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Summary

Seventeen core samples were obtained from this building. Analysis of these produced two dated site chronologies, and dated one sample individually. The first site chronology, CHTASQ01, contains five samples of overall length 86 rings, dated as spanning AD 1655 to AD 1740.

The second site chronology, CHTASQ02, contains three samples and is 84 rings long, these dated as spanning AD 1440 to AD 1561. The individually dated sample spans AD 1408 - 1469.

Interpretation of the sapwood would suggest more than one phase of felling. The earliest sample, from a floor frame, is estimated to have a felling date in the range AD 1543 - 78. Two other timbers, from the roof, may have been felled at about the same time, but it is equally possible they are later.

The latest phase is represented by five samples from the roof, indicating a felling of AD 1740.

The individually dated timber is unlikely to have been felled before AD 1484.

It would thus appear that at least one mid sixteenth-century timber from the floor frame could be original, but, apart from one, none of the dated timbers in the roof are, these mostly being eighteenth-century replacements, but including some timber felled earlier.

Keywords

Dendrochronology
Standing Building

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Introduction

Clifton Hall, at Clifton, Cumbria, lies about five kilometres south of Penrith along the medieval road to Kendal (NY530271; Figs 1 and 2). The only part of the Hall now surviving is a small tower, roughly 10 by 8 metres, of three floors added to the late medieval manor buildings. The date of the tower's construction is uncertain but on architectural evidence it is usually considered to be early in the sixteenth century, or possibly very late in the fifteenth.

The principal room of the tower, with its large fireplace, large window, and its garderobe chamber, occupied the first floor. The original entry was at this level with a newel stairs in the southwest corner giving access to the second floor and the roof. The ground floor was originally self contained, entry being gained through a door in the north wall.

Some time later part of the south wall was rebuilt to allow for the insertion of a new ground-floor fireplace and its chimney. Other alterations to the tower were associated with the building of a new hall to the south involving the insertion of new doorways through the south wall of the tower, and the extension of the newel stair to the ground floor.

The original roof of the tower does not survive, with only the corbels which carried its tiebeams giving any clue as to its form. This first roof was replace by a hipped roof with king posts supporting a ridge. On architectural grounds it is unlikely that such a roof would be earlier than the mid-sixteenth century. This present roof contains quantities of reused material, as evidenced by the redundant mortices, joint beds, and peg holes. There also appear to be quantities of modern, twentieth-century, repair timbers.

The Hall, including all the post-medieval extensions, was demolished in the nineteenth century when the present Hall Farm was built. The tower is an English Heritage guardianship site and a Scheduled Ancient Monument.

Sampling

Sampling and analysis by tree-ring dating of timbers from this building were commissioned by English Heritage. The purpose of this was to provide a better understanding of the building to assist with its interpretation for visitors. The English Heritage brief requested samples from two areas of the tower, firstly the roof, and secondly the main cross-beams and joists of the first- and second-floor frames. It was hoped that sampling would show how much, if any, of the roof or floors survived from the original early sixteenth-century build, and possibly show at what date the original roof was replaced by the present hipped covering. Given the extensive re-use of material it was felt that some intimation of intermediate repair dates might also be evidenced.

Examination of the timbers revealed that all the common joists of the first and second floor were small timbers, approximately 8 - 10 cms square, mostly, though not all characterised by wide annual growth-rings. A number of such timbers that were cored provided samples with 10 - 30 rings, far too few for satisfactory analysis. The main bressumer beams of the floor frames, though larger in size had similar growth rings. The timbers of the roof structure were larger and much more varied in their growth-ring type.

Thus, from the timbers available only seventeen core samples with sufficient rings for tree-ring analysis were obtained. Each sample was given the code CHT-A (for Clifton Hall Tower, site "A") and numbered 01 - 17. Thirteen samples, CHT-A01 - A13, were obtained from the roof, and four samples, CHT-A14 - A17, were obtained from the frame of the first floor only. No samples were taken from the second-floor frame, not only because of the poor prospect for satisfactory samples, but also because it appeared to be unsafe.

The positions of these cores were recorded at the time of sampling on Department of the Environment drawings provided by English Heritage, these being reproduced here as Figures 3 - 5. Details of the samples are given in Table 1 and can be used in conjunction with the drawing to locate timbers sampled. In this report all elements of timbering, trusses, rafters, beams, etc, have been numbered and described on a north to south, or east to west basis, as appropriate.

The Laboratory would like to take this opportunity to thank Mrs Holiday of Clifton Hall Farm for assisting in accessing the site on the day of sampling.

Analysis

Each of the seventeen samples from the tower was prepared by sanding and polishing and its annual growth-ring widths measured. The data of these measurements are given at the end of the report. These data were then compared with each other by the Litton/Zainodin grouping procedure (see appendix). At a minimum *t*-value of 4.5 two satisfactory groups of samples form.

The first group consists of five samples, CHT-A02, 03, 06, 07, and 08, cross-matching with each other at the relative positions shown in the bar diagram Figure 6. The growth-ring widths of these samples were combined at their indicated relative off-set positions to form site chronology CHTASQ01, with a combined overall length of 86 rings. Site chronology CHTASQ01 was then compared with a series of relevant reference chronologies for oak with a first ring date of AD 1655 and a last measured ring date of AD 1740. Evidence for the dating of this site chronology is given in the *t*-values of Table 2.

The second group consists of three samples, CHT-A09, 10, and 14, cross-matching with each other at the relative positions shown in the bar diagram Figure 7. The growth-ring widths of these samples were combined at their indicated relative off-set positions to form site chronology CHTASQ02, with a combined overall length of 84 rings. Site chronology CHTASQ02 was then compared with a series of relevant reference chronologies for oak with a first ring date of AD 1454 and a last measured ring date of AD 1537. Evidence for the dating of this sample is given in the *t*-values of Table 3.

Each site chronology was then compared with the other, and with the eight remaining ungrouped samples. There was, however, no further satisfactory cross-matching. Each of the eight remaining ungrouped samples was then compared individually with a full range of relevant reference chronologies for oak. This indicated a cross-match for only one sample, CHT-A11, with a first ring date of AD 1408 and a last ring date of AD 1469. Evidence for the dating of this sample is given in the *t*-values of Table 4.

This analysis is summarised below:

Site chronology	Number of samples	Number of rings	Date span
CHTASQ01	5	86	AD 1655 - 1740
CHTASQ02	3	84	AD 1440 - 1561
CHT-A11	1	62	AD 1408 - 1469

Interpretation

Analysis by dendrochronology has produced two site chronologies and dated one individual sample. One sample (CHT-A08) in site chronology CHTASQ01 retains complete sapwood, that is, it has the last ring produced by the tree it represents before felling. This sample has a last ring date of AD 1740 and this is thus the felling date of the tree represented. The relative positions of the heartwood/sapwood boundaries on the other samples in this site chronology are consistent with a group of timbers from a single phase of felling, and they are all very likely to have been cut in AD 1740 too.

It is difficult, on the other hand, to be certain about the felling date of the three timbers represented by the three samples, CHT-A09, A10, and A14, in site chronology CHTASQ02. Sample CHT-A09 does not have the heartwood/sapwood boundary, it is thus unlikely to have been felled before AD 1529 at the earliest. Sample CHT-A14 does have the heartwood/sapwood boundary, and the earliest that this timber might have been felled is estimated to be AD 1543. Sample CHT-A10 is again without the heartwood/sapwood boundary, and this timber is unlikely to have been felled before AD 1552. All these dates are based on a figure of 15 rings for the minimum number of sapwood rings the trees are likely to have had.

It is possible that all three timbers represented by site chronology CHTASQ02 are of a single felling phase. It is estimated that this is unlikely to have been before AD 1552. However, it is equally possible that two, or even three, different felling dates are represented. The only thing that is calculable is that the timber represented by sample CHT-A14 is estimated to have been felled between AD 1543 - 78, this upper limit date being base on a figure of 50 rings for the maximum number of sapwood rings the tree is likely to have had.

Sample CHT-A11, last measured ring date AD 1469, is also lacking the heartwood/sapwood boundary and it is again not possible to estimate the felling date of the timber concerned. It is unlikely, however, to be before AD 1484.

This interpretation may be summarised below:

Site chronology	Sampling area	Sample numbers	Felling date (actual or estimated)
CHTASQ01	Roof timbers	A02, A03, A06, A07, A08	AD 1740
CHTASQ02	Roof timbers	A09	Not before AD 1529
	Roof timbers	A10	Not before AD 1552
	First-floor frame	A14	AD 1543 - 78
	Roof timber	A11	Not before AD 1484

Conclusion

Analysis by dendrochronology has produced two dated site chronologies, and dated one sample individually. It would appear that the earliest certain material in the tower is that of the first-floor frame, represented by a single sample, CHT-A14, with an estimated felling date in the range AD 1543 - 78. It is possible that some of the roof timbers, represented by samples CHT-A09 and 10, are of this felling date too, but equally possible that they are later. Although such a simple interpretation is by no means certain, a mid sixteenth-century felling date for some timber seems possible.

The latest work is represented by several timbers in the roof which all almost certainly have a felling date of AD 1740. This felling probably represents the felling of timber used in the replacement of the original roof by a hipped roof. Such a date does not appear to have an obvious historical context.

Apart from one possibility, the timber represented by sample CHT-A11, none of the dated timbers appears to belong to an original roof dated to the AD 1540s or earlier. It is possible, however, that even this timber relates to a later felling phase.

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Table 1: Details of samples from Clifton Hall Tower, Clifton, Cumbria

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Roof timbers					
CHT-A01	North principal rafter, truss 1	79	23C	------	------	------
CHT-A02	North-east hip rafter	57	9	AD 1667	AD 1614	AD 1723
CHT-A03	Tiebeam, truss 1	72	11	AD 1659	AD 1619	AD 1730
CHT-A04	Southern east to west beam, truss 1 - 2	122	h/s	------	------	------
CHT-A05	South-east diagonal ceiling beam	57	13	------	------	------
CHT-A06	North principal rafter, truss 2	70	17	AD 1666	AD 1718	AD 1735
CHT-A07	South principal rafter, truss 2	68	11	AD 1662	AD 1718	AD 1729
CHT-A08	Tiebeam, truss 2	86	16C	AD 1655	AD 1624	AD 1740
CHT-A09	South purlin, truss 1 - 2	61	no h/s	AD 1454	------	AD 1514
CHT-A10	Purlin to west hip	80	no h/s	AD 1458	------	AD 1537
CHT-A11	West ceiling beam	62	no h/s	AD 1408	------	AD 1469
CHT-A12	North-west diagonal ceiling beam	55	15	------	------	------
CHT-A13	Common rafter to north roof pitch	56	h/s	------	------	------
	Floor-frame timbers					
CHT-A14	First-floor frame, joist 3 (from east)	71	h/s	AD 1458	AD 1528	AD 1528
CHT-A15	First-floor frame, joist 4	65	h/s	------	------	------
CHT-A16	First-floor, joist 6	57	14	------	------	------
CHT-A17	Cross beam	58	h/s	------	------	------

*h/s = the heartwood/sapwood boundary is the last ring on the sample
C = complete sapwood retained on sample, last measured ring date is felling date of tree

Table 2: Results of the cross-matching of chronology CHTASQ01 and relevant reference chronologies when the date of the first ring is AD 1655 and the last ring date is AD 1740

Reference chronology	Span of chronology	*t*-value	
Blidworth, Notts	AD 1625 – 1717	7.2	(Laxton and Litton 1988)
Catholme, Staffs	AD 1649 – 1750	6.6	(Howard *et al* 1994 unpubl)
Basing, Hants	AD 1684 – 1788	6.4	(Bridge 1996)
East Midlands	AD 882 – 1981	5.7	(Laxton and Litton 1988)
Quenby Hall, Leics	AD 1648 – 1765	5.3	(Howard *et al* 1996 unpubl)
Chatham2, Kent	AD 1615 – 1780	5.1	(Bridge 1998)
Cosby, Leics	AD 1642 – 1734	4.6	(Alcock *et al* 1991 unpubl)

Table 3: Results of the cross-matching of chronology CHTASQ02 and relevant reference chronologies when the date of the first ring is AD 1454 and the last ring date is AD 1537

Reference chronology	Span of chronology	*t*-value	
Scotby, Carlisle	AD 1460 – 1564	7.3	(Howard *et al* 1997)
Cartledge Hall, Holmesfield, Derbys	AD 1459 – 1581	4.9	(Howard *et al* 1993a)
Moorhouse Farm, Moorhouse, Cumbria	AD 1469 – 1608	5.8	(Howard *et al* 1998)
Hornby Hall, Penrith, Cumbria	AD 1453 – 1549	5.3	(Howard *et al* 1993b)
Kepier Hospital, Durham	AD 1304 – 1522	4.7	(Howard *et al* 1996a)
England	AD 401 – 1981	3.8	(Baillie and Pilcher 1982 unpubl)
East Midlands	AD 882 – 1981	3.6	(Laxton and Litton 1988)

Table 4: Results of the cross-matching of sample CHT-A11 and relevant reference chronologies when the date of its first ring is AD 1408 and the last ring date is AD 1469

Reference chronology	Span of chronology	*t*-value	
Ughill Manor, Bradfield, Derbys	AD 1349 – 1504	6.8	(Howard *et al* 1994)
Manor Farm, Bradfield, Derbys	AD 1380 – 1550	5.9	(Howard *et al* 1996b)
The College, Durham Cathedral	AD 1364 – 1531	5.9	(Howard *et al* 1992a)
Little Carlton, Notts	AD 1389 – 1516	5.9	(Howard *et al* 1986)
Horbury, Wakefield, Yorks	AD 1368 – 1473	5.6	(Howard *et al* 1992b)
Kepier Hospital, Durham	AD 1304 – 1522	5.6	(Howard *et al* 1996a)
England	AD 401 – 1981	5.6	(Baillie and Pilcher 1982 unpubl)
East Midlands	AD 882 – 1981	5.6	(Laxton and Litton 1988)

Figure 1: Map to show general location of Clifton

Figure 2: Map to show general location of Clifton Hall, Clifton

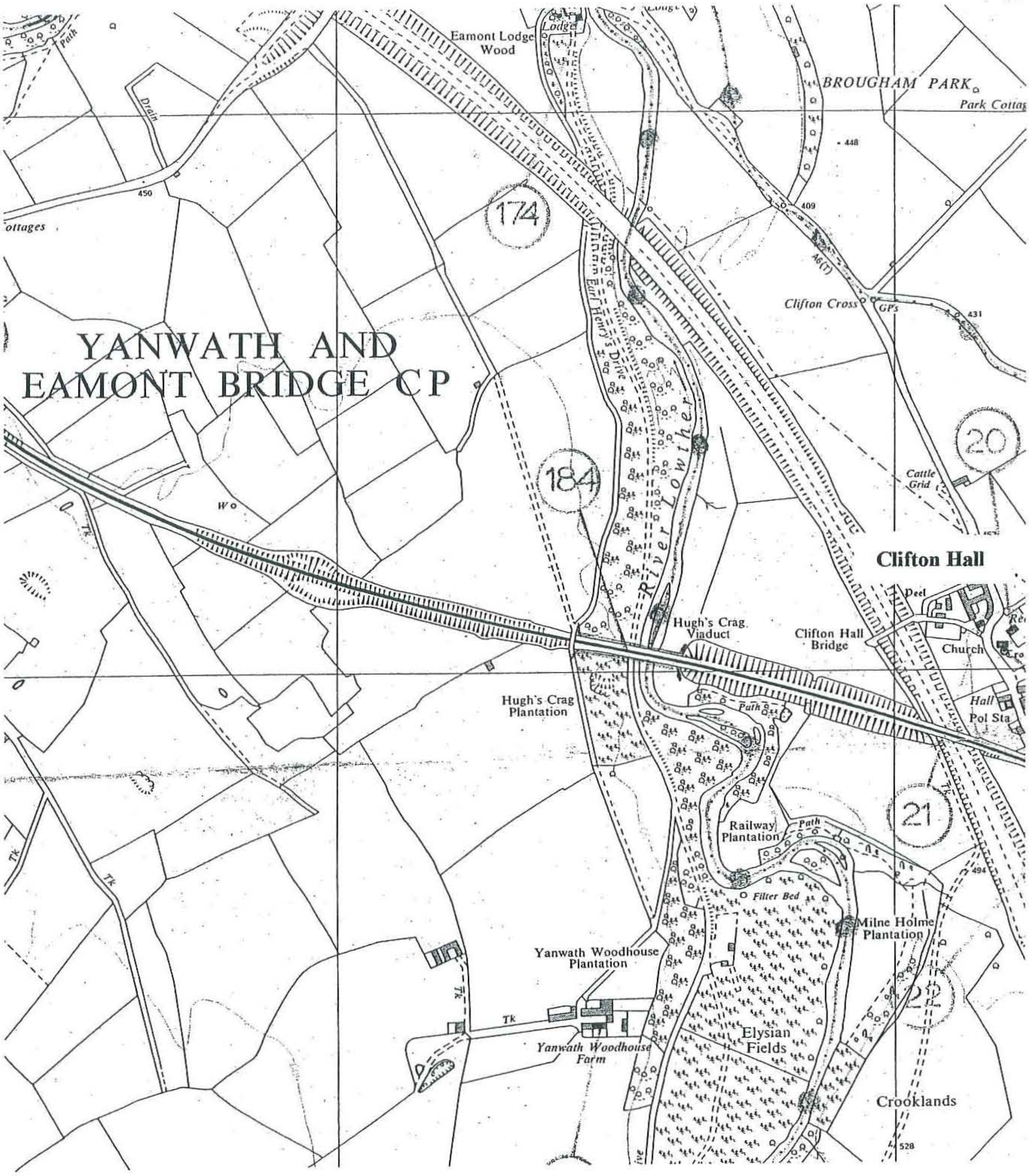


Figure 3: Plan at ceiling level to show timbers sampled

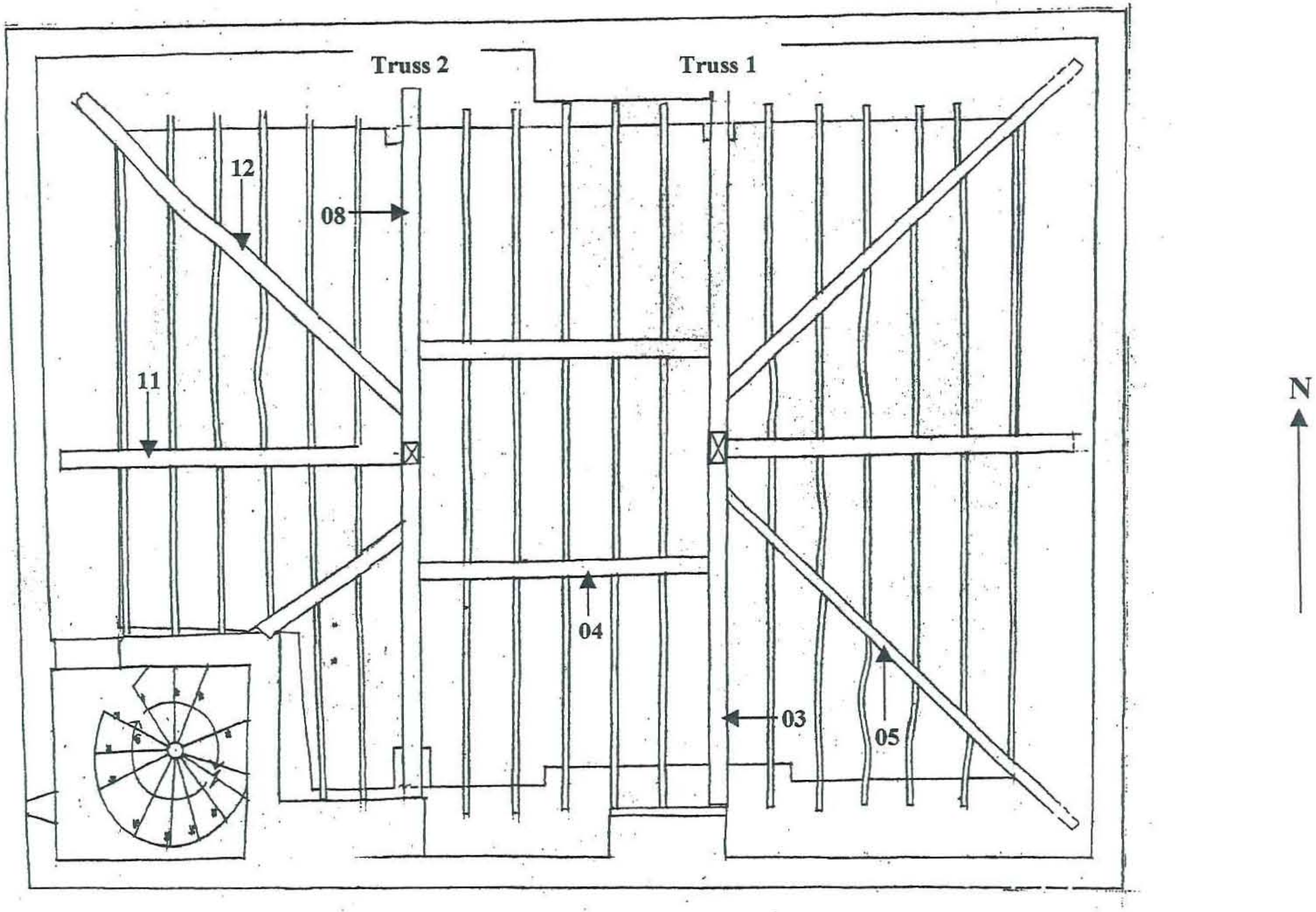


Figure 4: Drawing at above ridge level to show timbers sampled

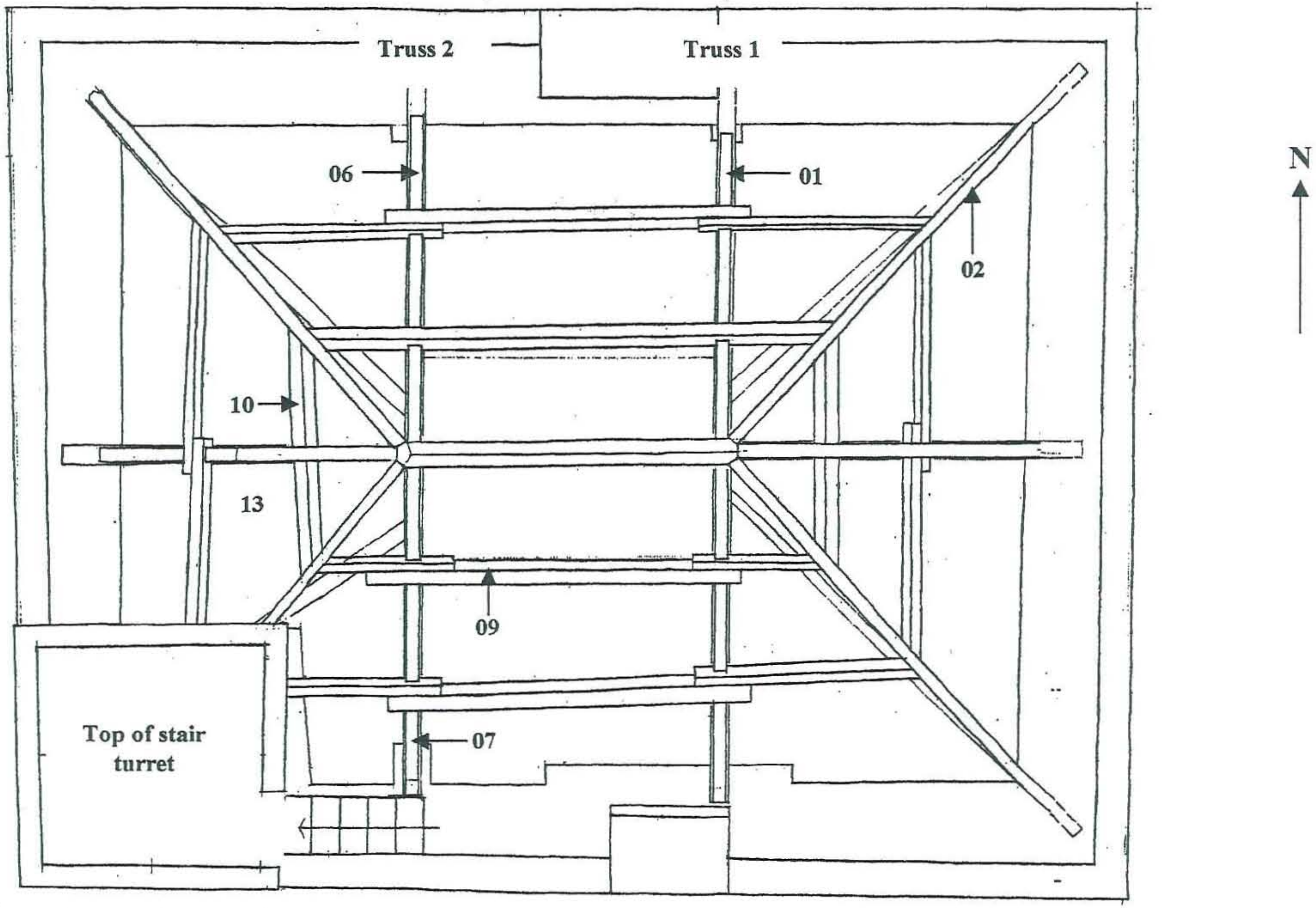


Figure 5: Plan of first-floor frame to show timbers sampled

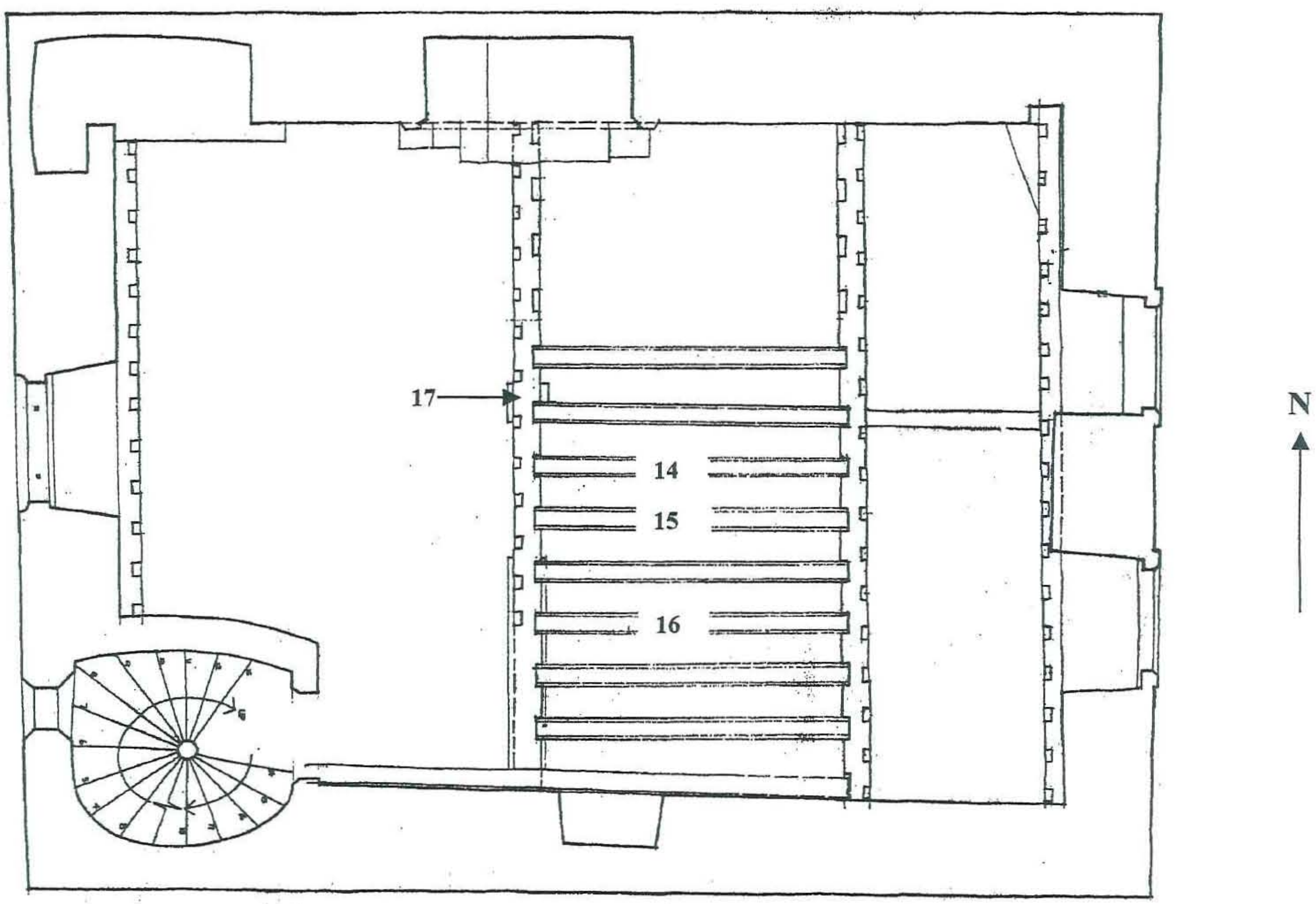


Figure 6: Bar diagram of the samples in site chronology CHTASQ01

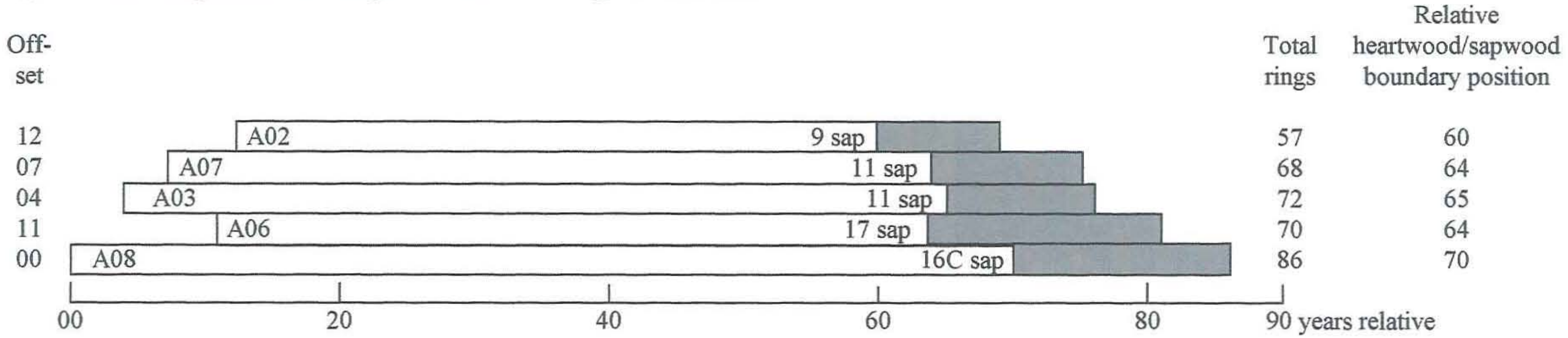
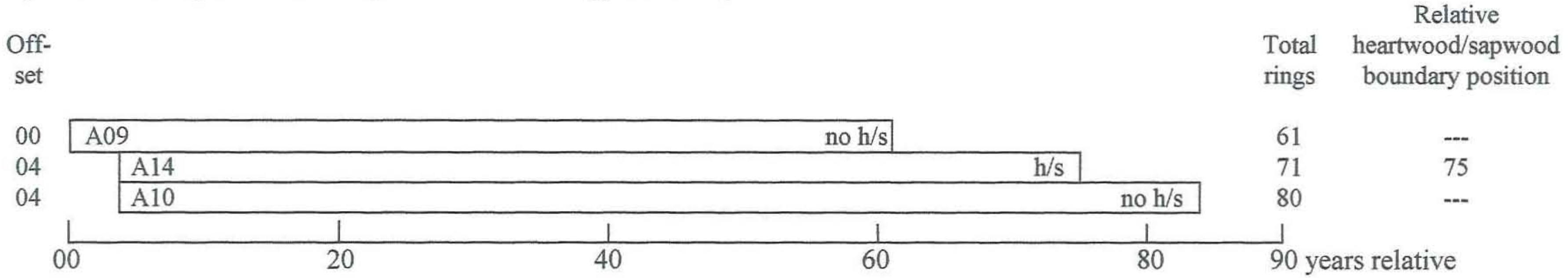


Figure 7: Bar diagram of the samples in site chronology CHTASQ02



white bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary is last ring on sample
C = complete sapwood retained on sample

Data of measured sanples – measurements in 0.01 mm units

CHT-A01A 79
165 180 162 132 163 141 187 223 298 251 251 292 272 235 211 168 208 268 289 236
285 187 271 184 220 294 342 292 216 260 233 292 219 218 257 241 266 220 198 201
218 253 234 230 182 191 200 194 167 123 210 224 196 190 244 291 228 206 149 191
142 208 153 169 173 156 137 187 154 193 186 200 167 148 111 65 91 72 116
CHT-A01B 79
209 157 162 149 163 146 195 236 293 256 270 275 272 244 222 169 196 278 284 236
265 197 261 196 233 278 338 310 250 293 220 298 215 214 252 243 259 231 199 201
219 244 234 223 188 199 202 199 174 134 194 228 195 195 248 269 245 190 161 190
143 205 164 157 167 153 141 185 161 192 158 208 158 181 99 73 85 85 116
CHT-A02A 57
245 284 192 178 137 179 214 259 211 297 284 263 307 248 244 328 259 227 186 268
248 238 218 215 273 307 315 339 245 254 253 302 243 222 205 194 271 253 218 266
332 268 375 216 299 374 299 292 284 275 357 292 306 287 223 236 329
CHT-A02B 57
224 298 192 174 129 189 206 275 238 293 276 267 290 252 245 321 272 225 185 267
247 231 223 220 269 318 278 337 232 255 274 297 242 225 199 220 266 255 219 265
307 289 347 226 282 381 340 281 289 290 340 314 288 296 208 257 339
CHT-A03A 72
315 393 385 409 360 469 342 234 194 196 204 246 208 179 236 203 191 233 221 201
181 189 199 262 230 200 163 250 198 181 191 168 226 179 168 186 183 196 172 161
169 123 169 139 177 112 94 146 143 151 143 118 166 191 176 109 156 141 192 167
179 144 135 132 147 130 154 154 126 94 118 154
CHT-A03B 72
351 405 389 412 354 465 336 221 205 201 210 241 217 176 244 192 196 246 200 207
182 181 205 264 202 227 161 247 197 169 201 167 220 183 172 177 190 196 171 150
148 155 172 142 164 123 102 132 151 166 147 121 164 186 183 115 153 141 189 170
163 148 119 134 141 123 149 147 123 100 143 149
CHT-A04A 122
161 203 96 219 177 138 122 108 92 108 99 155 194 221 205 189 171 116 82 100
98 92 80 93 114 107 110 166 176 149 160 153 130 124 137 238 179 174 152 113
174 154 73 82 67 89 85 88 75 52 53 50 42 32 35 62 100 94 83 58
62 44 42 78 115 153 139 130 143 139 140 133 95 115 131 140 124 110 150 127
115 99 117 103 118 108 156 134 154 135 129 145 124 144 194 197 213 266 240 282
260 188 140 87 99 128 131 167 144 140 175 227 142 164 132 129 108 112 183 128
161 191
CHT-A04B 122
181 197 112 240 191 138 124 107 90 114 105 155 189 226 199 205 167 112 90 88
109 91 86 90 112 108 112 162 178 147 147 149 124 123 133 228 198 166 143 147
134 147 75 65 75 88 66 92 71 52 47 51 37 28 31 58 78 93 80 56
60 43 43 82 108 157 142 133 137 142 138 127 98 122 132 131 126 106 153 120
118 95 117 106 126 101 153 144 144 141 135 148 136 137 191 202 217 263 230 292
260 196 155 80 102 122 121 170 148 138 166 224 151 162 135 122 92 117 175 145
154 249

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 156 155 158 215 150 175 142 161 147 168 107  77  90 113 138 147 182
CHT-A05B 57
 258 263 389 334 218 273 131 131 240 224 176 132 116 100 102  73  84 115 176 173
 196 225 279 237 217 242 170 205 166 205 207 121 113 188 190 152 121 192 166 246
 172 129 167 228 192 182 165 161 167 168 102  71  90 108 132 150 179
CHT-A06A 70
 263 129 217 166 194 257 217 249 172 132 208 155 173 208 211 152 290 256 152 114
 231 244 183 190 165 209 249 261 181 237 295 198 222 196 180 184 158 220 162 156
 176 213 222 244 143 111 151 191 145 209 199 208 221 211 117 119 117 178 167 202
 167 133 146 176 208 196 195 190 178 221
CHT-A06B 70
 231 127 236 159 222 256 213 231 166 128 209 148 164 195 214 156 293 246 164 116
 227 239 180 199 173 203 243 277 196 219 290 201 226 201 175 190 157 220 150 166
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 164 139 134 168 207 201 189 209 161 210
CHT-A07A 68
 230 216 261 193 219 166 298 216 305 358 267 378 284 226 306 257 319 296 329 207
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 247 156 159 149 160 104 129 172
CHT-A07B 68
 231 223 233 193 226 170 296 214 292 362 286 404 311 243 296 251 300 322 308 209
 392 273 200 118 323 406 356 371 204 228 284 247 169 203 297 259 234 202 167 206
 174 191 184 159 272 253 233 214 112  83 118 204 138 172 181 203 253 159 136 139
 256 160 174 143 173  88 114 167
CHT-A08A 86
 359 387 312 447 384 354 303 240 221 255 186 163 171 163 218 285 253 199 260 228
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 233 185 164 234 256 178
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 203 272 206 210 191 128 146 120 129 125 122 124 155 187 201 138 144 212 231 149
 145 139 187 181 200 154 170 200 190 211 211 289 405 257 237 255 167 254 238 259
 234 194 150 215 276 184
CHT-A09A 61
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 240 312 294 256 252 295 221 182 122 144 188 205 190 288 248 264 192 200 198 124
 168 194 251 172 217 201 211 147 212 159 191 165 203 163 165 149 129 149 160 151
 193
CHT-A09B 61
 423 375 431 439 374 379 335 275 232 325 357 195 295 325 272 272 246 278 182 196
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 159 200 235 171 215 207 206 145 210 173 174 176 188 175 170 127 140 151 138 143
 210
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CHT-A10A 80
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 115 136 109  82  95  82  87  92 100  83  46  65  54  77  73  92  97 135 120 115
CHT-A10B 80
 276 292 244 222 240 276 237 199 264 256 211 194 197 181 121 150 151 205 189 209
 165 213 167 107  70 125 125 141 141 149 133 120 136 116 157 107 133 163 197 141
 152 162 154 108 134 124 137 121 111  99 103  95  86  90  90 119 131 118 108  94
 110 128 104 104  91  84  71  84 118  70  57  72  62  65  94  86 100 115 111 140
CHT-A11A 62
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 135 131 157 142 215 173 129 118 196 156  75  70  94  83 131  77  80  83 127 109
 126 142
CHT-A11B 62
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 124 173 150 182 161 137 131 126 104 115 111 106  81 120  82 126 137 112  80 111
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CHT-A12A 55
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CHT-A15A 65
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CHT-A15B 65
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 320 268 251 263 176 152 165 223 309 310 321 222 271 281 238 128 163 226 375 352
 324 323 293 353 286 330 265 227 324 334 205 151  89  66  60  54  44  50  84  98
  90 102 101  80  82
CHT-A16A 57
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 178 192 160 116 103  86 106  79  92 156 118  99  98  91 121 123 163
CHT-A16B 57
 230 286 163 164 105  89  78 131 211 264 280 273 229 200 181 138 181 161 150 140
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CHT-A17A 58
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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.

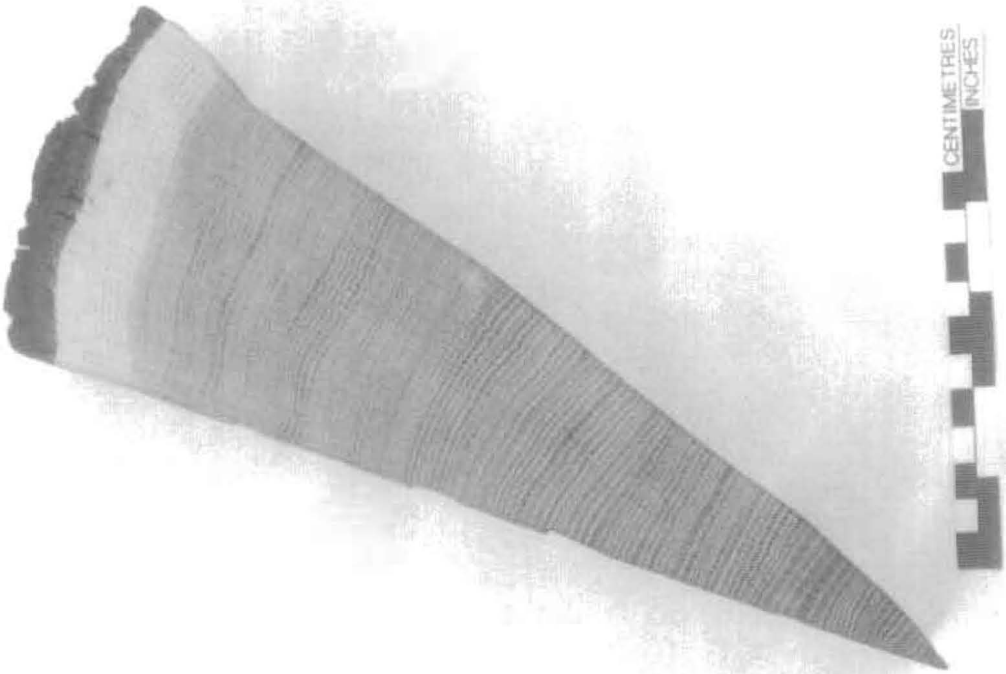

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

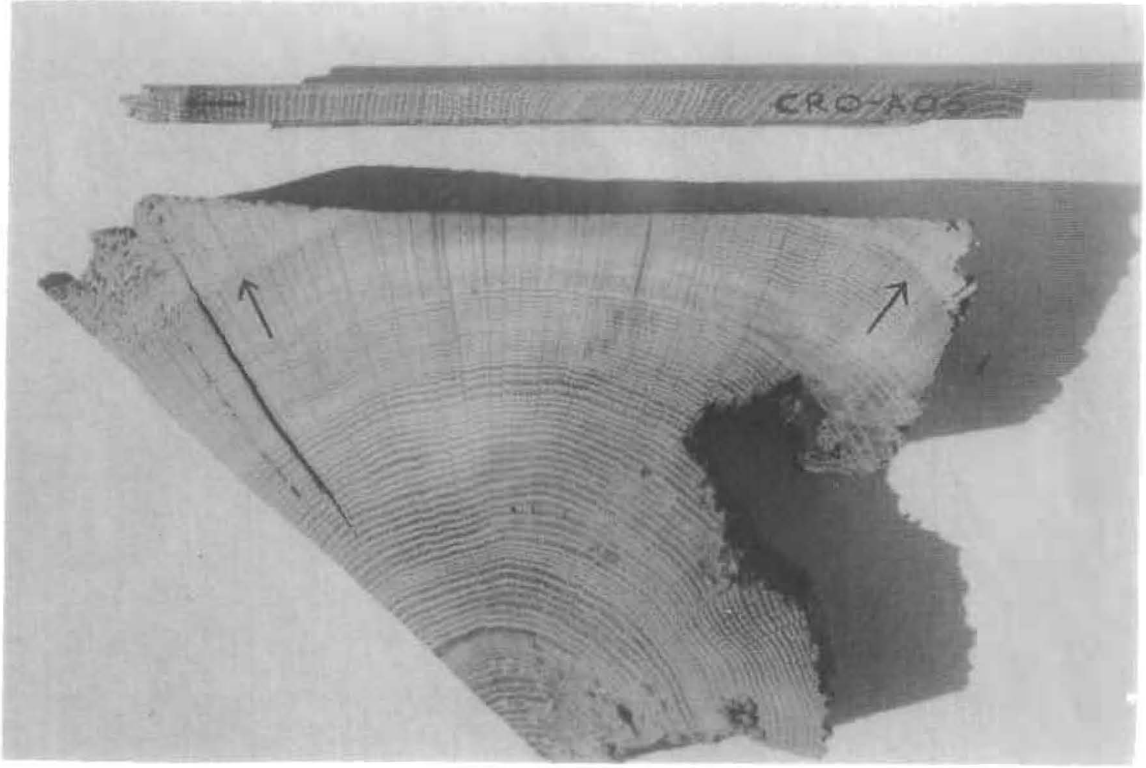

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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.

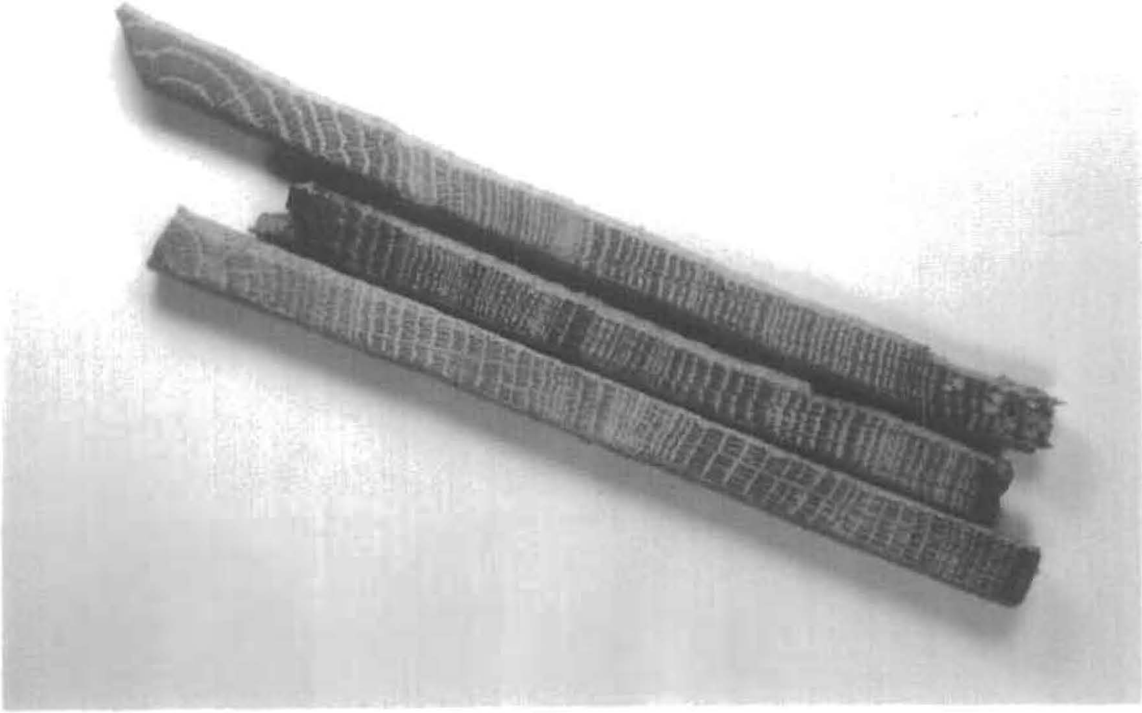

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

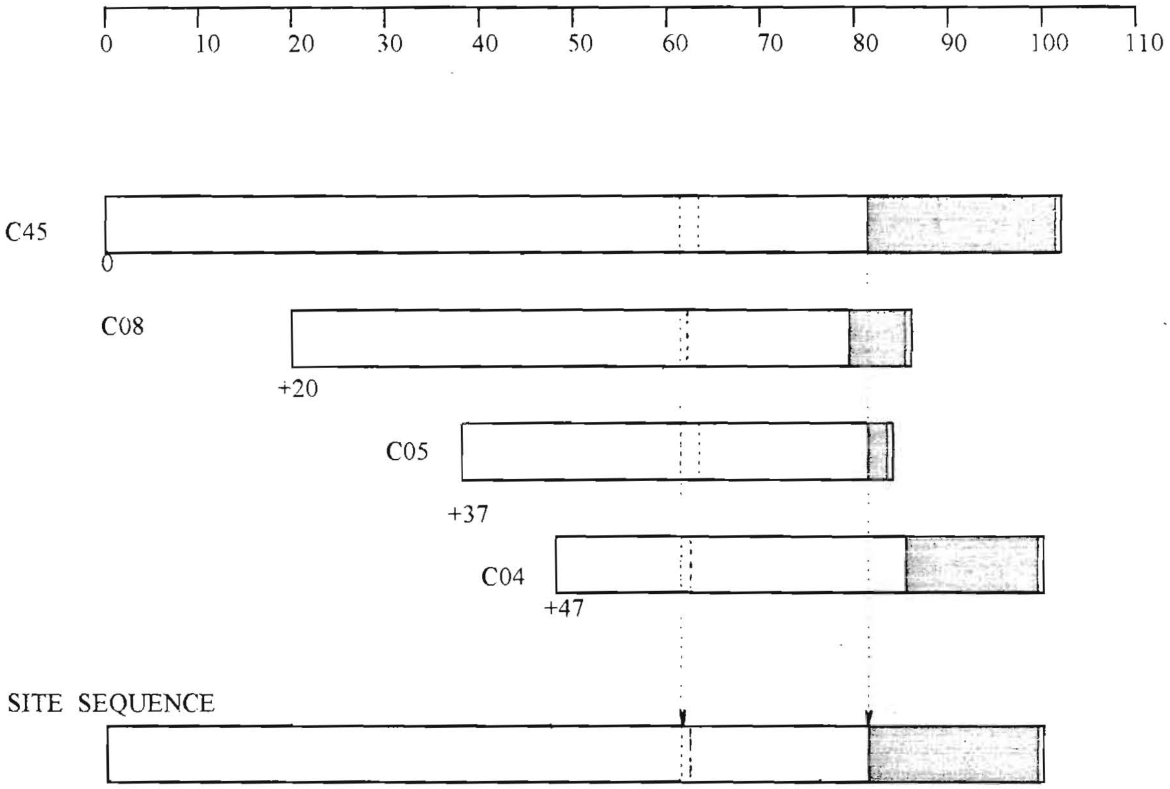

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set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

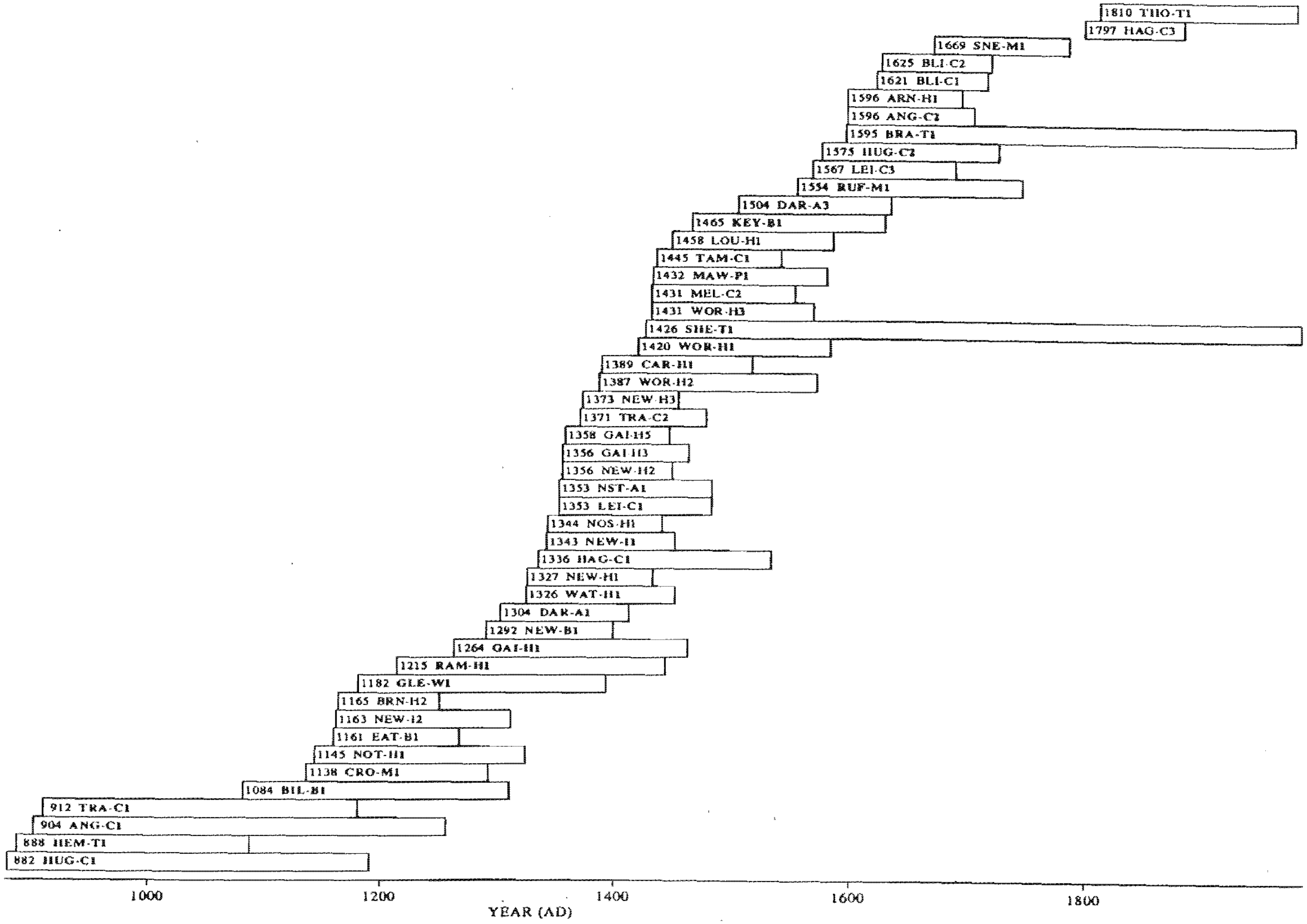

Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

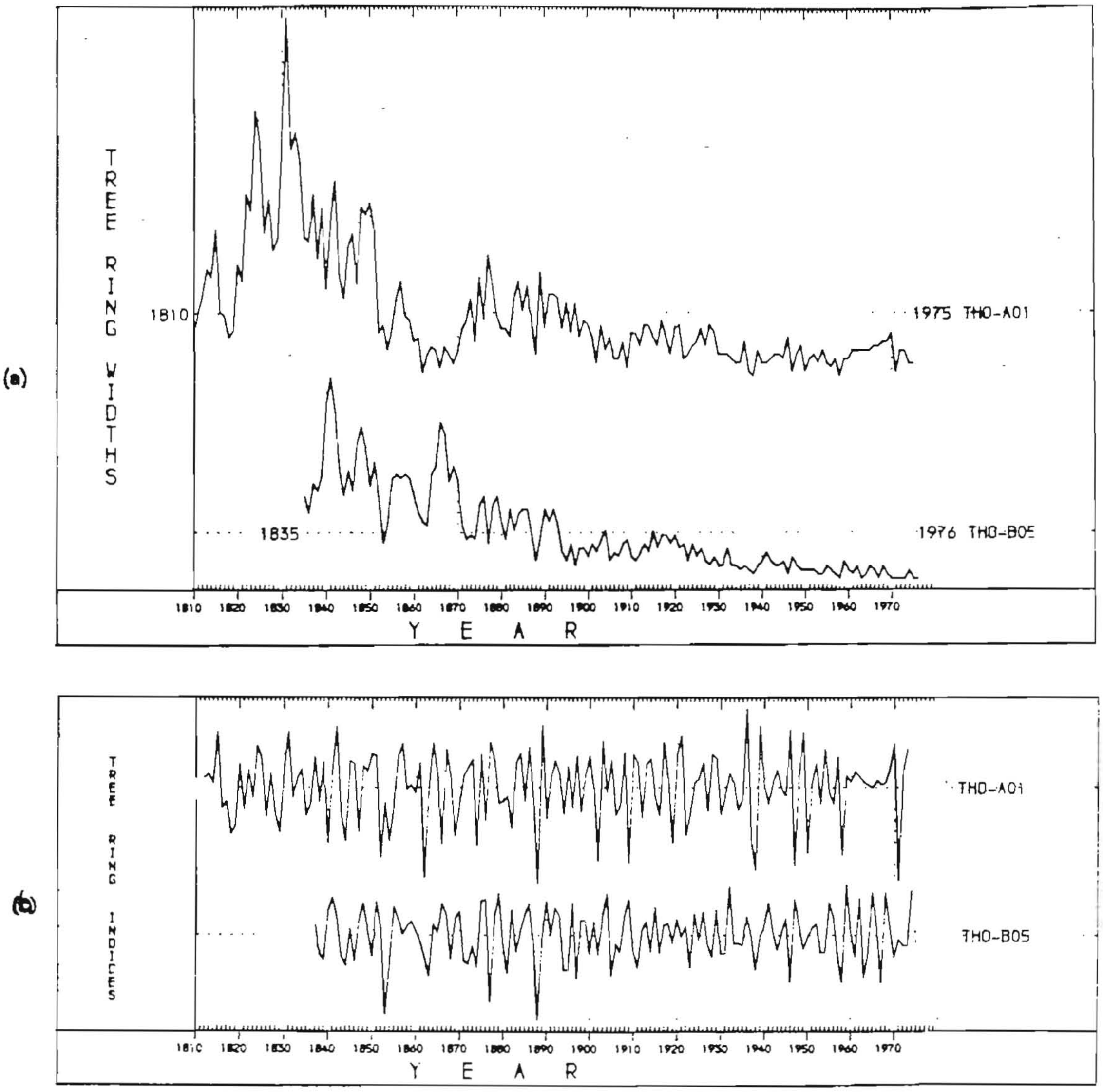

Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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