 93 100 121 88 67 63 60 67
WLS-C20B 117
141 88 106 68 103 104 170 138 103 85 54 63 51 82 103 89 83 103 101 60
81 96 121 189 179 191 127 98 84 196 234 164 141 159 154 247 219 218 167 150
158 249 296 334 216 183 176 254 286 234 156 139 114 121 150 180 167 180 185 172
134 123 152 141 133 165 181 161 97 73 107 92 52 39 41 54 46 47 49 68
58 60 60 110 82 128 108 110 122 144 118 92 78 64 82 61 79 100 86 88
112 94 113 107 76 61 74 110 106 84 107 112 100 63 65 64 58
WLS-C21A 124
250 156 109 138 92 82 95 114 118 110 97 92 67 88 62 52 58 42 42 56
102 96 96 82 82 159 192 172 95 75 97 106 173 150 176 261 278 336 277 150
127 138 190 416 415 375 280 208 153 207 262 222 182 145 148 84 148 128 181 132
167 205 183 153 109 102 121 135 166 124 76 62 83 74 107 88 67 90 69 58
66 69 97 79 76 87 61 106 94 60 86 116 110 94 65 57 112 76 114 107
60 124 116 102 128 93 66 56 80 91 105 94 103 124 93 69 77 58 63 47
51 67 56 69
WLS-C21B 124
273 162 126 116 88 72 103 109 121 105 104 91 64 87 60 56 54 51 32 56
94 79 90 76 79 181 181 161 118 83 105 107 187 147 179 259 278 324 276 143
130 136 190 421 419 382 262 194 139 211 260 215 186 144 141 89 152 125 182 138
160 205 181 155 106 115 112 120 172 128 85 60 85 82 105 87 62 93 73 66
56 72 96 73 90 81 60 109 89 60 88 117 126 105 72 58 126 71 105 96
71 128 113 108 137 104 80 54 74 105 112 106 101 129 100 75 72 74 47 48
42 76 73 69
WLS-C22A 84
291 404 476 330 363 523 520 517 607 721 750 400 466 384 334 421 387 339 390 405
401 309 506 396 245 212 191 296 179 250 177 241 287 173 108 160 243 331 144 151
225 197 209 253 272 276 246 198 127 109 54 72 68 82 131 104 138 114 109 157
154 116 105 70 104 114 94 126 93 116 99 119 82 110 102 86 100 163 141 110
132 103 112 153
WLS-C22B 84
341 399 488 333 383 509 560 529 626 718 750 394 478 390 322 414 387 333 378 408
404 310 477 365 240 210 186 280 179 237 166 245 254 182 108 157 222 324 155 116
196 213 194 204 264 239 221 165 129 107 59 70 56 91 130 114 119 110 99 175
155 114 113 64 111 109 94 132 108 116 94 121 83 118 92 93 94 170 141 110
124 105 112 152
WLS-C23A 98
244 193 174 129 107 122 149 155 85 105 124 112 96 96 86 199 152 148 175 176
95 241 224 198 195 142 145 192 225 141 128 124 220 185 233 339 230 143 134 204
186 214 142 207 95 100 106 118 142 107 158 135 140 106 104 94 92 131 111 73
61 32 50 52 64 70 76 137 121 79 65 74 128 72 66 98 112 112 98 60

110 76 116 48 41 96 36 24 42 48 58 70 74 125 83 63 51 82
WLS-C23B 98
177 199 175 134 98 131 144 162 93 112 120 86 103 86 87 194 177 165 198 182
118 222 218 198 202 160 164 184 223 145 121 105 196 186 236 326 228 132 137 207
188 218 133 207 106 94 104 120 135 106 171 142 131 107 100 94 81 145 111 78
65 32 47 48 65 76 79 146 118 88 57 74 126 65 72 97 119 109 92 67
106 95 101 51 52 91 35 30 36 38 54 80 78 126 78 65 61 79
WLS-C24A 80
301 304 189 151 203 204 230 240 144 119 139 158 170 199 208 228 154 86 119 108
124 196 140 185 181 216 255 127 140 200 119 106 169 183 184 203 139 140 170 142
94 84 67 119 112 118 150 140 247 201 159 258 201 161 134 220 244 264 229 270
350 339 210 141 126 132 112 141 226 427 266 255 208 155 302 157 214 280 267 222
WLS-C24B 80
263 305 181 152 204 201 234 241 151 114 145 166 196 186 195 222 151 85 125 99
119 198 136 168 197 225 256 128 143 194 112 104 175 186 182 209 135 135 177 145
95 86 60 116 126 118 155 146 246 210 156 255 210 155 132 221 249 256 241 272
354 335 213 140 141 117 116 135 233 431 275 257 196 168 299 154 213 279 255 240
WLS-C25A 66
215 166 207 187 164 193 206 313 343 286 295 156 220 293 223 216 218 301 326 182
128 144 210 195 141 146 73 130 143 142 187 182 325 235 180 340 220 152 132 191
324 329 268 310 281 319 264 299 206 142 149 179 201 271 231 286 282 212 279 203
256 326 301 302 310 326
WLS-C25B 66
155 156 207 182 178 222 200 309 338 237 295 189 216 292 221 231 244 301 315 189
145 130 203 190 158 143 83 124 141 149 184 168 334 250 170 336 241 147 140 173
309 340 293 298 291 323 273 296 183 162 119 185 193 246 236 300 279 215 274 214
245 343 295 294 312 282
WLS-C26A 111
131 90 121 169 112 189 171 154 150 156 202 134 163 140 125 208 178 133 162 113
107 178 272 195 161 141 202 222 210 107 101 79 173 161 250 332 204 103 109 175
188 219 141 179 85 77 103 159 147 150 200 207 177 133 99 120 83 138 99 84
59 35 37 57 76 61 67 95 107 49 45 64 107 76 104 129 120 111 117 89
105 155 152 74 63 48 108 57 59 101 83 122 143 123 227 123 99 73 122 186
147 109 136 130 135 80 75 78 79 77 90
WLS-C26B 111
140 92 122 159 113 186 158 156 149 154 201 139 163 136 121 196 181 133 137 118
113 177 274 222 141 128 196 232 203 124 95 93 164 167 239 307 207 105 101 177
193 208 148 180 80 73 99 164 149 148 187 203 189 131 102 115 87 129 96 83
59 38 36 55 74 61 67 106 99 54 45 59 113 67 105 146 126 114 125 85
93 146 159 79 62 35 109 56 64 96 84 124 142 124 214 122 100 81 122 185
145 137 140 125 141 77 69 73 103 66 92
WLS-C27A 113
240 124 168 118 170 194 103 61 88 70 76 177 136 103 84 98 102 140 124 83
78 153 186 151 123 95 89 105 205 153 127 118 160 268 229 93 78 77 171 200
224 283 190 97 102 178 202 187 111 99 71 57 92 91 99 96 124 119 127 113
83 62 83 141 121 71 48 31 48 42 45 55 58 107 97 71 60 74 123 74
101 123 115 99 113 75 157 134 121 63 75 52 110 57 68 107 104 171 162 120
234 93 85 66 102 136 153 130 148 137 155 112 95
WLS-C27B 113
230 119 166 120 176 165 100 60 88 70 84 172 133 101 77 95 108 134 118 88
81 167 187 145 117 97 90 96 196 152 132 117 165 262 232 92 79 75 174 198

225 284 194 94 95 190 192 184 116 96 72 57 89 94 97 101 121 126 123 110
86 64 76 143 123 77 43 36 43 38 57 59 67 99 102 74 58 72 123 77
95 130 110 110 115 69 149 141 110 69 57 56 108 54 58 122 86 193 165 100
237 97 95 60 107 133 156 142 134 167 145 85 107
WLS-C28A 86
81 154 96 100 63 36 28 62 69 63 46 74 108 136 80 66 81 78 48 51
94 117 120 85 107 80 84 83 118 137 61 90 77 60 59 50 47 54 57 72
64 96 80 46 39 47 70 38 58 61 72 30 57 44 61 77 59 40 48 41
63 47 44 71 53 40 41 43 68 60 39 48 53 77 75 70 116 73 74 48
67 66 63 46 45 72
WLS-C28B 86
79 160 96 95 63 34 29 64 71 56 57 77 104 136 60 83 79 82 54 46
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70 98 81 44 41 55 59 52 60 70 67 45 49 47 64 78 55 41 51 47
55 49 50 62 50 41 47 40 67 59 42 38 57 74 88 65 113 76 85 49
57 68 54 55 50 73
WLS-C29A 105
147 137 167 224 222 246 167 190 216 135 161 134 117 222 197 197 143 92 61 138
221 180 146 133 212 246 253 148 120 95 145 215 254 339 207 115 76 140 175 168
126 109 75 70 121 146 145 116 124 124 110 92 79 90 61 90 63 54 32 27
25 28 32 29 44 68 57 51 49 48 84 50 42 101 94 81 89 54 42 82
51 41 27 30 43 36 43 53 48 71 93 148 101 90 67 91 136 165 149 146
164 165 94 106 156
WLS-C29B 105
131 137 163 236 225 215 169 204 204 149 170 114 119 229 192 192 149 106 73 135
190 173 154 125 213 239 227 142 126 114 150 210 246 320 221 118 99 146 174 158
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32 22 32 31 37 59 69 54 42 49 76 52 61 83 75 93 99 44 51 75
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160 175 91 102 143
WLS-C30A 60
258 144 101 109 90 88 88 108 149 107 103 124 155 144 105 71 91 58 100 72
56 58 51 43 61 73 81 133 120 115 152 118 119 161 179 102 114 115 113 128
150 237 198 173 111 105 83 120 172 121 118 177 112 121 128 114 111 92 90 121
WLS-C30B 60
241 154 102 110 78 90 86 100 115 105 100 121 181 144 110 69 94 59 100 86
60 49 60 51 63 77 65 143 126 123 130 100 100 159 140 110 102 117 133 145
128 233 198 179 111 107 88 110 181 136 130 161 129 112 120 119 103 91 98 125
WLS-C31A 119
100 95 102 150 242 197 193 244 227 222 129 168 74 52 146 184 221 215 190 184
190 294 198 202 307 304 247 148 47 47 44 55 54 104 95 67 62 50 71 121
110 93 165 163 101 152 156 160 151 236 137 124 135 121 111 113 204 223 159 80
88 74 91 122 130 115 191 163 67 52 42 51 59 70 81 113 136 104 69 54
83 72 84 63 68 102 113 149 133 113 155 127 89 140 140 94 69 99 107 68
58 82 105 70 72 68 72 79 54 66 108 156 117 144 156 132 99 134 176
WLS-C31B 119
99 91 101 143 251 197 198 245 229 214 130 166 78 60 124 177 215 242 168 192
210 338 203 206 309 296 243 152 50 45 45 56 49 105 87 67 61 45 79 117
117 88 167 155 107 160 157 165 138 235 144 118 137 122 122 104 202 222 155 90
82 73 101 114 135 115 186 155 77 46 41 61 61 70 79 109 130 112 69 55
76 77 84 56 76 103 110 150 138 110 151 129 100 133 140 92 64 103 110 69

60 78 110 66 71 68 78 71 59 62 108 156 114 149 152 130 102 142 175
WLS-C32A 45
241 215 223 208 226 209 231 155 167 183 229 306 171 285 284 199 259 209 202 263
188 270 210 149 169 249 174 182 165 209 230 192 172 144 175 131 186 180 168 125
135 159 105 134 240
WLS-C32B 45
220 208 226 213 219 217 218 159 148 222 233 305 155 322 289 226 254 228 183 280
207 277 196 143 163 241 172 177 174 225 233 183 182 156 165 125 190 184 177 139
130 149 124 129 213
WLS-C33A 85
160 134 108 140 174 101 96 102 84 67 96 119 142 206 97 116 165 78 112 70
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101 101 77 79 109 114 117 110 77 92 72 119 109 85 98 144 125 168 155 106
103 118 164 108 100 111 116 114 78 96 112 132 122 107 95 83 104 119 116 110
124 148 111 109 142
WLS-C33B 85
140 134 103 138 175 103 94 101 85 65 92 128 141 200 96 121 164 78 105 60
104 113 118 109 148 158 115 124 117 220 384 227 367 377 332 252 132 167 143 112
100 91 82 71 107 110 129 102 78 90 71 118 116 83 106 143 117 174 153 108
106 121 159 99 90 118 121 127 76 114 107 143 121 104 98 87 101 123 111 114
124 134 108 118 137
WLS-C34A 71
505 325 154 203 144 288 283 175 148 178 177 159 118 149 181 216 96 107 154 200
257 113 194 218 200 297 305 256 238 239 230 194 205 205 224 132 168 206 165 140
246 190 230 237 160 165 161 228 164 100 149 225 152 157 128 179 183 191 186 213
296 203 199 136 202 252 231 141 291 196 203
WLS-C34B 71
527 343 156 203 145 276 280 168 150 183 184 161 144 144 183 202 109 108 168 195
262 107 182 221 195 322 290 258 248 235 234 188 205 203 225 135 167 198 161 141
255 186 225 254 146 168 168 241 144 92 142 224 169 156 139 156 179 195 185 228
269 200 196 150 207 258 233 149 236 205 227
WLS-C35A 73
307 226 278 205 201 270 220 201 250 164 185 173 310 367 258 272 263 373 249 243
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WLS-C43B 54
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263 305 181 152 204 201 234 241 151 114 238 519 324 282 304 282 204 294 317 368
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105 116 124 153 116 109 104 108 70 109 74 96 127 90 119 144 159 125 107 103
WLS-C45B 60
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APPENDIX

Tree-Ring Dating

The Principles of Tree-Ring Dating

Tree-ring dating, or *dendrochronology* as it is known, is discussed in some detail in the Laboratory's Monograph, '*An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Buildings*' (Laxton and Litton 1988b) and, for example, in *Tree-Ring Dating and Archaeology* (Baillie 1982) or *A Slice Through Time* (Baillie 1995). 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 Figure1 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, 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 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 1, 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. 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 University of Nottingham Tree-Ring dating Laboratory

1. ***Inspecting the Building and Sampling the Timbers.*** Together with a building historian we inspect the timbers in a building 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 2 has about 120 rings; about 20 of which are sapwood rings. Similarly the core has just over 100 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 to 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.

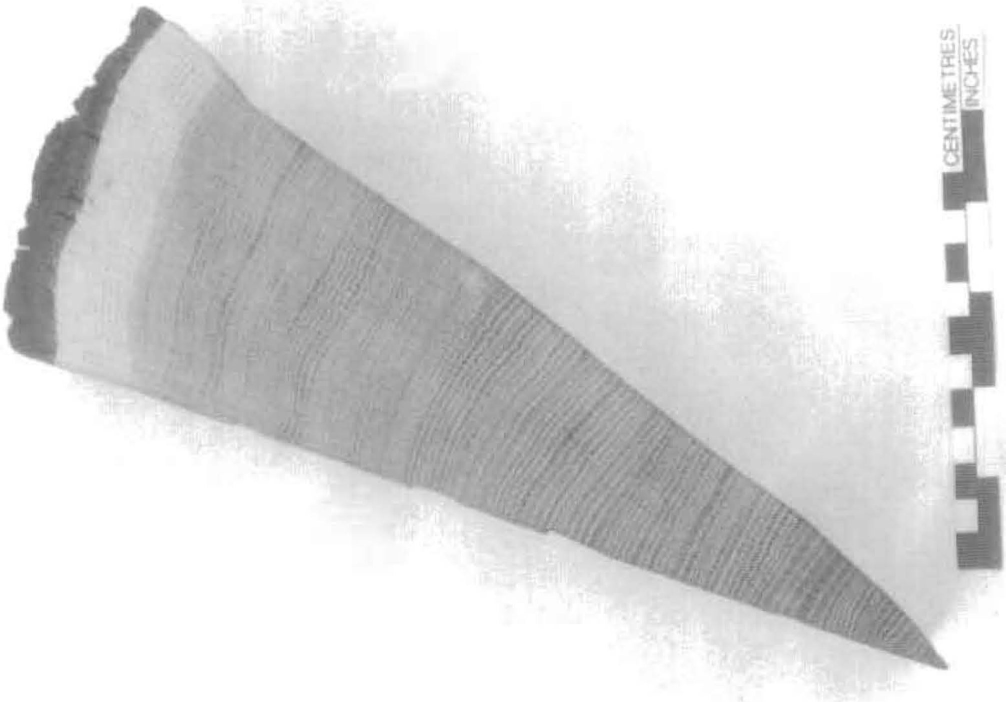

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

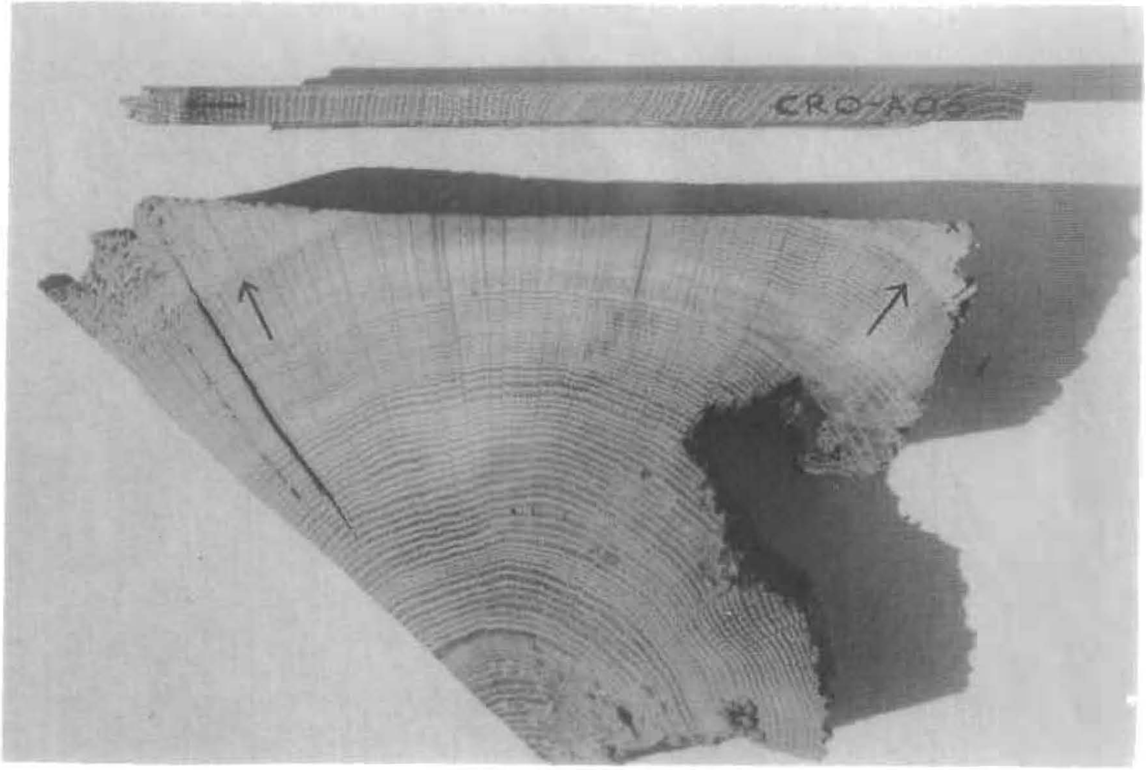

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

Fig 3. 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.

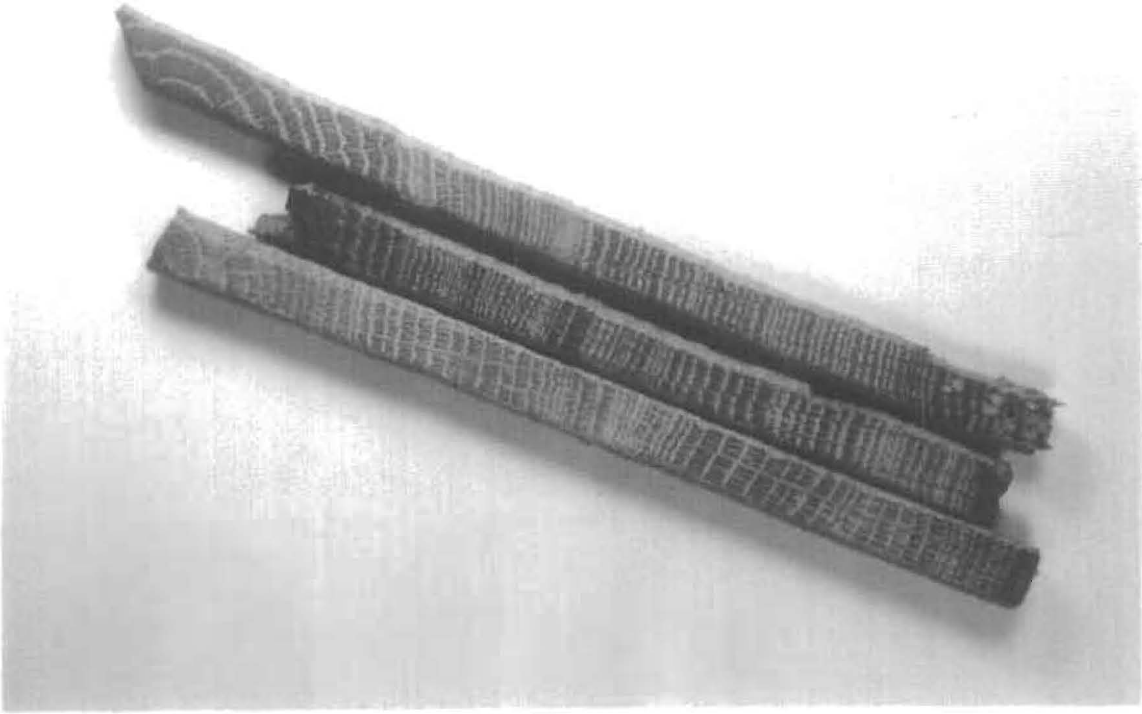

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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 2; it is about 15cm long and 1cm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost. 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 inspecton 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 is insured with the CBA.

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 2. 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 3).

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 4). 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 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton *et al* 1988a,b; Howard *et al* 1984 - 1995).

This is illustrated in Fig 5 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. C08 matches C45 best when it is at a position starting 20 rings after the first ring of 45. 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 between these two whatever the position of one sequence relative to the other.

It is standard practice in our Laboratory first to cross-match as many as possible of the 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 Fig 5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences from 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. 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.

average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

This 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'. This was developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988a). To illustrate the difference between the two approaches with the above example, consider sequences C08 and C05. They are the most similar pair with a t-value of 10.4. Therefore, these two are first averaged with the first ring of C05 at +17 rings relative to C08 (the offset at which they match each other). This average sequence is then used in place of the individual sequences C08 and C05. The cross-matching continues in this way gradually building up averages at each stage eventually to form the site sequence.

4. ***Estimating the Felling Date.*** If the bark is present on a sample, then the date of its last ring is the date of the felling of its tree. Actually it could be the year after if it had been felled in the first three months 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, they can be seen in two upper corners of the rafter and at the outer end of the core in Figure 2. 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 for 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. Thus in these circumstances the date of the present last ring is at least close to the date of the original last ring on the tree, and so to the date of felling.

Various estimates have been made for the average number of sapwood rings in a mature oak. One estimate is 30 rings, based on data from living oaks. So, in the case of the core in Figure 2 where 9 sapwood rings remain, this would give an estimate for the felling date of 21 (= 30 - 9) years later than of the date of the last ring on the core. Actually, it is better in these situations to give an estimated range for the felling date. Another estimate is that in 95% of mature oaks there are between 15 and 50 sapwood rings. So in this example this would mean that the felling took place between 6 (= 15 - 9) and 41 (= 50 - 9) years after the date of the last ring on the core and is expected to be right in at least 95% of the cases (Hughes *et al* 1981; see also Hillam *et al* 1987).

Data from the Laboratory has shown that when sequences are considered together in groups, rather than separately, the estimates for the number of sapwood can be put at between 15 and 40 rings in 95% of the cases with the expected number being 25 rings. We would use these estimates, for example, in calculating the range for the common felling date of the four sequences from Lincoln Cathedral using the average position of the heartwood/sapwood boundary (Fig 5). These new estimates are now used by us in all our publications except for timbers from Kent and Nottinghamshire where 25 and between 15 to 35 sapwood rings, respectively, is used instead (Pearson 1995).

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 2 was taken still had complete sapwood. Sapwood rings were only lost in coring, because of their softness. By measuring in the timber the depth of sapwood lost, say 2 cm., a reasonable estimate can be made of the number of sapwood rings missing from the core, 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 40 years later we would have estimated without this observation.

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

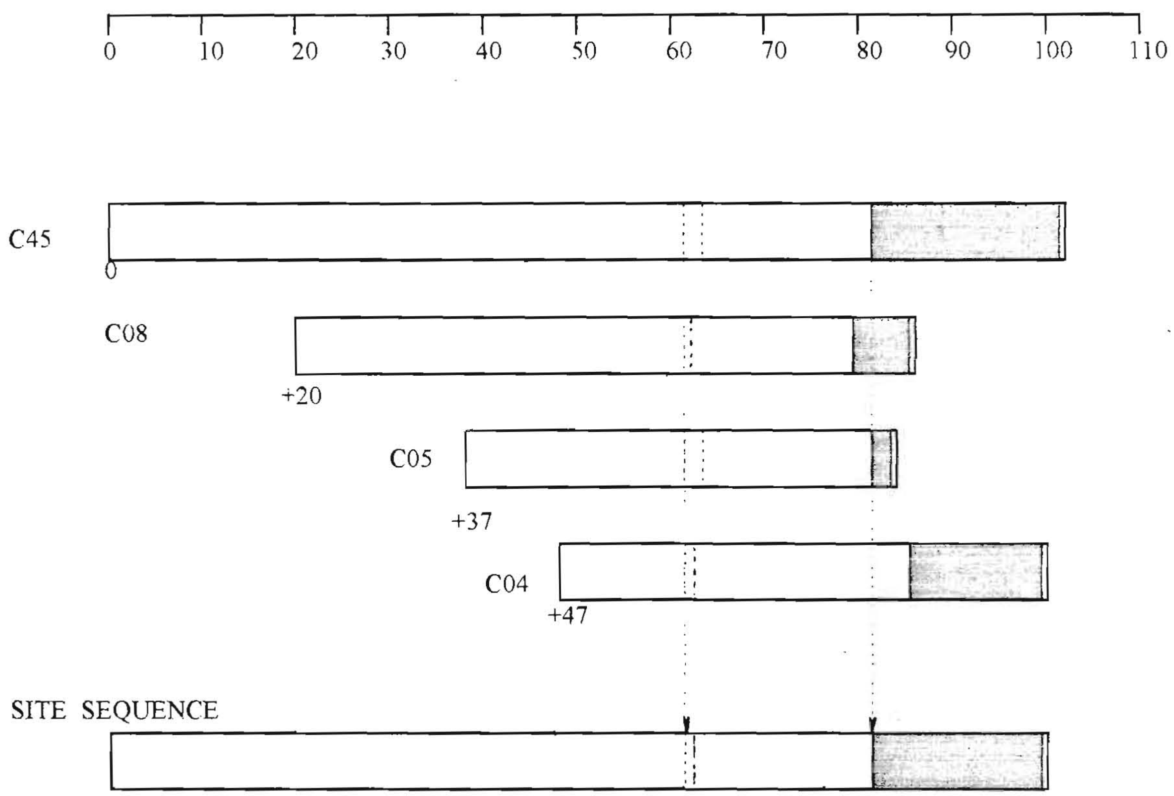

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set 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.

Even if all the sapwood rings are missing on all the timbers sampled, an estimate of the felling date is still possible in certain cases. For provided the original last heartwood ring of the tree, called the heartwood/sapwood boundary (H/S), is still on some of the samples, an estimate for the felling date of the group of trees can be obtained by adding on the full 25 years, or 15 to 40 for the range of felling dates.

If none of the timbers have their heartwood/sapwood boundaries, then only a *post quem* date for felling is possible.

5. ***Estimating the Date of Construction.*** There is a considerable body of evidence in the data collected by the Laboratory that the oak timbers used in vernacular buildings, at least, were used 'green' (see also Rackham (1976)). Hence provided the samples are taken *in situ,* and several dated with the same estimated common felling date, then this felling date will give an estimated date for the construction of the building, or for the phase of construction. If for some reason or other we are rather restricted in what samples we can take, then an estimated common felling date may not be such a precise estimate of the date of construction. More sampling may be needed 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 Fig 6 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 Fig 6. 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 1988b, 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* 1988a). 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 (1988b) and is illustrated in the graphs in Fig 7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence (a), the generally large early growth after 1810 is very apparent as is the smaller generally later growth from about 1900 onwards. A similar difference can be observed in the lower sequence 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, hopefully corresponding to good and poor growing seasons, respectively. The two corresponding sequences of Baillie-Pilcher indices are plotted in (b) where the differences in the early and late growths have been removed and only the rapidly changing peaks and troughs remain only associated with the common climatic signal and so make cross-matching easier.

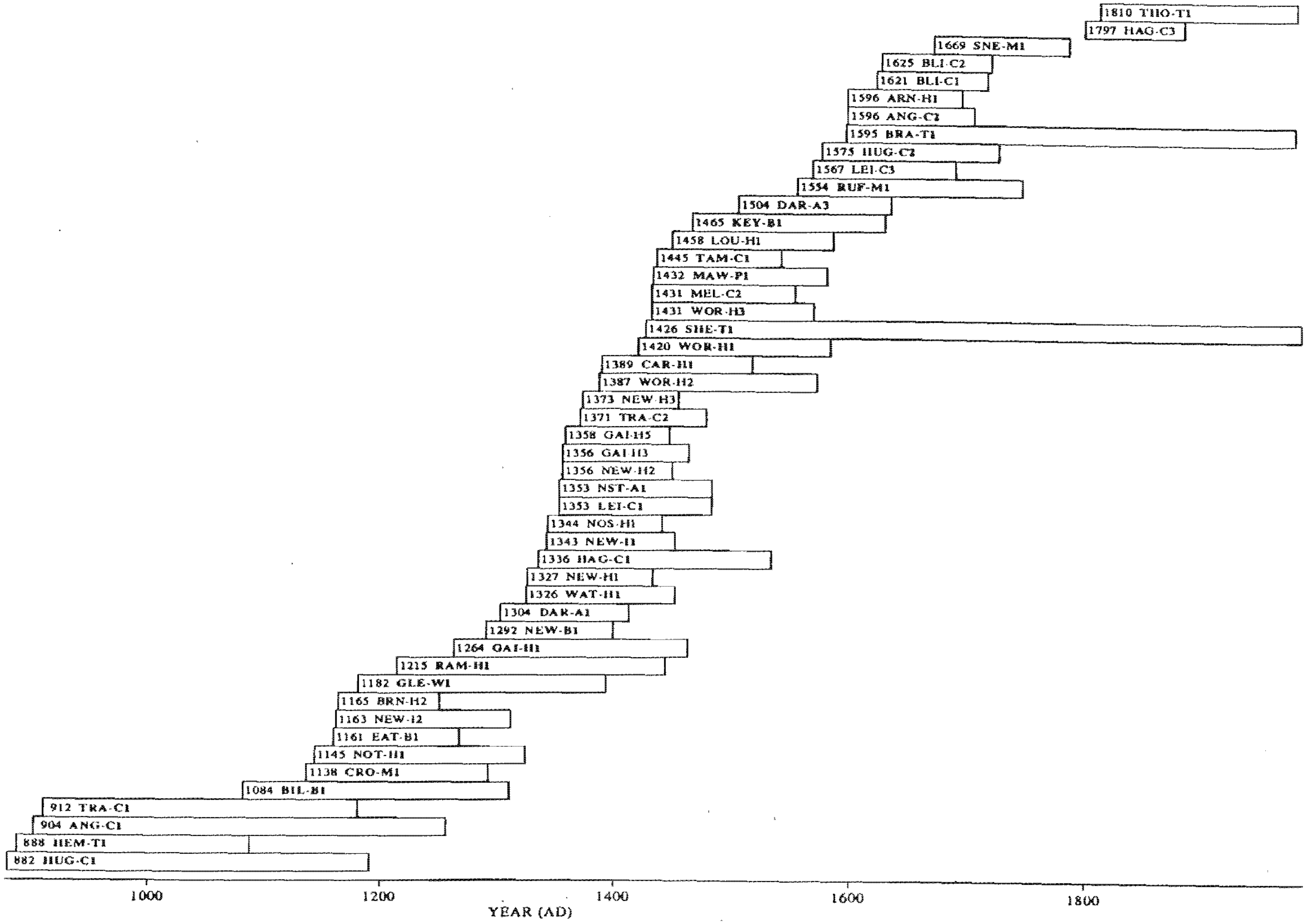

Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

(a)

(b)

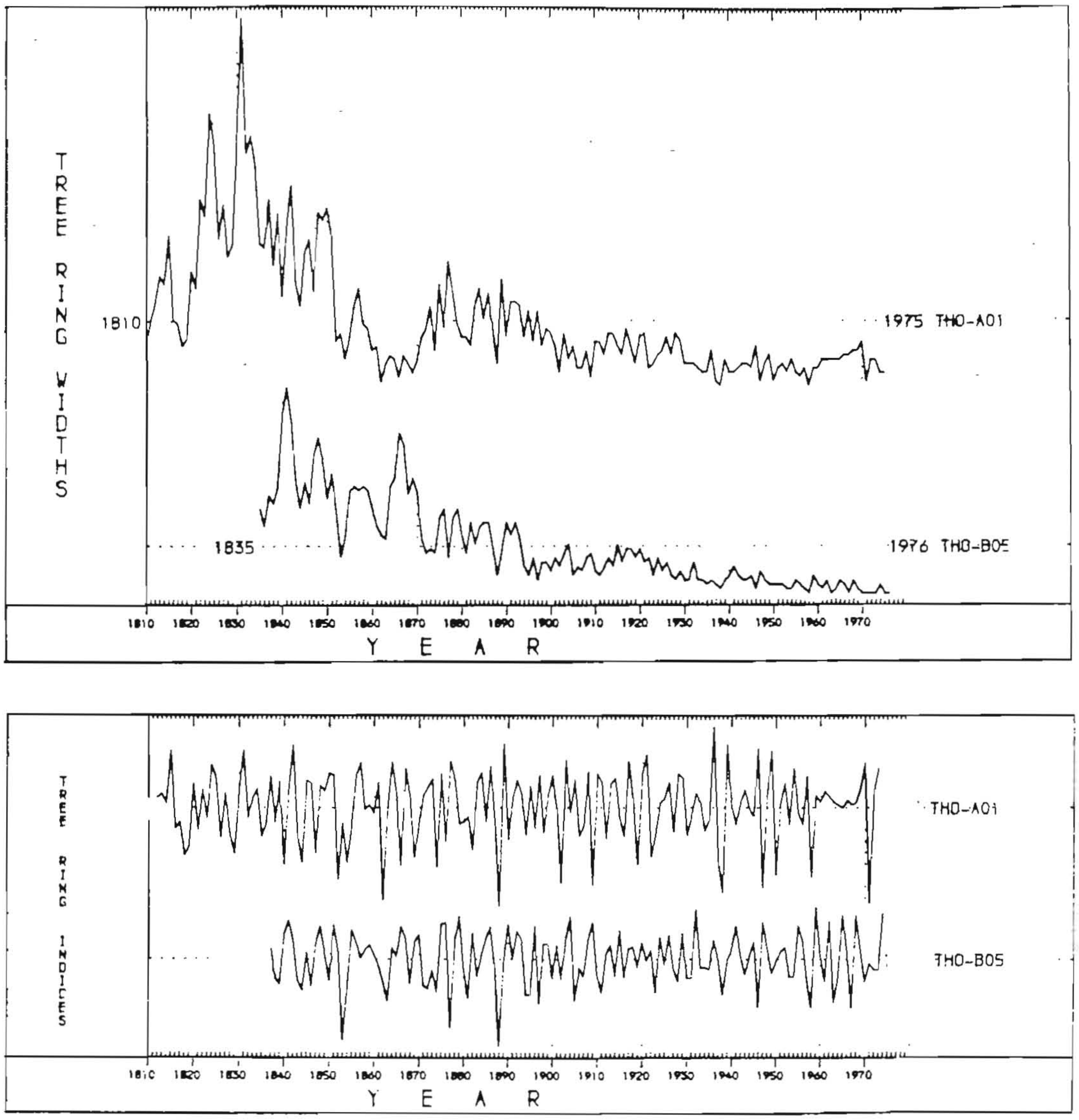

Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences.

(b) The *Baillie-Pilcher indices* of the above widths. The growth-trends have been removed completely.

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