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A J Arnold, R E Howard, R R Laxton & C D Litton

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Summary

Twenty-nine samples were taken from timbers of the aisled hall, and alterations made to it, and the roof of the cross-wing at this building; fifteen of these were not analysed because of their short ring-width sequences. The analysis carried out on the remaining fourteen samples resulted in the construction of two site chronologies.

The first, THOHSQ01, of 56 rings was matched at a first ring date of AD 1198 and a last-ring date of AD 1253. One of the two samples making up this sequence has complete sapwood and a last-ring date of AD 1253, this being the felling date for the timber represented. The heartwood/sapwood boundary ring date of the second sample is also consistent with a felling date of AD 1253.

The second site chronology, THOHSQ03, of 101 rings, containing eleven samples, was found to span the period AD 1275-AD 1375. Interpretation of the heartwood/sapwood boundaries on those timbers represented gives an estimated felling date range of AD 1383-AD 1403.

A further sample, THO-H20, was successfully dated individually, to a first-ring date of AD 1326 and a last-ring date of AD 1392, with an estimated felling date for the timber of *c* AD 1397.

The earlier site chronology contains samples from the aisled hall; the timbers represented are from trees felled in *c* AD 1253/4. This site chronology only relates to two timbers and so should not be used as positive dating of the hall itself. The second site chronology, and the individually dated samples, are from the cross-wing and the low tiebeam in the aisled hall. These samples are from timbers which are estimated to have been felled in *c* AD 1397, indicating that the cross-wing was built and low tiebeam inserted at or soon after this date.

Keywords

Dendrochronology
Standing Building

Authors' addresses
University of Nottingham, University Park, Nottingham, NG7 2RD

TREE-RING ANALYSIS OF TIMBERS FROM THORLEY HALL, BISHOP'S STORTFORD, HERTFORDSHIRE

Introduction

The building of Thorley Hall (TL476188; Figs 1, 2a, and 2b), attributed to a member of the Gebergh family who held the manor from the mid-thirteenth century until AD 1390 (Smith 1993, 189), began life as a moated house with a two-bayed aisled hall. The remains of the early phase seen today is the hall's central truss, consisting of posts with octagonal moulded capitals, arcade plates (and cornices) with arcade braces, and a tiebeam with its braces. Empty side lapped joints on the posts and tiebeam show there to have once been passing braces (one side only illustrated in Fig 3). On the basis of this, and the overall style of construction, the aisled hall was thought to date to AD 1280-AD 1300 (Adrian Gibson pers comm). Some time later, the passing braces were removed and replaced by a crown-post. A cross-wing with a crown-post roof was added and thought to date to *c* AD 1380-AD 1400 (Fig 4). The proposed date is based upon a splayed scarf joint in one of the cross-wing wall-plates, which however was considered to date to the early-fourteenth century by Hewett (1980, 266). Further alterations were made to the aisled hall central truss; with the arcade posts being cut beneath their capitals and a low bearing tiebeam inserted across the hall. Under this tiebeam are curved brackets coming from the outer walls, probably put in at the same time to help support it. In this way, a roof of raised aisled form was created. This was thought to have happened in the fourteenth or fifteenth century (Smith 1992, 177). Later still the middle of this low tiebeam was cut away creating the shape of a hammer-beam roof and the aisle walls reworked so that a first-floor and appropriate windows could be inserted. The wall-plates bear halved and bridle-butted scarfs, commonly seen in the fifteenth-century and sixteenth-century work (Hewett 1980, 267). A drawing illustrating the suggested sequence of development is reproduced as Figure 3. This house has continued to be modified and enlarged in the seventeenth, eighteenth, and nineteenth centuries.

This house is acknowledged to be of great importance in demonstrating the evolution of domestic architecture and timber-framing techniques in East Hertfordshire and West Essex. Sampling and analysis by tree-ring dating was commissioned and funded by English Heritage, as part of their training programme in dendrochronology, and in order to gain a greater understanding of these developments and perhaps provide a model for dating other buildings.

The Laboratory would like to take this opportunity to thank Mr and Mrs Timmis, the owners of the property, for allowing us access to the home for sampling and also Adrian Gibson for his help in interpreting the various phases of this site and for providing drawings upon which the location of samples could be shown.

Sampling

After discussion with Adrian Gibson on the probable phasing of the buildings and inspection of the timbers available, and in conjunction with the brief provided by English Heritage, a total of twenty-nine core samples were obtained from these premises. Access to the crown-post roof above the aisled hall was considered too dangerous for sampling to be carried out there, as it would have required getting across a deep void in the roof space. However, it is thought that the much more easily accessible cross-wing is contemporary with it and so sampling was carried out here. Each sample was given the code THO-H (for Thorley, site "H") and numbered 01 – 29.

Eleven samples, THO-H01-07, THO-H09-11, and THO-H14 were obtained from the posts, braces, arcade plates, and tiebeam of the central hall truss of the aisled hall. The low, bearing tiebeam and wall plates, relating to timbers associated with the alterations to the aisled hall, were also sampled, resulting in four samples, THO-H08, THO-H12-13, and THO-H15. Fourteen samples, THO-H16-29 were taken from the rafters, tiebeams, and a soulace of the cross-wing. The timbers associated with the aisled hall, although quite substantial in some cases, had relatively few growth rings. The growth rings of the timbers from the cross-wing roof were narrower and many retained some sapwood, although only three were complete. This, however, proved to be very crumbly and most samples lost these outer rings during sampling. The positions of the samples in the house were marked at the time of coring on plans provided and reproduced here as Figure 5. Details of the samples are given in Table 1.

Analysis

Each sample was prepared by sanding and polishing and the growth-ring widths of all twenty-nine were measured; the data of these measurements are given at the end of the report. Fifteen of the samples were not included in the subsequent analysis as they were deemed to have too few rings for secure dating. The growth-ring widths of the remaining fourteen samples were compared with each other by the Litton/Zainodin grouping procedure (see appendix).

At a minimum t-value of 4.5 twelve samples matched each other to form two groups. Two of the samples, THO-H04 and THO-H14, both from the aisled hall, matched at the relative positions shown in Figure 6. The growth-ring widths of these two samples were combined at these relative offset positions to form THOHSQ01, a site chronology of 56 rings. Site chronology THOHSQ01 was successfully compared with a series of relevant reference chronologies giving it a first-ring date of AD 1198 and a last measured ring date of AD 1253. Evidence for this dating is given in the t-values of Table 2.

Ten samples, eight from the cross-wing and two from the (cut) low tiebeam in the hall, also matched at a least value of t=4.5 at the relative positions shown in the bar diagram, Figure 7. The growth-ring widths of these ten samples were combined at these relative offsets to form THOHSQ02, a site chronology of 101 rings. This site chronology was successfully compared with a series of relevant reference chronologies at which point it matched at a first-ring date of AD 1275 and a last-ring date of AD 1375. It was then noted that sample THO-H21 matched the site chronology at a value of t=4.2 and a third site chronology, THOHSQ03, was constructed, containing all eleven samples at the relative positions shown in the bar diagram, Figure 8. This was successfully matched, again at a first-ring date of AD 1275 and a last-ring date of AD 1375. The evidence for the dating of these two chronologies is given by the t-values in Table 3 and 4.

Attempts were then made to date the remaining unmatched sample, THO-H20, individually by comparing it with the reference chronologies. This resulted in the sample being successfully dated to a first-ring date of AD 1326 and a last-ring date of AD 1392. The evidence for this dating is given by the t-values in Tables 5.

Interpretation

Analysis of samples from Thorley Hall produced two site chronologies. The earlier of these, THOHSQ01, contained two samples and spanned the period AD 1198-AD 1253. These two samples are from a brace (THO-H04) and an arcade plate (THO-H14) in the aisled hall central truss. Sample THO-H14 has complete sapwood and a last-ring date of AD 1253, this being the felling date for the timber represented. Under the microscope it can be seen that all of the summer cell growth for AD 1253 has taken place on this sample. It is thus probable that the tree it represents was felled late in that year, or in the very early part of AD 1254. The heartwood/sapwood boundary ring date for the other sample, THO-H04, is also consistent with a felling date of AD 1253/4.

The second site chronology, THOHSQ03, spanned the years AD 1275 to AD 1375 and contained samples from the cross-wing and the bearing tiebeam of the aisled hall. Although none of these samples had complete sapwood, a number did have the heartwood/sapwood boundary ring. The average heartwood/sapwood boundary ring date of AD 1368 allows an estimated felling date range for the timbers to be calculated to AD 1383-AD 1403.

A further sample from the cross-wing was dated, THO-H20, to a last-ring date of AD 1392. At the time of sampling it was noticed that this timber had complete sapwood but 4mm of this was lost in sampling. By noting how many rings this 4mm represents on the sample it was possible to estimate, although not say definitely, that *c* 5 sapwood rings were missing; thus giving the timber a felling date of *c* AD 1397. This date is entirely consistent with the range calculated for the timbers represented by site chronology THOHSQ03. All estimated felling dates and date ranges have been based on the estimate that mature oaks growing in this area have between 15-35 sapwood rings.

Conclusion

Following analysis by tree-ring dating it has been possible to obtain dates for some of the timbers, and consequently phases, in this building. Two timbers from the aisled hall are from trees felled in AD 1253/4, which may suggest construction in, or soon after, *c* AD 1253/4. However, in saying this it should be remembered that the date of two timbers cannot be used to positively date the construction as a whole. The cross-wing and, if assumptions about its contemporaneous nature are correct, the crown-post roof above the aisled hall, were constructed from timbers felled in *c* AD 1397. It has also shown that rather than representing a different phase, the modification of the aisled hall into a raised aisle, was carried out at the same time as the cross-wing was added. Unfortunately, it was not possible to date the final phase, as represented by two wall plates, as these samples only had 45 and 50 rings each.

As mentioned above access to the crown-post above the aisled hall was hindered by there being a deep void, between it and the rest of the roof, which would have had to be crossed and this was deemed unsafe; under the circumstances sampling was not requested of it. However, if in the future a platform could be constructed over this void making access possible, it would be useful to sample this to confirm the contemporaneous nature of it with the crown-post roof already dated.

Figure 1: Map showing the general location of Thorley Hall

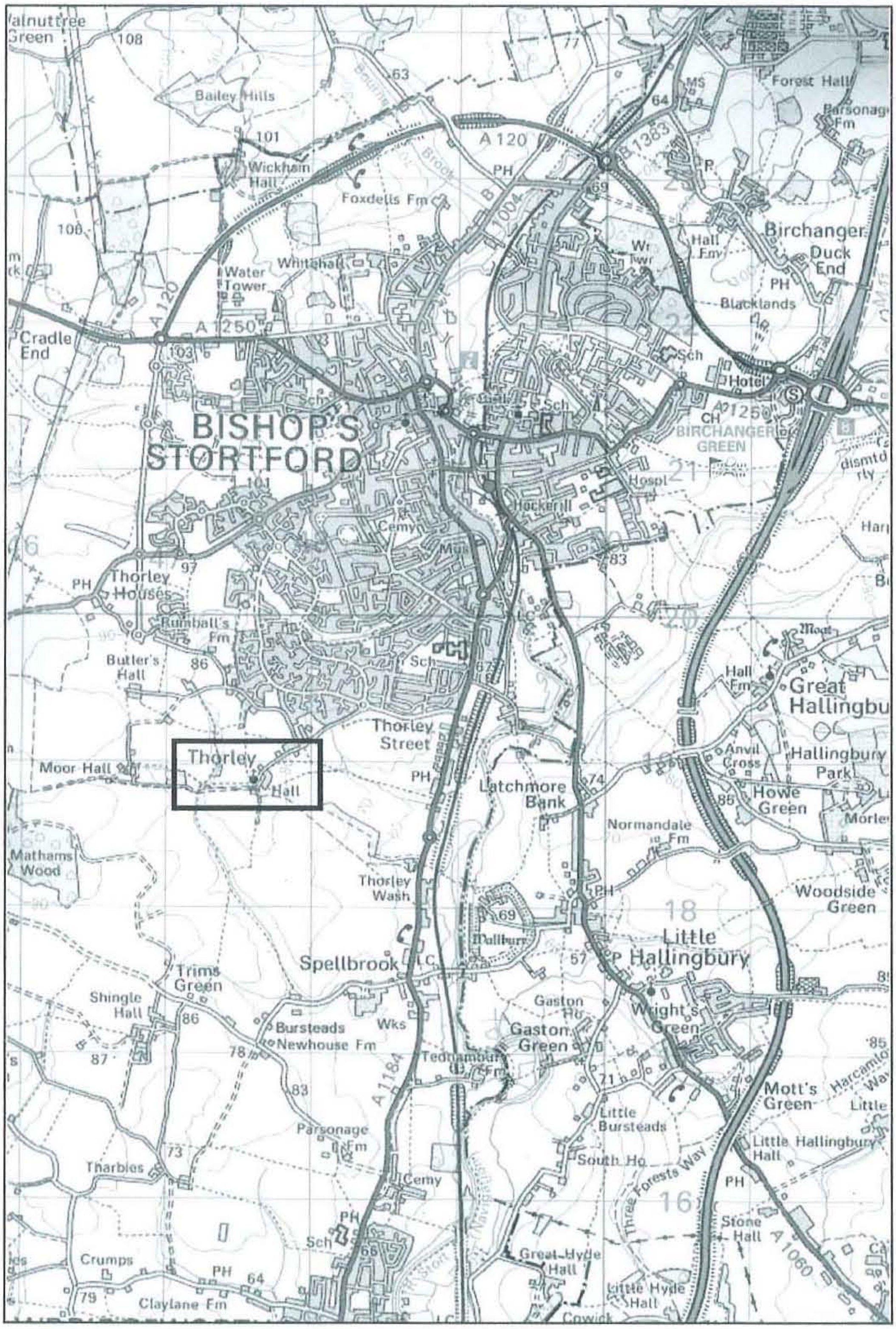


Figure 2a: Thorley Hall, from the north-west: the surviving aisled hall bay is to the left of the chimney stack, with the cross-wing at the right of the picture, *supplied by English Heritage, ©Crown copyright. NMR (BB70/7707)*

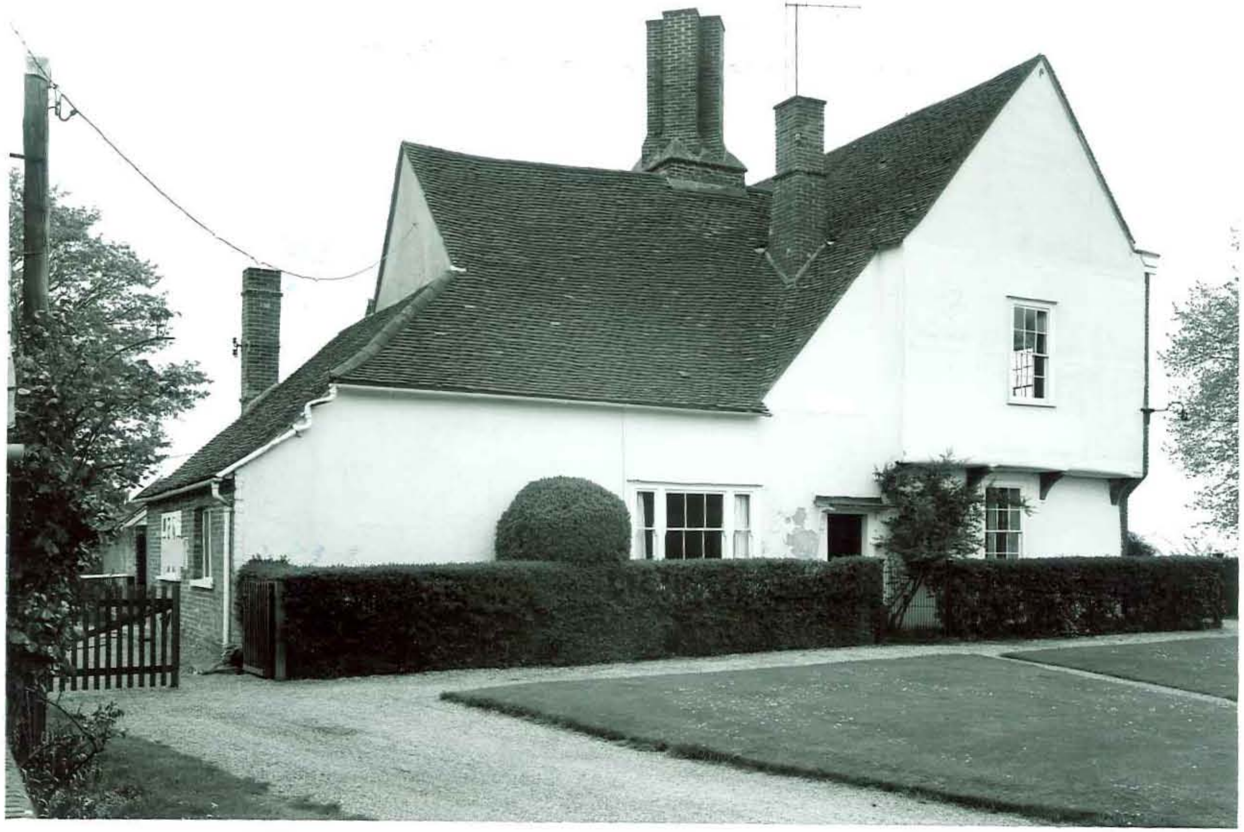
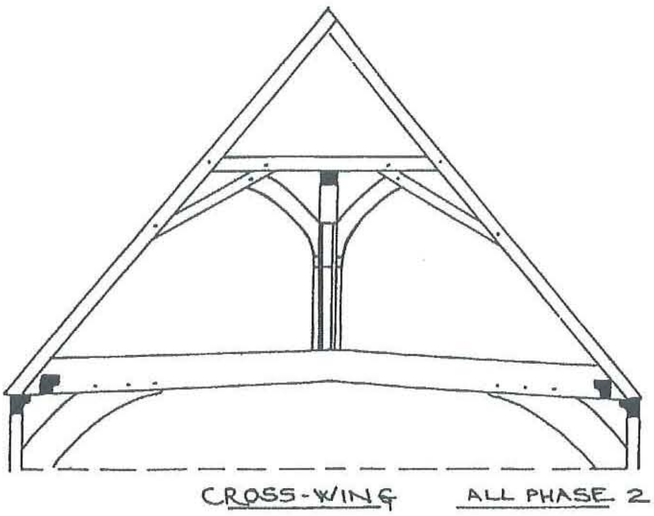


Figure 2b: Thorley Hall, from the north-east: the aisled hall to the right with Georgian addition to the cross-wing on the left, supplied by English Heritage, ©Crown copyright. NMR (BB70/7705)

Figure 4: The roof of the cross-wing, from the north-west (see Fig 5), supplied by English Heritage, ©Crown copyright. NMR (BB70/7716)

Figure 3: Illustrations of the cross-wing and aisled hall, showing the suggested phasing (after Bailey and Hutton 1966)



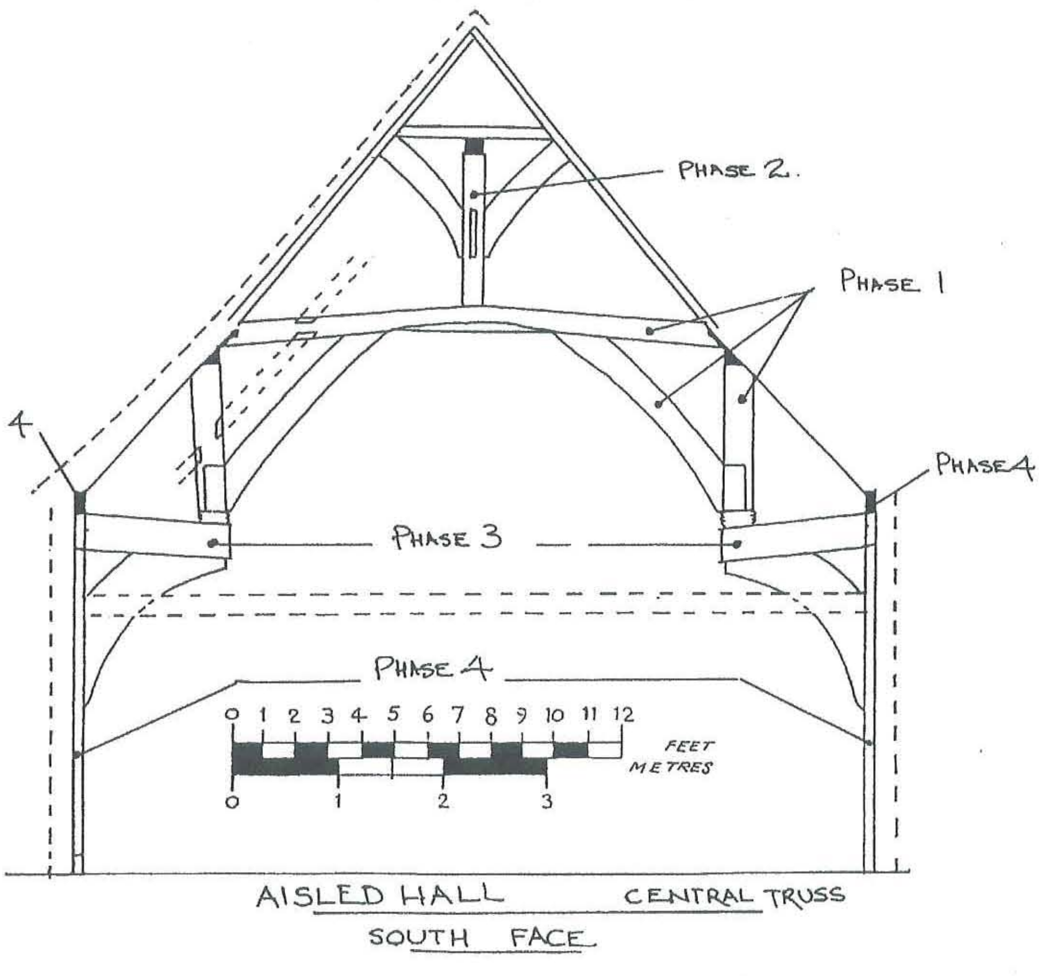


Figure 5: Thorley Hall, plan showing the location of samples THO-H01-29 (based on RCHME 1993)

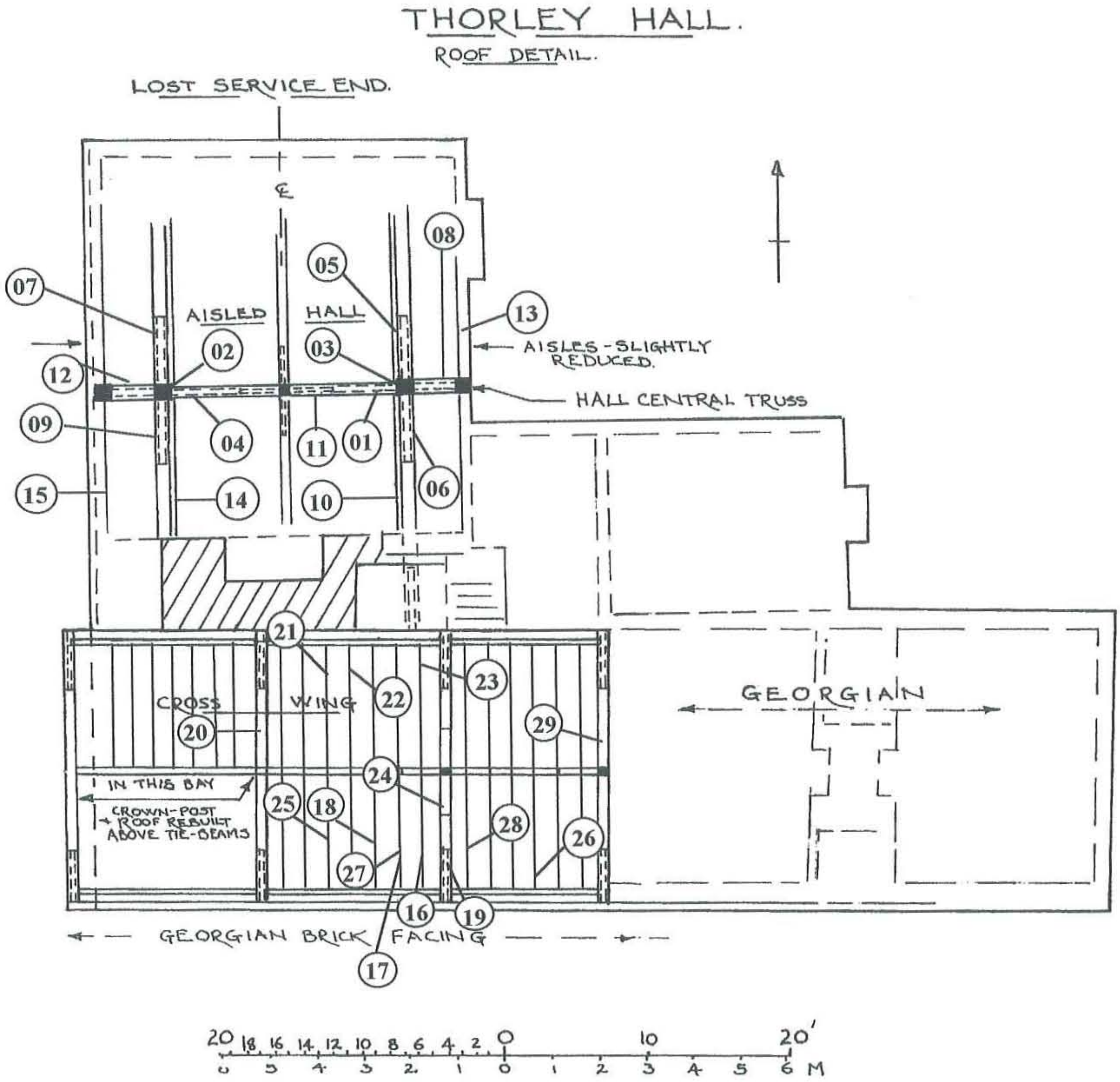


Figure 6: Bar diagram of samples in site chronology THOHSQ01

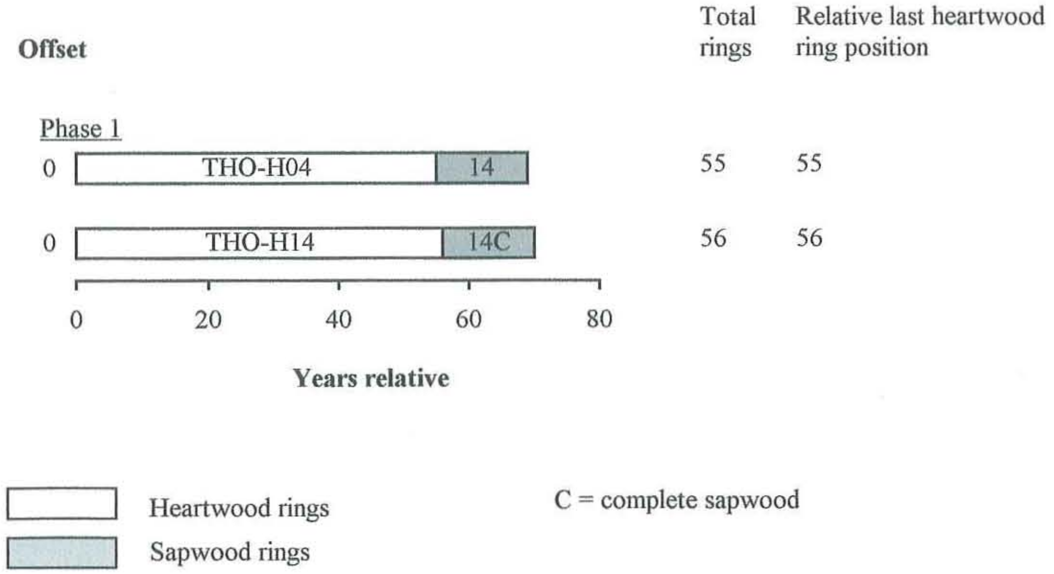


Figure 7: Bar diagram of samples in site chronology THOHSQ02

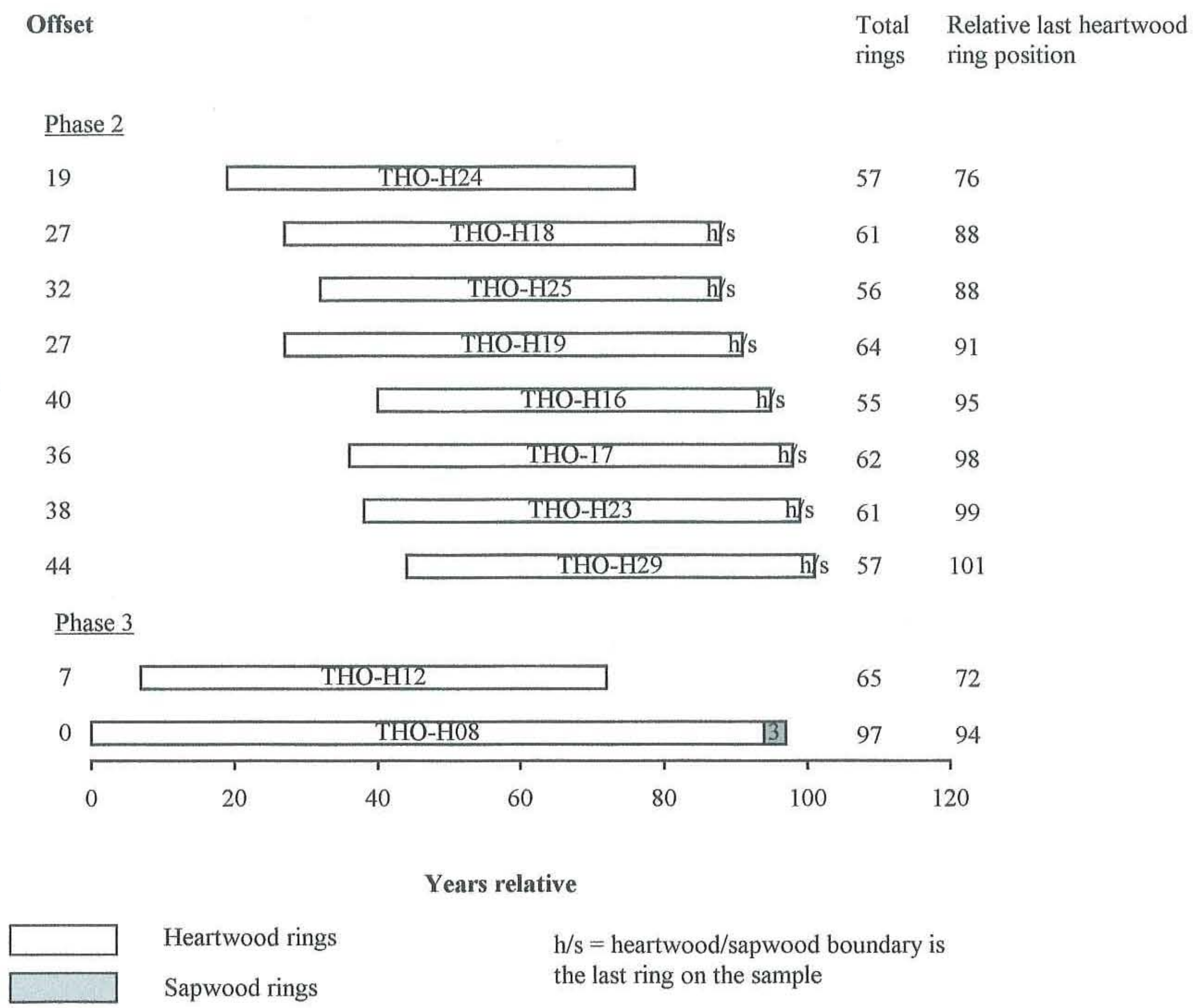
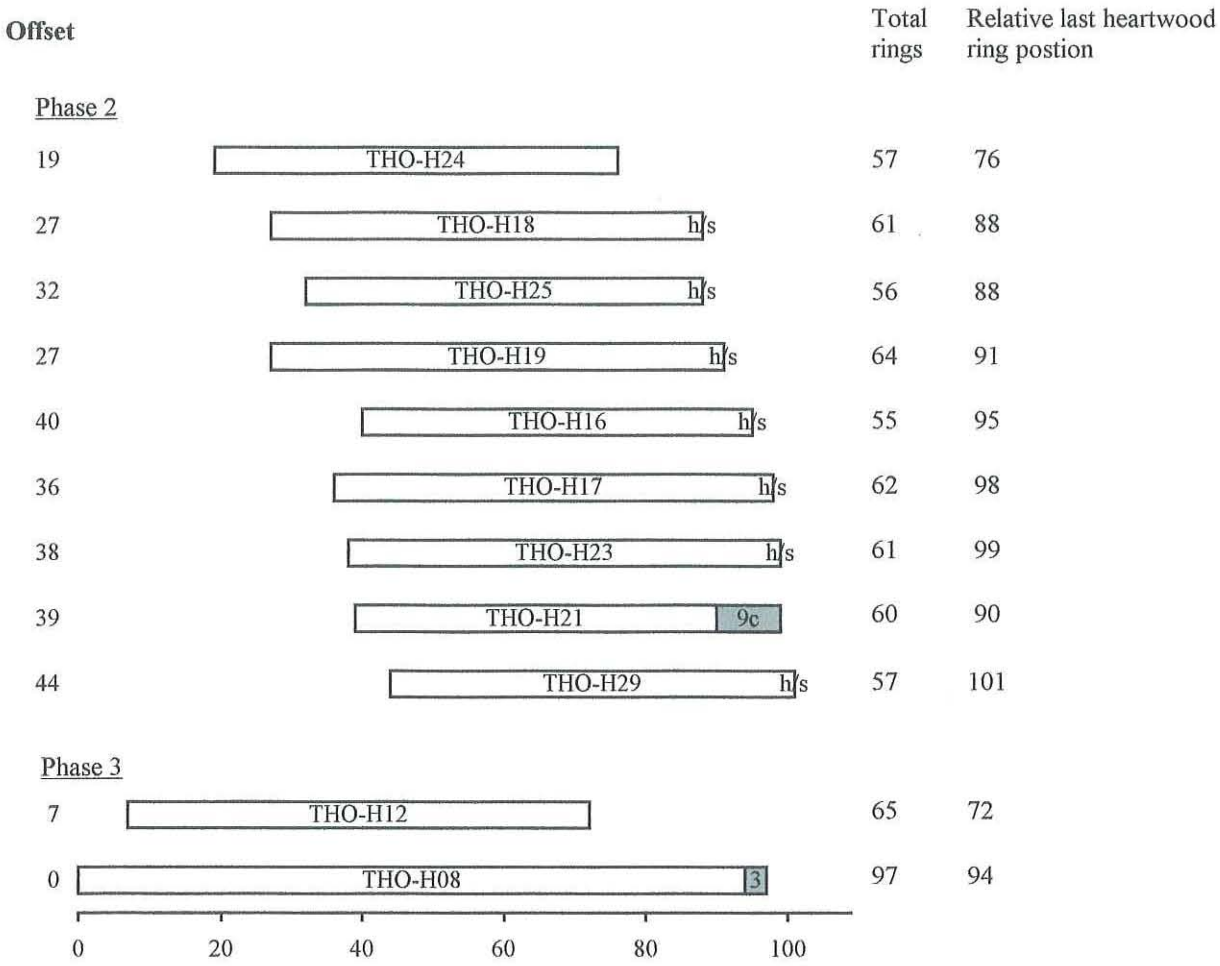


Figure 8: Bar diagram of samples in site chronology THOHSQ03



Heartwood rings

Sapwood rings

h/s = heartwood/sapwood boundary is the last ring on the sample

c = complete sapwood on timber, all or part lost in sampling

Table 1: Details of samples from Thorley Hall, Bishop's Stortford, Hertfordshire

Sample number	Sample location	Total Rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Aisled hall					
	Suggested phase 1					
THO-H01	Tiebeam brace, east post	NM	--	------	------	------
THO-H02	West arcade post	NM	--	------	------	------
THO-H03	East arcade post	NM	--	------	------	------
THO-H04	West tiebeam brace	55	14	AD 1198	AD 1238	AD 1252
THO-H05	North arcade brace, east post	NM	--	------	------	------
THO-H06	South arcade brace, east post	NM	--	------	------	------
THO-H07	North arcade brace, west post	NM	--	------	------	------
THO-H09	South arcade brace, west post	NM	--	------	------	------
THO-H10	East arcade plate	NM	--	------	------	------
THO-H11	Principal tiebeam	NM	--	------	------	------
THO-H14	West arcade plate	56	14C	AD 1198	AD 1239	AD 1253
	Suggested phase 3					
THO-H08	Low tiebeam (east end)	97	03	AD 1275	AD 1368	AD 1371
THO-H12	Low tiebeam (west end)	65	--	AD 1282	------	AD 1346
	Suggested phase 4					
THO-H13	East wall plate	NM	--	------	------	------
THO-H15	West wall plate	NM	--	------	------	------

Table 1: Details of samples from Thorley Hall, Bishop's Stortford, Hertfordshire; cont.

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Cross-wing					
	Suggested phase 2					
THO-H16	South common rafter, frame 1, bay 2	55	h/s	AD 1315	AD 1369	AD 1369
THO-H17	South common rafter, frame 2, bay 2	62	h/s	AD 1311	AD 1372	AD 1372
THO-H18	South common rafter, frame 3, bay 2	61	h/s	AD 1302	AD 1362	AD 1362
THO-H19	South rafter, truss 2	64	h/s	AD 1302	AD 1365	AD 1365
THO-H20	Tiebeam, truss 3	67	16c	AD 1326	AD 1376	AD 1392
THO-H21	North common rafter, frame 5, bay 2	60	09c	AD 1314	AD 1364	AD 1373
THO-H22	North common rafter, frame 4, bay 2	NM	--	------	------	------
THO-H23	North common rafter, frame 1, bay 2	61	h/s	AD 1313	AD 1373	AD 1373
THO-H24	Tiebeam, truss 2	57	--	AD 1294	------	AD 1350
THO-H25	South common rafter, frame 5, bay 2	56	h/s	AD 1307	AD 1362	AD 1362
THO-H26	South common rafter, frame 3, bay 1	NM	--	------	------	------
THO-H27	South soulace, frame 2, bay 2	NM	--	------	------	------
THO-H28	South common rafter, frame 6, bay 1	NM	01	------	------	------
THO-H29	Tiebeam, truss 1	57	h/s	AD 1319	AD 1375	AD 1375

*h/s = the heartwood/sapwood boundary is the last ring on the sample
c = complete sapwood on timber, all or part lost in sampling.
C = complete sapwood is retained on sample, last measured ring date is felling date of timber
NM = not measured

Table 2: Results of the cross-matching of site chronology THOHSQ01 with relevant reference chronologies when the first ring date is AD 1198 and last ring date is AD 1253

Reference chronology	Span of chronology	*t*-value	Reference
Hull	AD 1126-1297	6.0	Hillam 1979
Southern England	AD 1083-1589	4.6	Bridge 1988
East Midlands	AD 882-1981	4.5	Laxton and Litton 1988
London	AD 413-1728	4.3	Tyers and Groves 1998 unpubl
Chichester Cathedral, West Sussex	AD 1173-1295	5.9	Howard *et al* 1992
Chicksands Priory, Bedfordshire	AD 1200-1541	5.1	Howard *et al* 1998

Table 3: Results of the cross-matching of site chronology THOHSQ02 with relevant reference chronologies when the first-ring date is AD 1275 and last-ring date is AD 1375

Reference chronology	Span of chronology	*t*-value	Reference
London	AD 413-1728	7.1	Tyers and Groves 1998 unpubl
East Midlands	AD 882-1981	5.4	Laxton and Litton 1988
Southern England	AD 1083-1589	5.2	Bridge 1988
Readinga	AD 1160-1407	8.7	Groves *et al* 1985
Sutton Valence, Hennikers, Kent	AD 1255-1354	6.4	Howard *et al* 1988
Chicksands Priory, Bedfordshire	AD 1200-1541	6.1	Howard *et al* 1998
The New Inn, 26-28 Cornmarket, Oxford	AD 1164-1386	5.9	Haddon-Reece and Miles 1989
Lacock Abbey, Lacock, Wilts	AD 1314-1448	5.5	Esling *et al* 1990

Table 4: Results of the cross-matching of site chronology THOHSQ03 with relevant reference chronologies when the first-ring date is AD 1198 and the last-ring date is AD 1375

Reference chronology	Span of chronology	*t*-value	Reference
London	AD 413-1728	6.9	Tyers and Groves 1998 unpubl
East Midlands	AD 882-1981	5.2	Laxton and Litton 1988
Southern England	AD 1083-1589	5.9	Bridge 1988
Readinga	AD 1160-1407	8.7	Groves *et al* 1985
Sutton Valence, Hennikers, Kent	AD 1255-1354	6.4	Howard *et al* 1988
Queens Head, Crowmarsh, Gifford, Oxon	AD 1203-1341	6.4	Haddon-Reece *et al* 1990
The New Inn, 26-28 Cornmarket, Oxford	AD 1164-1386	5.8	Haddon-Reece and Miles 1989
Chicksands Priory, Bedfordshire	AD 1200-1541	5.8	Howard *et al* 1998

Table 5: Results of the cross-matching of sample THO-H20 with relevant reference chronologies when the first-ring date is AD 1326 and the last-ring date is AD 1392

Reference chronology	Span of chronology	*t*-value	Reference
Kent	AD 1158-1543	7.2	Laxton and Litton 1989
London	AD 413-1728	4.4	Tyers and Groves 1998 unpubl
East Sutton BH-H1	AD 1293-1461	5.9	Laxton and Litton 1989
Chicksands Priory, Bedfordshire	AD 1200-1541	5.8	Howard *et al* 1998
East Sutton NA-H1	AD 1337-1446	5.6	Laxton and Litton 1989
Horsmonden RP-W1	AD 1313-1426	4.5	Laxton and Litton 1989
East Sutton WT-H1	AD 1219-1393	4.4	Laxton and Litton 1989
Lacock Abbey, Lacock, Notts	AD 1314-1448	4.2	Esling *et al* 1990

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Data of measured samples – measurements in 0.01mm units

THO-H04A 55
43 65 60 63 72 149 179 243 226 187 241 181 217 281 128 154 264 208 245 243
147 199 265 293 155 280 365 279 318 263 260 287 218 148 112 223 286 260 225 265
259 283 217 201 144 219 109 237 163 217 72 136 133 144 131
THO-H04B 55
49 51 73 67 68 130 173 221 236 200 240 175 217 285 127 156 258 213 232 229
157 196 267 292 165 266 373 275 307 254 274 287 232 149 113 222 283 258 227 279
267 286 216 206 139 228 109 213 208 191 99 126 135 144 126
THO-H08A 97
291 295 338 278 283 389 330 239 310 304 295 354 246 262 292 211 203 222 234 223
245 246 202 183 165 158 168 220 98 140 110 119 119 164 119 111 52 100 174 178
223 200 128 211 198 264 252 203 238 173 181 118 158 128 171 160 146 114 144 138
103 139 98 75 138 126 111 87 183 166 181 231 217 140 101 134 168 161 133 154
145 133 190 95 133 110 70 64 120 84 105 105 111 128 117 139 82
THO-H08B 97
296 269 344 278 290 368 328 234 310 300 297 349 241 249 287 213 208 225 228 227
247 233 214 174 161 179 162 208 99 139 115 131 104 169 109 110 54 107 173 168
228 209 120 213 186 260 255 206 242 170 176 122 149 136 158 155 155 107 135 143
114 126 110 77 127 139 111 99 178 172 170 259 207 148 110 116 163 159 144 146
153 132 188 104 123 121 72 63 114 85 105 115 94 140 122 137 80
THO-H12A 65
157 310 279 238 233 218 196 362 285 280 292 242 248 261 309 266 178 205 214 261
310 177 174 127 143 156 139 91 84 56 95 126 144 198 190 94 201 140 208 189
180 211 151 161 124 167 203 160 135 143 125 174 197 140 158 131 112 170 162 141
132 174 193 167 171
THO-H12B 65
147 305 293 255 245 214 195 357 275 281 288 245 253 269 318 274 178 186 215 269
320 180 166 121 148 164 142 88 87 65 86 139 141 202 192 94 186 150 234 161
184 208 153 164 136 159 203 164 132 141 122 173 197 148 158 122 120 166 157 151
133 169 191 162 197
THO-H14A 56
419 730 448 442 352 393 330 414 397 298 370 251 303 355 293 454 484 366 317 315
313 349 384 282 203 303 348 398 423 296 263 263 291 248 147 299 331 352 226 256
271 319 246 236 188 168 184 140 210 217 115 176 190 152 154 188
THO-H14B 56
410 725 411 433 338 371 327 413 372 308 368 264 303 356 287 439 450 367 321 307
299 350 398 296 208 298 362 386 418 300 256 276 297 253 141 310 333 348 221 256
273 325 251 249 181 164 182 138 214 224 121 167 184 162 146 181
THO-H16A 55
99 379 353 318 469 384 424 323 424 376 307 218 281 356 308 213 160 158 141 201
265 145 140 79 346 248 235 110 152 147 130 226 208 211 210 128 245 184 232 125
89 107 99 72 71 54 48 70 91 87 107 68 53 93 144

THO-H16B 55
98 373 370 337 515 397 408 328 419 385 288 225 278 352 311 212 153 158 139 202
263 144 140 77 344 186 221 122 137 154 119 243 219 223 223 131 251 183 232 117
96 99 104 72 67 60 52 66 94 86 102 71 53 94 136
THO-H17A 62
224 331 272 313 374 268 211 206 332 279 237 229 263 217 197 118 265 222 263 218
127 113 80 111 142 123 81 101 212 139 203 163 133 124 108 157 125 103 148 194
292 152 263 191 175 162 227 111 136 113 70 96 180 157 142 123 161 162 220 169
113 110
THO-H17B 62
236 324 267 316 372 265 212 211 327 270 240 234 260 214 201 122 257 224 251 215
121 112 86 103 151 119 97 87 223 131 187 162 134 120 118 155 130 100 142 198
292 143 271 179 184 159 220 106 132 109 71 92 183 149 139 134 146 174 212 186
113 127
THO-H18A 61
323 228 227 168 160 214 251 251 230 183 268 196 262 316 324 388 267 341 296 299
259 209 174 202 100 167 182 205 159 113 93 64 101 140 98 59 52 129 158 103
96 96 158 129 171 131 124 113 135 144 146 114 82 64 55 128 61 77 76 41
70
THO-H18B 61
330 223 235 191 177 196 237 240 236 204 275 197 260 330 343 383 285 346 294 298
269 207 181 196 101 176 179 205 157 111 86 69 108 129 97 65 54 133 155 103
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THO-H29A 57
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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.

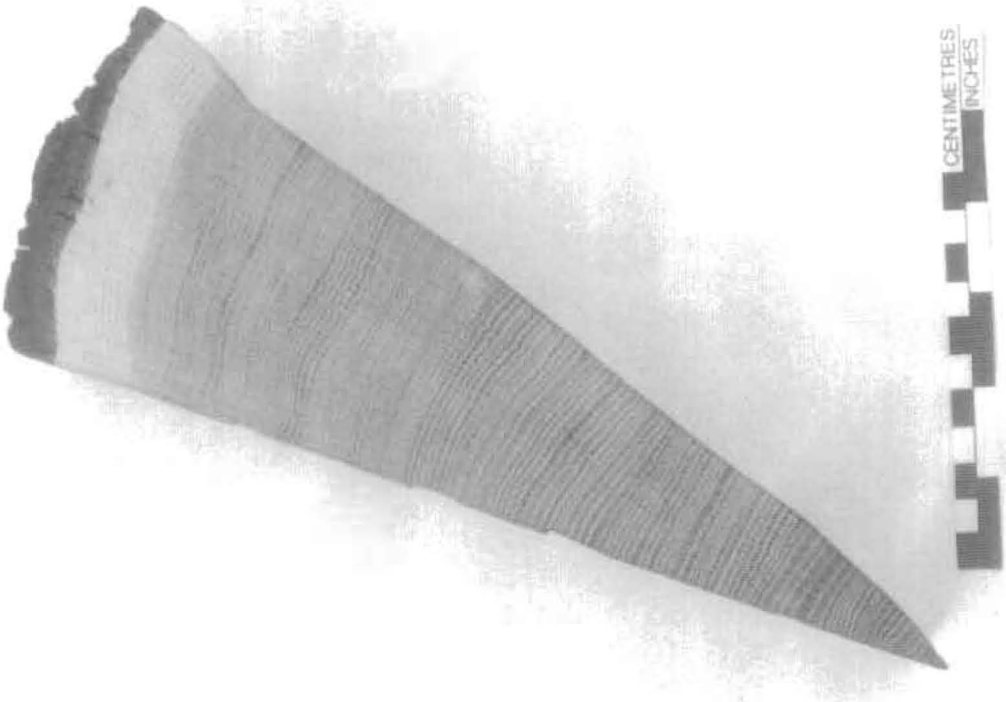

Fig 1. A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976.

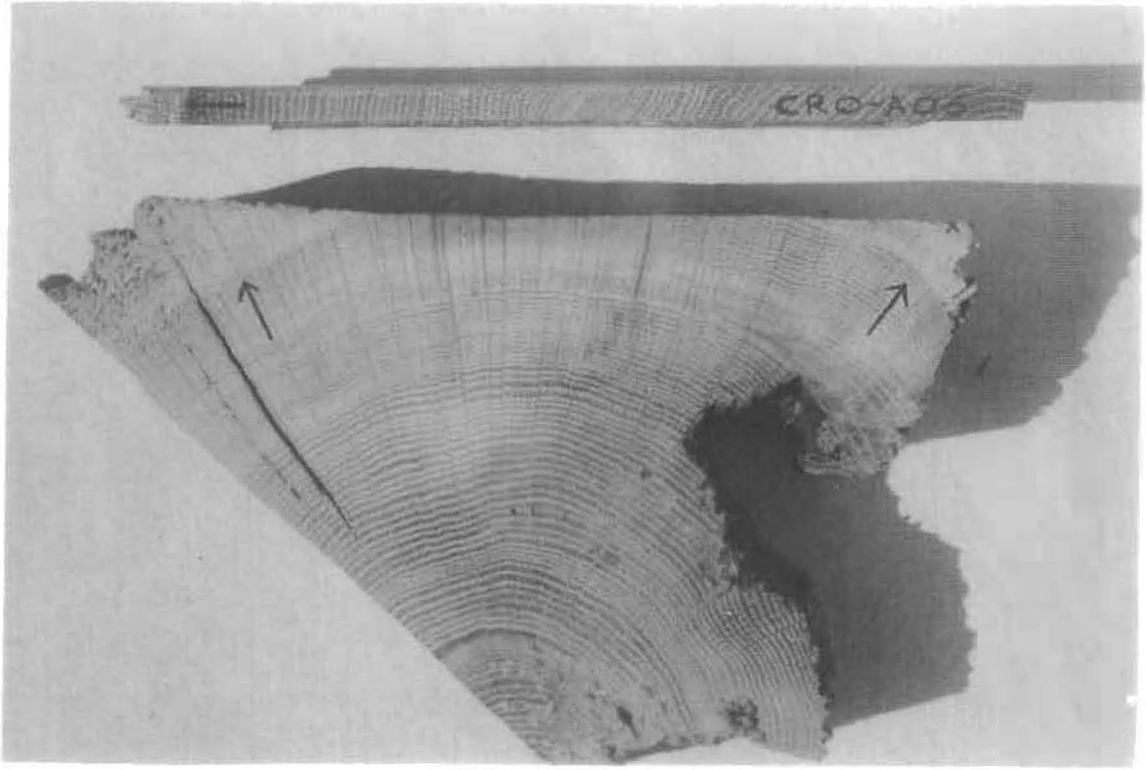

Fig 2. Cross-section of a rafter showing the presence of sapwood rings in the corners, the arrow is pointing to the heartwood/sapwood boundary (H/S). Also a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil.

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.

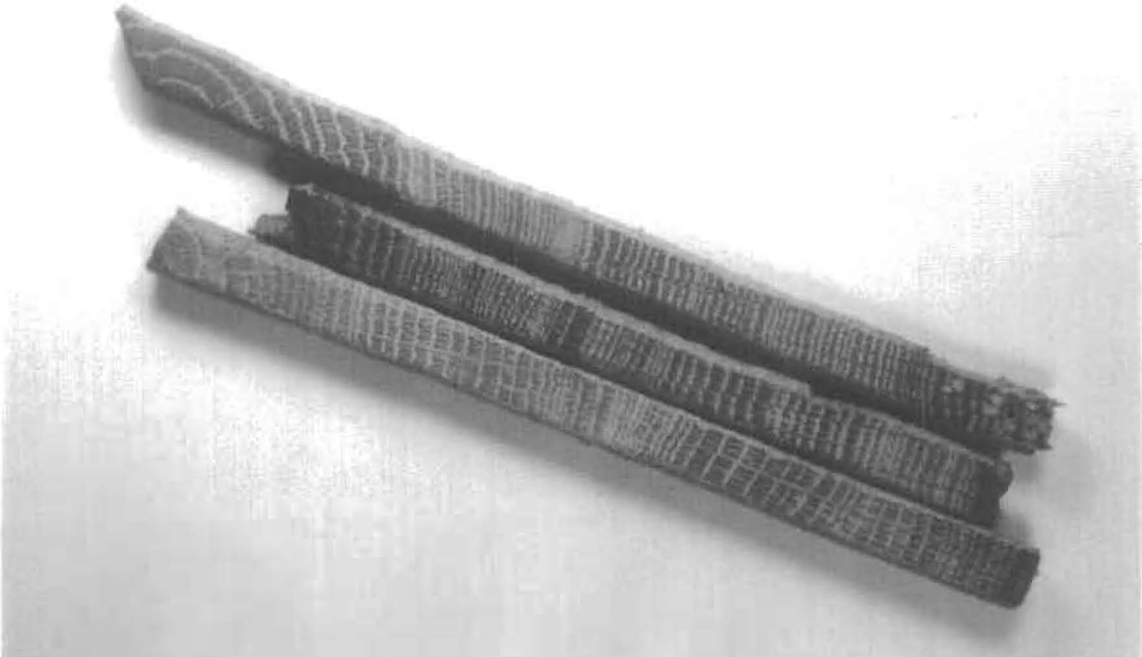

Fig 4. Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

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

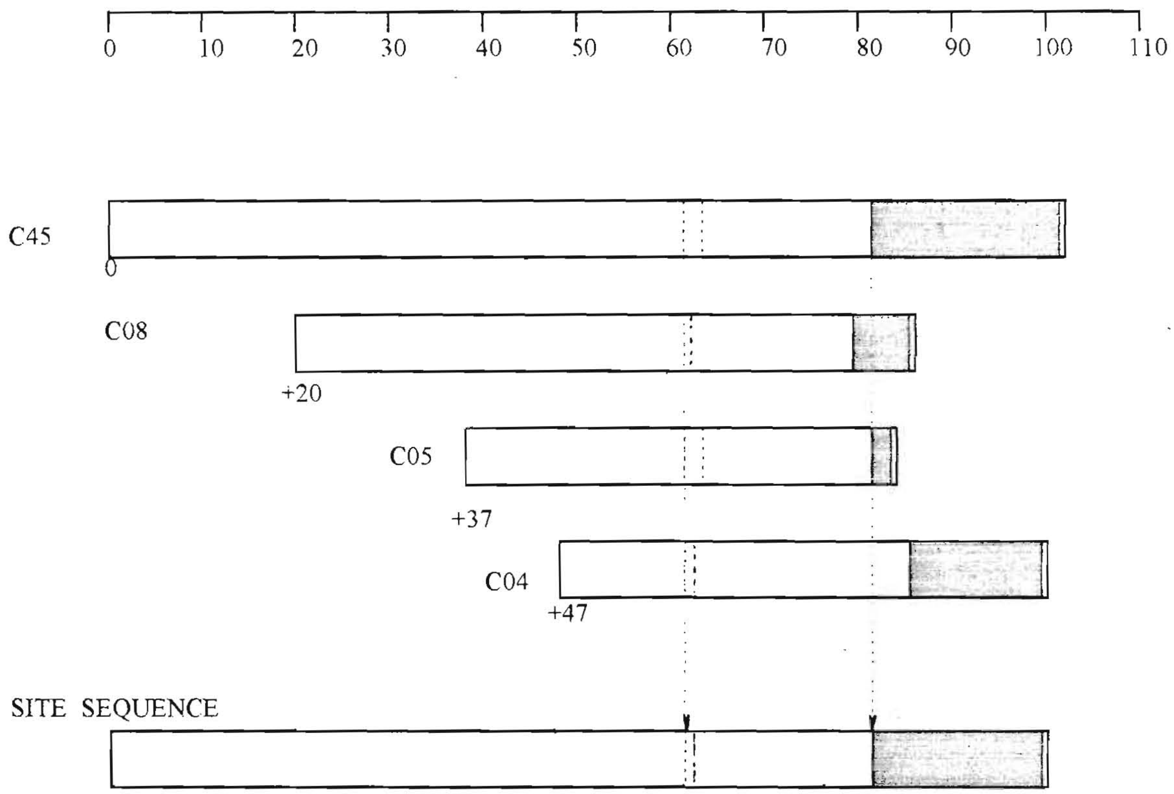

Fig 5. Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.
The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set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

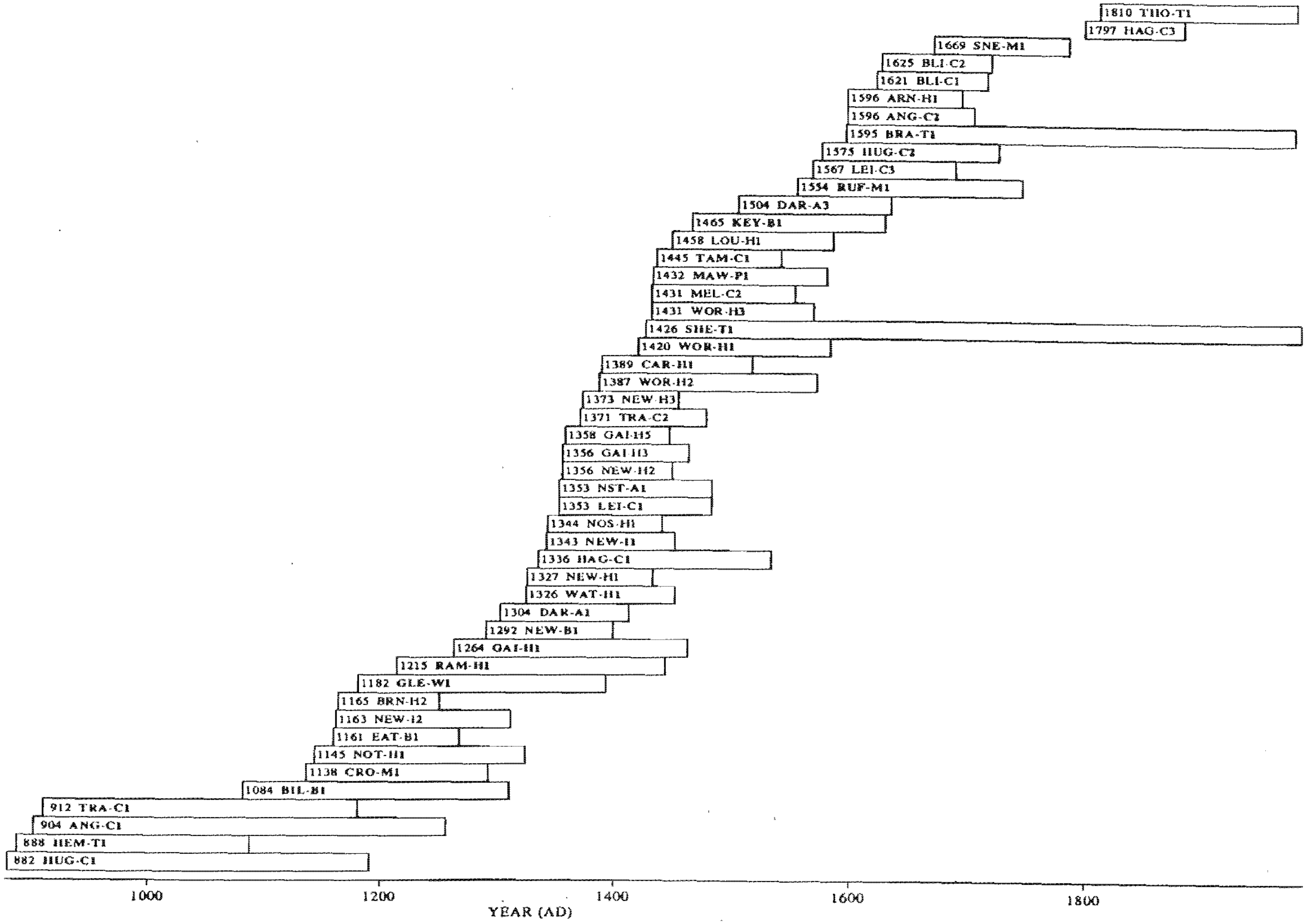

Fig 6. Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87.

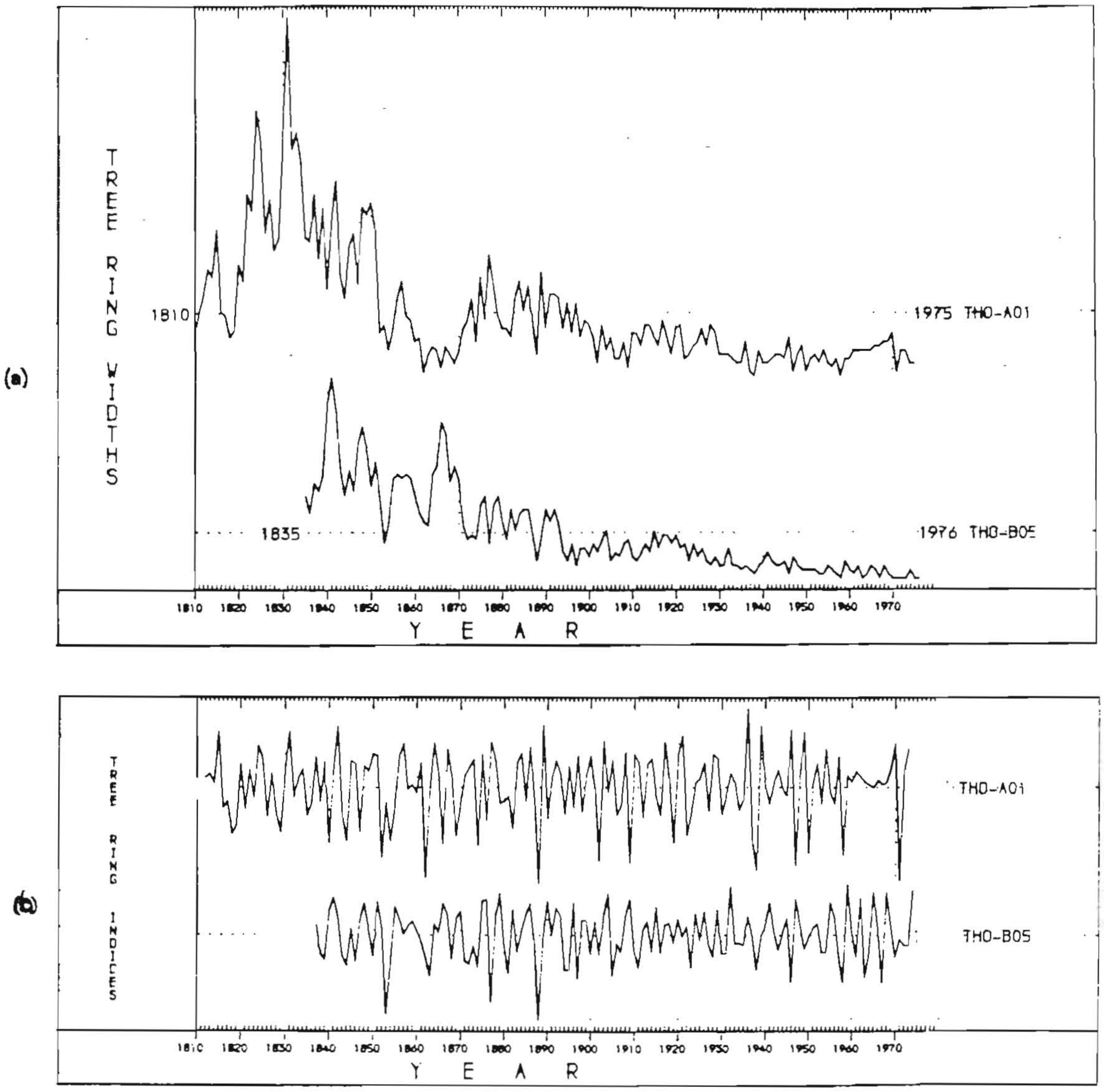

Fig 7. (a) The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree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