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Walmer Castle, Kingsdown Road, Deal, Kent

Tree-ring Analysis of Oak and Pine Timbers

Alison Arnold and Robert Howard

Discovery, Innovation and Science in the Historic Environment

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KINGSDOWN ROAD,
DEAL, KENT

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SUMMARY

Dendrochronological analysis was undertaken on a series of oak and pine samples obtained from various areas of Walmer Castle, including samples previously analysed from reused timbers in the Keep roof. This analysis produced one oak and one pine site chronology accounting for 11and six samples respectively.

Interpretation of the sapwood on the dated oak timbers indicates that the majority of the reused timbers from the roof of the Keep are likely to have been felled in the range AD 1535–60, presumably for the Henrician construction during *c* AD 1539–42, although it is possible that one of the reused timbers could be slightly earlier. Two of the ceiling joists from the stockroom/utility room were felled in AD 1500–25 and AD 1533–58 respectively, whilst a third joist was unlikely to have been felled before AD 1475. A stud post to a ground-floor partition wall has an estimated felling date of AD 1490–1515.

Interpretation of the sapwood on the pine timbers from the Gatehouse roof suggests that that they were likely to have been felled in the later-seventeenth century or possibly the early eighteenth century.

Ten measured oak and two pine samples remain ungrouped and undated.

CONTRIBUTORS

Alison Arnold and Robert Howard

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The Nottingham Tree-ring Dating Laboratory would firstly like to thank Abigail Budd, site Manager at Walmer Castle, and all the English Heritage staff there, for facilitating access throughout the castle and for cooperating so enthusiastically during sampling. Secondly, we would like to thank Roy Porter, Territory Properties Curator South, for both his assistance during sampling and the valuable information and advice provided on the possible phasing of the timbers here. Finally we would like to thank Shahina Farid and Cathy Tyers (English Heritage Scientific Dating Team) for commissioning this programme of Tree-ring Dating, and for the help and assistance provided during the analysis and production of this report.

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INTRODUCTION

Walmer Castle (Fig 1a/b) is the most southerly of three such fortifications known to have been constructed by Henry VIII *c* AD 1539–42. The castles were built within three miles of each other and designed to cover shipping in The Downs within Goodwin Sands, as well as to protect the south-east coast from seaward attack (Fig 2a). The other castles are at Deal, immediately to the north, with Sandown beyond, this latter castle now almost totally destroyed by sea action. All three sites were linked to each other by massive earthworks; these now are also obliterated. Information for the building of this and the related sites at Deal and Sandown can be found in *The History of the Kings Works* (Colvin 1982).

Walmer Castle conforms to-type for these fortresses in being a low, stone-built, quatrefoil structure with a somewhat higher circular core or Keep, the whole building set within a deep circular moat. To the seaward side the walls were originally pierced on four tiers by 39 deep, widely-splayed, gun-ports for heavy cannon, as well as by many smaller hand-gun embrasures. Unlike Deal and Sandown, where entrance to the castles across their moats is via a separate gatehouse fore-building, entry to Walmer is via a bridge directly into one of the quatrefoil lobes (Figs 2b and 3).

Following possible earlier undocumented changes, Walmer Castle has undergone various alterations during the eighteenth and nineteenth centuries in becoming the official residence of the Lord Warden of the Cinque Ports in the early eighteenth century. Further works were also undertaken during the twentieth century.

SAMPLING

Walmer Castle was the subject of a small programme of tree-ring analysis some years ago when samples were obtained exclusively from the limited number of oak timbers found within the roof of the central tower or Keep that were thought to be reused from the original construction (Howard *et al* 1997). The extant roof of the circular Keep comprises 16 pine trusses which radiate from the centre of the building to the outer walls (Fig 4a). Each pine truss consists of a tiebeam, a principal rafter, and a central vertical post or strut. Set below the pine trusses, forming the floor of the roof space or attic and the ceilings of the rooms below, are several large oak timbers. These too radiate out from the centre and, while some span the full width of the roof, others are cut short and do not quite reach the outer walls (Fig 4b). They are quite separate from the pine trusses and apart from holding much smaller ceiling joists, also of oak, these larger radial oak timbers do not appear to serve any structural function such as tiebeams. Some of these radial oak timbers have empty mortises indicating an earlier use.

This additional programme of sampling and analysis by dendrochronology at Walmer Castle was requested by Roy Porter to determine with more precision the dates of certain other areas of development within the castle. It was hoped that dating by dendrochronology would determine, with more precision, the dates of various areas of timberwork and enhance the understanding of the castle The information gained would also to feed into a new scheme of presentation.

An initial comprehensive assessment of timbers from throughout the castle as to their suitability for tree-ring analysis led to this second programme of sampling being focused on a number of specific areas that appeared to contain sufficient numbers of suitable timbers and that had the potential to enhance the overall understanding of the development of the castle. The areas selected for sampling are shown in Figure 3. The Gatehouse roof contains two trusses, each comprising a pine tiebeam carrying an oak king-post and two pine principal rafters. These timbers in turn support a single inclined pine roof beam, the roof covering being pitched at one angle. A partition wall at ground-floor level, in what had once been the Servant's Hall, comprises sill and top plates supported by posts and studs with cross-rails between them. It is uncertain if this partition wall is primary to the original construction or a substantially later insertion. The ground-floor ceiling, in what was once the Porter's Lodge, comprises widely spaced main beams, spanned by smaller, close-set, common joists.

Thus, from the areas selected for analysis a total of 24 new samples was obtained by coring. Each newly acquired sample was given the code WLM-C (for Walmer Castle) and, allowing for the samples obtained in the earlier 1997 programme of analysis, were numbered 10–33 (Table 1). Ten of these additional samples (WLM-C10–C19) were obtained from the timbers of the two roof trusses to the Gatehouse, four samples (WLM-C20–C23) from the timbers of the partition wall to the Servant's Hall (tea room/kitchen) and finally, 10 samples (WLM-C24–C33) were taken from the common joists of the Porter's Lodge (stockroom/utility room).

The locations of these samples were recorded at the time of sampling on either plans taken from Colvin 1982 or annotated photographs, these being shown as Figures 4c-e. Details of the samples are given in Table 1. The reused oak timbers to the floor of the attic/roof space of the circular Keep have been located by reference to the pine roof trusses which have themselves been numbered 1–16 in a clock-wise direction. Elsewhere, where possible, the trusses and other timbers have been numbered from north to south, with individual timbers then being further identified on an east–west basis as appropriate.

ANALYSIS AND RESULTS

Each of the additional 24 samples obtained in this second programme of work was prepared by sanding and polishing. It was seen at this time that four of these samples had less than the 40 rings deemed necessary for reliable dating here and they were discarded from this programme of analysis. The annual growth ring widths of the remaining 20 samples were measured, the data of these measurements, plus those of the nine samples obtained in the 1997 programme of work, being given at the end of this report. The data of all 29 measured samples taken in the two programmes of sampling were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix). It should be noted that the methodology employed for the pine timbers sampled and analysed follows the same basic principles and practice as given in the Appendix.

This comparative process resulted in the production of one oak site chronology, WLMCSQ01, accounting for a total of 11 samples (Fig 5), and one pine site chronology, WLMCSQ02, this comprising six samples (Fig 6). Each site chronology was then compared respectively to an extensive corpus of either oak or pine reference material, this process indicating a consistent and repeated match for both site chronologies. Site chronology WLMCSQ01 (oak) cross-matches when its 128 rings span the years AD 1396–1523, and site chronology WLMCSQ02 (pine) cross-matches when its 255 rings span the years AD 1404–1658. The evidence for this dating is given in Tables 2 and 3 respectively.

Each site chronology was then compared to the remaining measured but ungrouped oak or pine samples, but there was no further cross-matching. Each of the measured but ungrouped oak and pine samples was then compared individually with the full corpus of its respective reference material, but again there was no conclusive cross-matching and all of these samples must remain undated for the moment.

This analysis may be summarised as follows:

	Number of samples	Number of rings	Date span AD (where dated)
Total samples obtained	33	---	---
Unmeasured samples	4	---	---
Measured samples	29	---	---
WLMCSQ01	11	128	1396–1523
WLMCSQ02	6	255	1404–1658
Ungrouped/undated	10 oak 2 pine	---	---

INTERPRETATION

Analysis by dendrochronology of timbers within specifically selected areas of Walmer Castle has produced one oak site chronology and one pine site chronology, both of which can be dated. All dated timbers are shown in Figure 7, which highlights the differences in the date of both the oak and the pine timbers.

Oak site chronology WLMCSQ01

The dated oak site chronology comprises a total of 11 samples (Fig 5): seven from the roof of the Keep, three from the ceiling of the Porter's Lodge (stock room/utility room), and one from the ground-floor partition wall to the Servant's Hall (tea room/kitchen).

None of the samples in this site chronology retains complete sapwood, the last growth ring produced by the tree before it was felled, and it is thus not possible to provide a precise felling date for any timber. Almost all the samples do, though, retain some sapwood or at least the heartwood/sapwood boundary, thus allowing felling date ranges to be obtained using a 95% probability limit of 15–40 for the number of sapwood rings the tree is likely to have.

Ground-floor partition wall - Servant's Hall

Sample WLM-C23 from the central stud post has a heartwood/sapwood boundary dated to AD 1475 which gives the timber an estimated felling date in the range of AD1490–1515.

Stock room/utility room ceiling - Porter's Lodge

The three dated joists, one from the east ceiling and two from the west ceiling, clearly represent more than one period of felling. Sample WLM-C31 (west ceiling) is without the heartwood/sapwood boundary and thus, with a last heartwood ring date of AD 1460, it is unlikely to have been felled before AD 1475. Sample WLM-C26 (east ceiling) has a heartwood/sapwood boundary dated to AD 1485 and hence an estimated felling date in the range AD1500–25. Sample WLM-C33 (west ceiling) has a heartwood/sapwood boundary dated to AD 1518 and hence an estimated felling date in the range AD1533–58.

Keep roof timbers

The heartwood/sapwood boundary on six of the seven samples from the timbers to the roof of the Keep appears to be consistent; the boundary varying by only six years from AD 1517 on sample WLM-C07 to AD 1523 on sample WLM-C03. This suggests that this group of timbers was cut as part of a single episode of felling. The average heartwood/sapwood boundary of these six samples is AD 1520 which produces an estimated felling date in the range AD 1535–60 for these timbers.

The exception amongst the Keep roof samples is WLM-C01 where the heartwood/sapwood boundary is several years earlier at AD 1498 and hence produces an estimated felling date in the range AD 1513–38.

Pine site chronology WLMCSQ02

Gatehouse roof

None of the pine samples appear to retain complete sapwood, although the presence of complete sapwood is always much more difficult to determine on softwood timbers, and thus their exact felling date cannot be determined precisely. However, given the level of similarity between some of the individual ring sequences and the similarity in heartwood/sapwood boundary dates, which range from AD 1595 (WLM-C17) to AD 1609 (WLM-C11), it seems likely that this group of dated pine timbers is coeval. The latest dated ring (AD 1658) is found on sample WLM-C11, which has 49 sapwood rings. The amount of sapwood found on pines is more variable than oak but bearing in mind the Scandinavian source of the timber (Table 3) it is likely that these timbers were felled in the later seventeenth century or possibly the early eighteenth century.

DISCUSSION AND CONCLUSION

The 11 dated oak timbers from Walmer Castle appear to represent several different felling episodes. Six of the reused timbers in the roof of the Keep, plus one joist (WLM-C33) to the ceiling of the stock room/utility room (former Porter's Lodge), were all felled in the mid-sixteenth century and are likely to have been felled for the original Henrician construction of the castle in *c* AD 1539–42. Whilst it is possible that the other dated Keep roof timber (WLM-C01) is of this date, if it had more than the usual number of sapwood rings, it is also possible that it was felled slightly earlier in the sixteenth century. At least one other joist (WLM-C26) to the stock room/utility room ceiling (former Porter's Lodge) and a stud post (WLM-C23) to the ground-floor partition wall (former Servant's Hall) pre-date the original Henrician construction being felled in the late-fifteenth or early decades of the sixteenth century.

The overall cross-matching between the samples from the roof of the Keep thought to be felled for the initial Henrician construction suggests the likelihood that the trees used for these timbers may have been growing reasonably close to each other in the same woodland. Indeed, such is the cross-matching (t=14.8) between two samples, WLM-C02 and C03, that it is likely that the two timbers represented are derived from the same tree. Such levels of cross-matching provide additional support for the view that the majority of the trees utilised for the Keep roof were felled at the same time as each other. However the remaining dated oak samples cross-match somewhat more variably, although all can be dated individually when compared with reference chronologies. This suggests that the source of the trees from which these other timbers were derived is somewhat more disparate. These timbers represent several different felling events and, given that several of these timbers pre-date the Henrician construction, it seems likely that they represent timbers that were either stored or gifted some decades earlier, or that they are reused timbers.

As may be seen from Table 2, although cross-matched with reference chronologies for all parts of England, the oak site chronology WLMCSQ01 cross-matches best with reference chronologies made up of material from Kent and south-east England. This suggests that the timbers, although possibly from different woodlands, are all from relatively local sources.

The determination of the felling date for the six dated pine timbers from the Gatehouse roof is somewhat more difficult than for the oak timbers. However, as indicated above, the evidence suggests that they are coeval and hence were all probably felled in the later seventeenth century or possibly the early eighteenth century. These could therefore potentially be associated with alterations relating to the castle becoming the official residence of the Lord Warden of the Cinque Ports.

The overall cross-matching between the samples in the pine site chronology, WLMCSQ02, suggests that the trees may have been sourced from an extensive forest area. This site chronology itself matches consistently with reference chronologies from Norway and Sweden, as well as those from other imported assemblages in the UK thought to be of Scandinavian origin, and hence it is likely that these timbers also have a Scandinavian origin and are likely to be Scots pine (*Pinus sylvestris* L.).

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TABLES

Table 1: Details of tree-ring samples from Walmer Castle, Kent

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Keep roof – all oak					
WLM-C01	Radial beam truss 15– 16	68	h/s	1431	1498	1498
WLM-C02	Radial beam truss 14 –15	108	h/s	1414	1521	1521
WLM-C03	Radial beam truss 13 –14	128	h/s	1396	1523	1523
WLM-C04	Radial beam truss 11 –12	110	h/s	------	------	------
WLM-C05	Radial beam, below truss 6	73	h/s	------	------	------
WLM-C06	Radial beam, below truss 8	122	h/s	1398	1519	1519
WLM-C07	Radial beam truss 8 –9	98	h/s	1420	1517	1517
WLM-C08	Radial beam truss 9 –10	118	h/s	1403	1520	1520
WLM-C09	Spliced beam to timber WLM-C01	70	h/s	1451	1520	1520
	Gatehouse roof					
WLM-C10	King post, truss 2 (oak)	60	h/s	------	------	------
WLM-C11	Tiebeam, truss 1 (north truss) (pine)	152	49	1507	1609	1658
WLM-C12	Roof beam, truss 1 (pine)	176	no h/s	1404	------	1579
WLM-C13	East rafter, truss 1 (pine)	162	10	------	------	------
WLM-C14	West rafter, truss 1 (pine)	223	no h/s	------	------	------
WLM-C15	King post, truss 1 (oak)	60	h/s	------	------	------
WLM-C16	Tiebeam, truss 2 (south truss) (pine)	136	no h/s	1410	------	1545
WLM-C17	Roof beam, truss 2 (pine)	142	17	1471	1595	1612
WLM-C18	East rafter, truss 2 (pine)	154	h/s	1455	1608	1608
WLM-C19	West rafter, truss 2 (pine)	135	h/s	1466	1600	1600

Table 1: Continued

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Central Tower, ground-floor partitions - all oak					
WLM-C20	South cross-rail	68	h/s	------	------	------
WLM-C21	South (right) door jamb	nm	---	------	------	------
WLM-C22	North (left) door jamb	nm	---	------	------	------
WLM-C23	Central stud post	67	h/s	1409	1475	1475
	Central Tower, stock/utility room ceiling – all oak					
WLM-C24	West ceiling joist 10	42	h/s	------	------	------
WLM-C25	East ceiling joist 1	64	h/s	------	------	------
WLM-C26	East ceiling joist 2	74	h/s	1412	1485	1485
WLM-C27	East ceiling joist 3	nm	---	------	------	------
WLM-C28	East ceiling joist 4	48	h/s	------	------	------
WLM-C29	East ceiling joist 5	41	no h/s	------	------	------
WLM-C30	West ceiling joist 3	nm	---	------	------	------
WLM-C31	West ceiling joist 4	45	no h/s	1416	------	1460
WLM-C32	West ceiling joist 5	71	no h/s	------	------	------
WLM-C33	West ceiling joist 6	80	h/s	1439	1518	1518

h/s = the heartwood/sapwood ring is the last ring on the sample
nm = sample not measured

Table 2: Results of the cross-matching of oak site sequence WLMCSQ01 and relevant reference chronologies when the first-ring date is AD 1396 and the last-ring date is AD 1523

Reference chronology	Span of chronology	*t*-value	Reference
Kent 88 master chronology	AD 1158–1540	11.5	(Laxton and Litton 1989)
Hays Wharf, Southwark, London	AD 1248–1647	10.7	(Tyers 1996a; Tyers 1996b)
Mary Rose refit timbers, Hampshire	AD 1372–1535	10.0	(Bridge and Dobbs 1994)
Ickenham Manor, Hillingdon, London	AD 1374–1483	9.5	(Arnold and Howard 2011)
Shurland Hall, Isle of Sheppy, Kent	AD 1405–1526	8.8	(Arnold and Howard 2008)
Headstone Manor Barn, Harrow, Middlesex	AD 1374–1505	8.5	(Howard *et al* 2000)
Cobham Hall, Cobham, Kent	AD 1317–1662	8.5	(Arnold *et al* 2003)
The Old Manor, West Lavington, Wiltshire	AD 1264–1497	8.4	(Tyers and Hurford 2014)

Table 3: Results of the cross-matching of pine site sequence WLMCSQ02 and relevant reference chronologies when the first-ring date is AD 1404 and the last-ring date is AD 1658

Reference chronology	Span of chronology	*t*-value	Reference
Norway: south-east region	AD 871–1986	7.4	(Thun pers comm)
Sweden: Dalarna	AD 1001–1852	7.2	(Bartholin pers comm)
Sweden: Stockholm	AD 1127–1671	6.1	(Bartholin pers comm)
Sweden: Helsingland	AD 1001–1861	5.8	(Bartholin pers comm)
Royal Academy, London Borough of the City of Westminster, London - imported	AD 1393–1582	7.0	(Tyers forthcoming)
Bromley Hall, London Borough of Tower Hamlets - imported	AD 1376–1686	7.0	(Bridge 2015)
107 Jermyn Street, City of Westminster, London (3) - imported	AD 1367–1710	6.6	(Groves and Locatelli 2005)
Kirkleatham Hall Stables, Redcar, North Yorkshire (1) - imported	AD 1395–1692	4.8	(Arnold and Howard 2013)

FIGURES

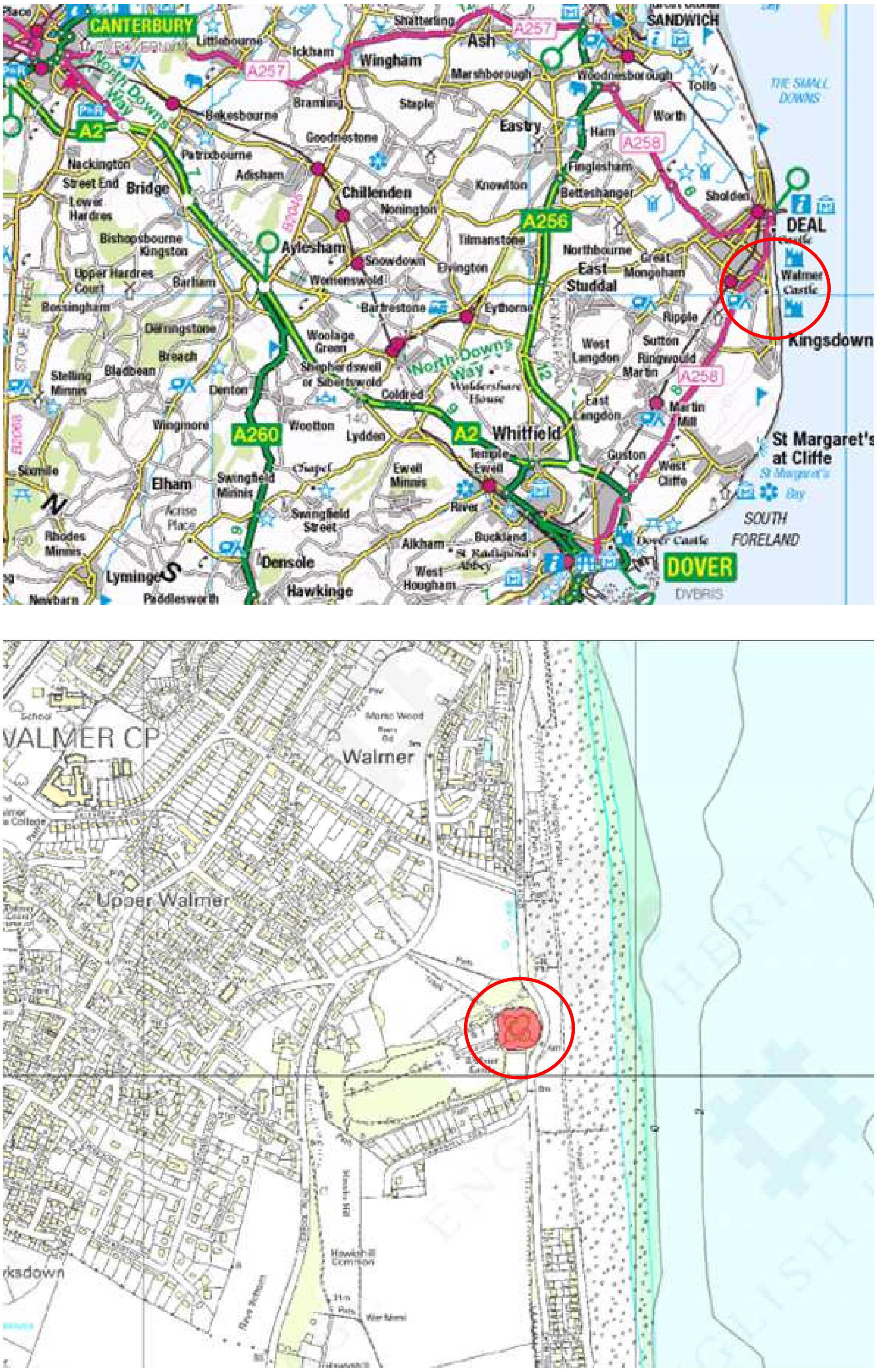


Figure 1a/b: Map to show the location of Walmer (top) and Walmer Castle (bottom) © Crown Copyright and database right 2015. All rights reserved. Ordnance Survey Licence number 100024900

Figure 2a/b: Seaward view from Walmer Castle today (top) and the entrance bridge across the moat directly into one of the quatrefoil lobes (bottom) (photographs Robert Howard)

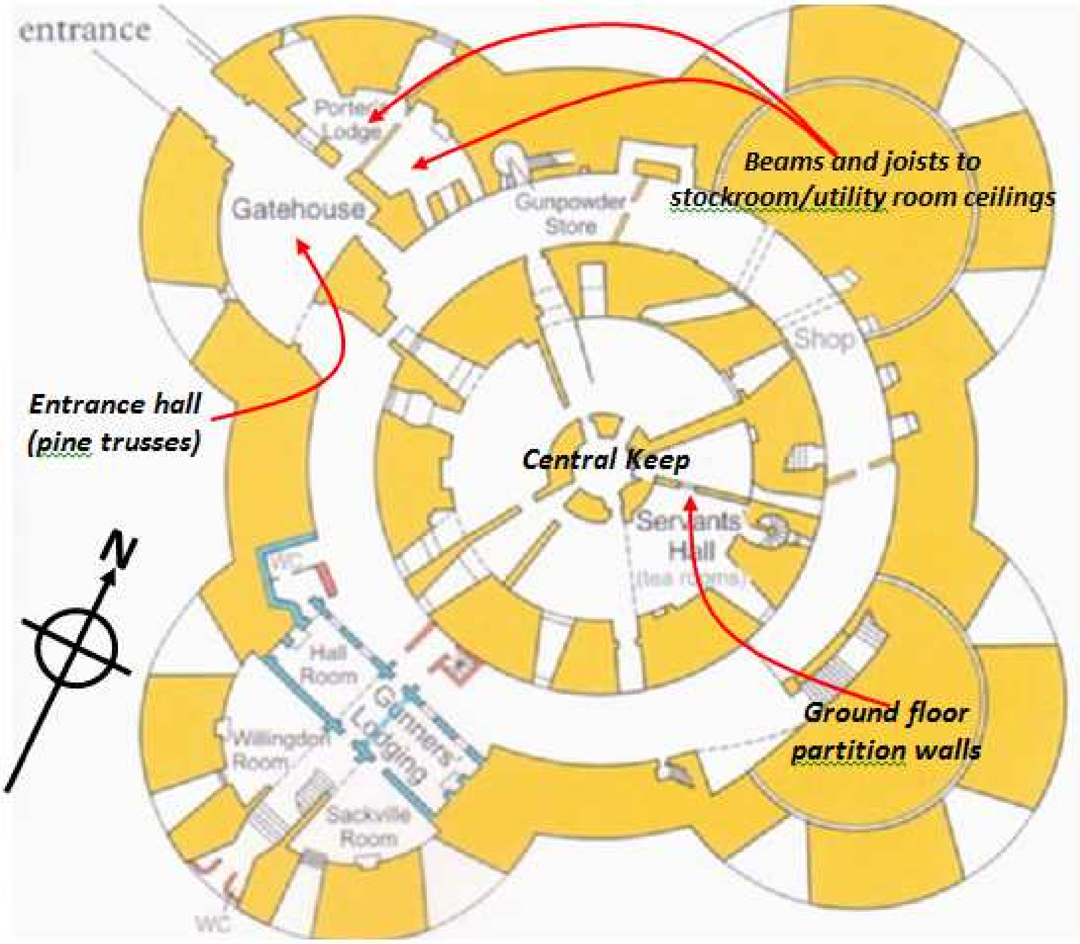


Figure 3: Plan of Walmer Castle at entrance level to show sample areas (after Coad and Shepherd 2003)

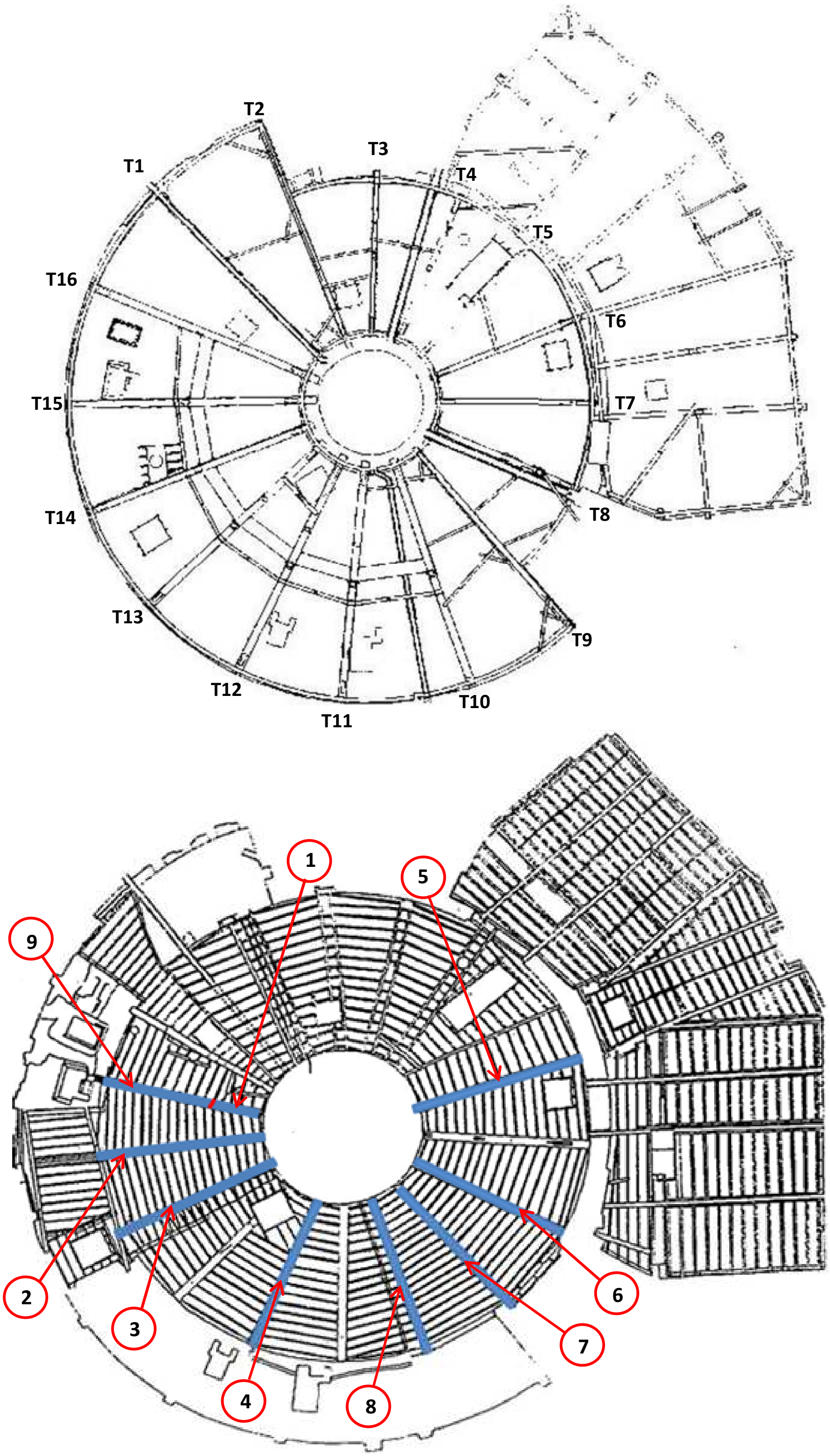


Figure 4a/b: Plan of the pine roof trusses (top) and oak attic floor (bottom) of the Keep to help locate sampled timbers (after Colvin 1982)

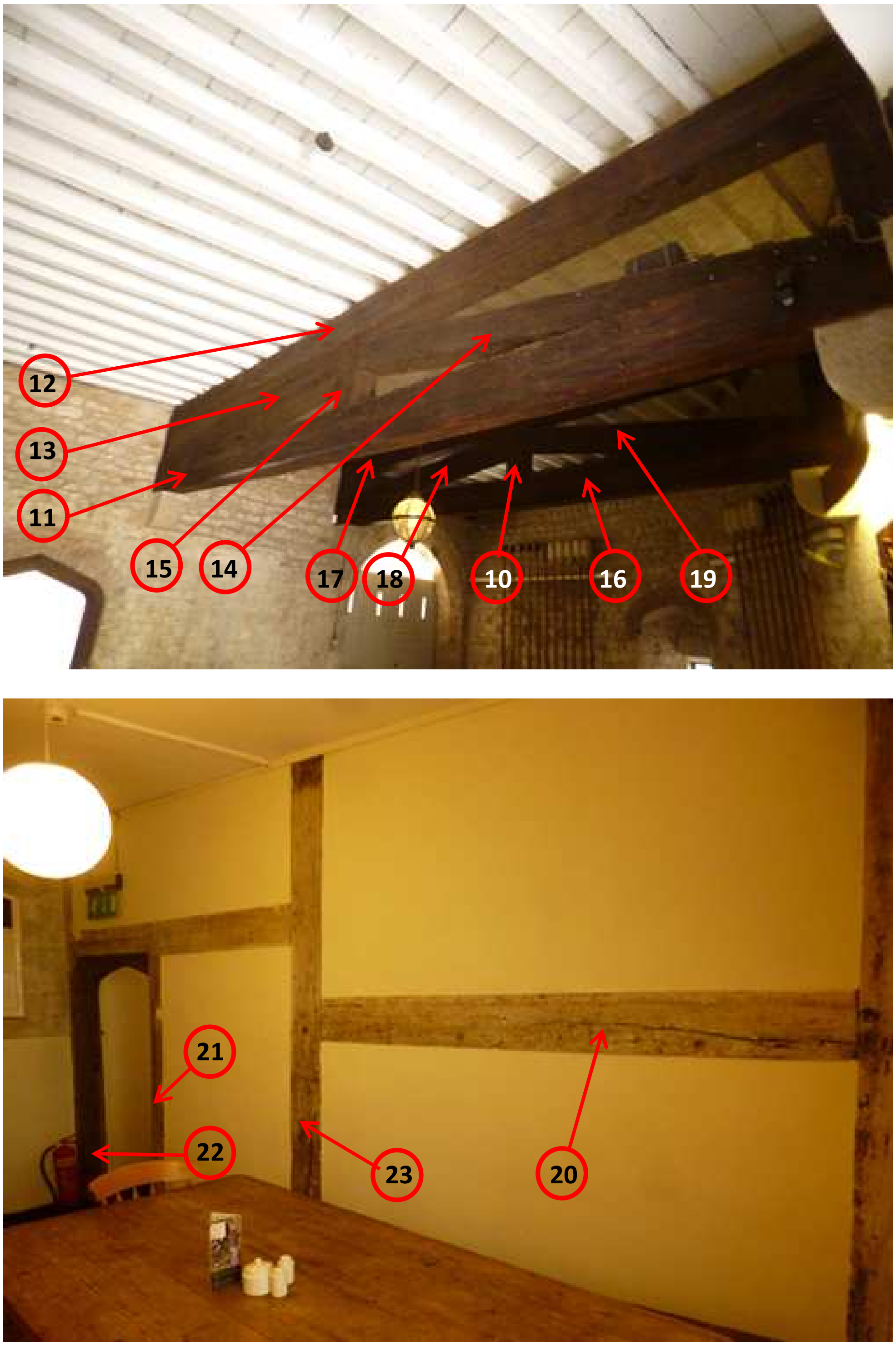
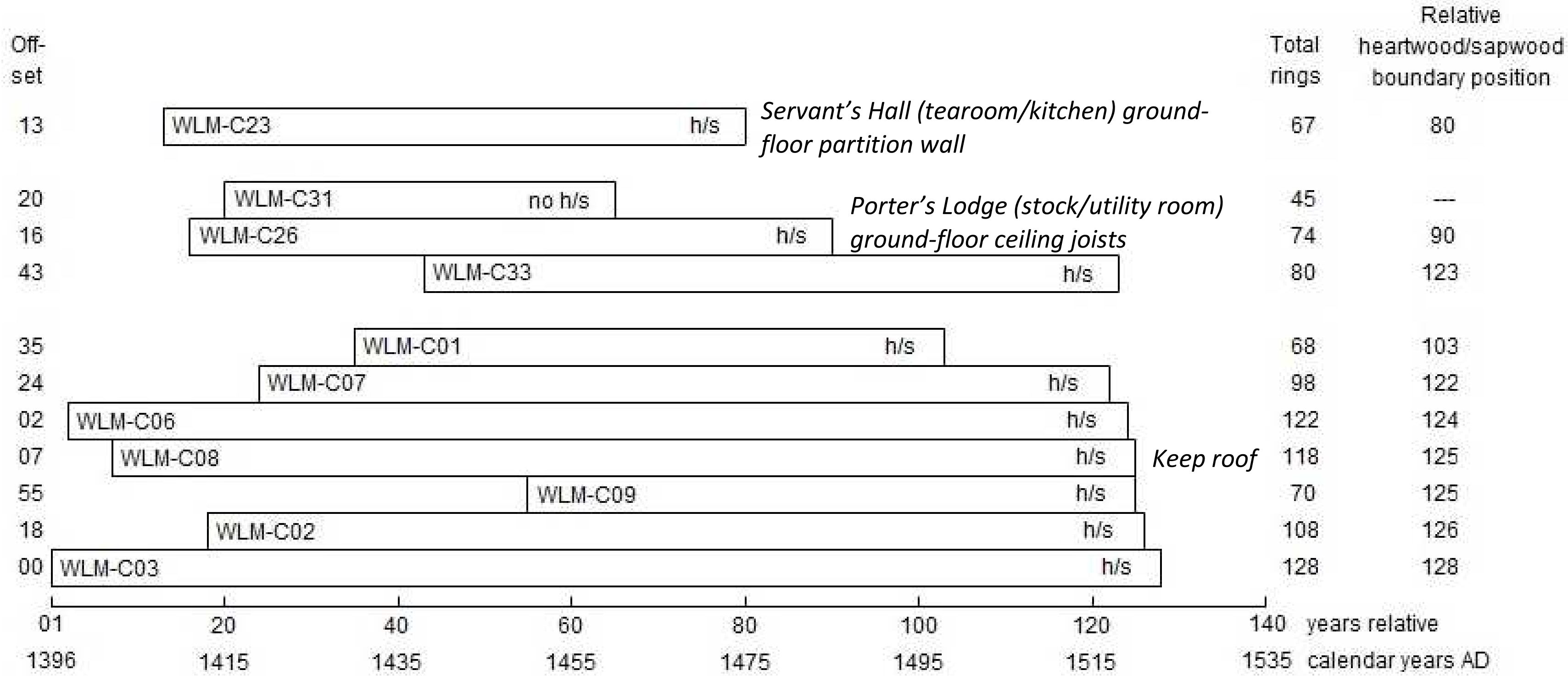


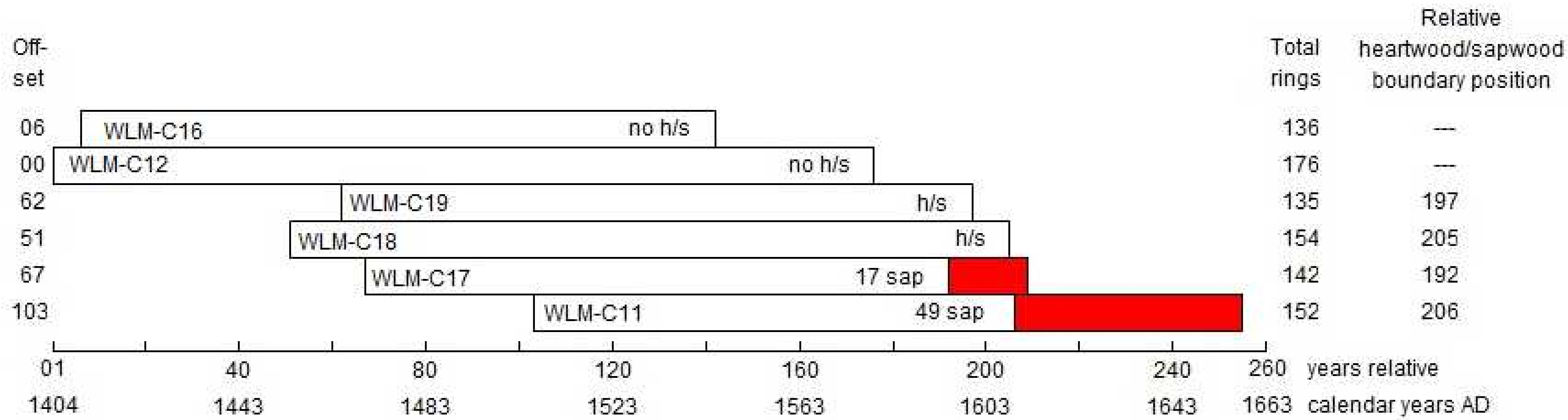
Figure 4c/d: Annotated photographs of the Gatehouse roof (top) and Servant's Hall ground-floor partition wall (bottom) to locate sampled timbers (photographs Robert Howard)

Figure 4e: Annotated photograph of the Porter's Lodge ground-floor ceiling to locate sampled timbers (photograph Robert Howard)



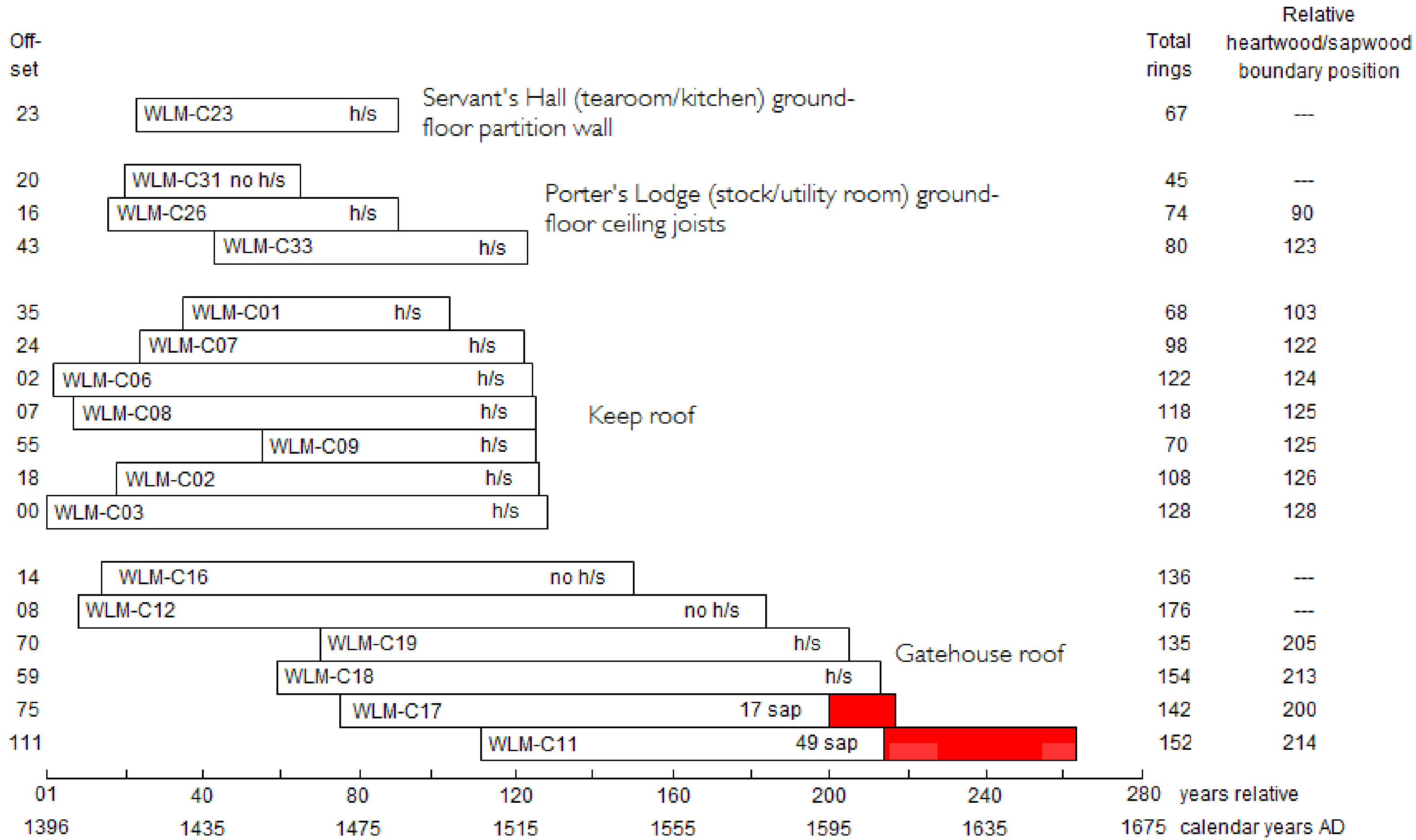
White bars = heartwood rings
h/s = heartwood/sapwood boundary

Figure 5: Bar diagram of the oak samples in site chronology WLMCSQ01



White bars = heartwood rings, shaded bars = sapwood rings; h/s = heartwood/sapwood boundary

Figure 6: Bar diagram of the pine samples in site chronology WLMCSQ02, all from the Gatehouse roof



White bars = heartwood rings, shaded bars = sapwood rings, h/s = the heartwood/sapwood ring is the last ring on the sample

Figure 7: Bar diagram of the dated oak and pine samples

DATA OF MEASURED OAK SAMPLES

Measurements in 0.01mm units

WLM-C01A 68
124 181 169 218 356 310 324 182 218 183 178 154 170 177 215 227 342 350 364 387
409 404 321 373 243 229 267 294 210 337 210 244 233 184 233 225 224 207 219 190
119 131 130 131 250 62 36 35 43 60 72 68 69 47 39 91 95 170 126 135
96 95 112 122 140 169 202 167
WLM-C01B 68
212 172 182 214 370 308 322 177 230 196 181 155 165 177 202 206 333 359 377 405
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100 84 118 124 157 171 153 197
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177 166 211 261 271 197 173 234 168 319 229 164 148 174 458 229 218 214 352 214
159 330 351 393 366 259 274 309 374 272 222 266 278 260 293 376 225 390 256 162
240 328 257 343 481 278 306 305 454 393 317 395 280 252 376 402 477 307 335 255
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221 125 317 188 119 223 151 143 210 183 191 224 182 154 147 174 139 166 153 266
166 208 188 162 269 236 161 172
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243 323 253 336 496 258 287 300 459 379 307 426 288 247 380 399 475 304 336 254
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128 321 306 193 213 262 260 250 211 282 207 172 215 282 275 201 209 147 186 196
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128 263 356 203 204 256 247 245 228 274 207 171 214 286 277 187 190 158 186 212
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212 88 166 135 220 180 208 238 189 83 92 134 206
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187 187 80 94 73 224 226 251 208 128 132 80 126 164 165 146 82 188 159 207
225 103 160 127 200 191 212 235 195 84 109 119 222
WLM-C06A 122
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83 117
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192 150 163 166 165 204 159 128 83 79 140 120 160 139 144 108 84 119 109 133
157 121 89 95 116 79 75 73 106 91 93 92 97 121 95 92 141 112 134 124
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90 125
WLM-C07A 98
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147 137 150 110 146 169 145 116 147 172 136 130 138 136 123 131 145 144 144 111
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146 177 141 142 148 127 147 151 156 135 135 122 93 106 126 116 175 109 96 126
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WLM-C07B 98
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141 141 171 151 115 161 142 163 166 158 160 167 166 137 123 113 130 140 233 182
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WLM-C08B 118
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269 223 196 149 156 162 131 144 172 247 159 135 167 138 156 196 145 148 143 140
130 114 146 120 117 138 154 107 132 126 148 159 168 207 208 222 142 219 153 169
144 138 166 151 118 152 142 160 167 165 158 170 167 125 126 117 134 152 216 182
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125 150 174 142 217 179 140 159 128 184 180 221 190 244 250 314 359 289 414 289
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197 158 249 197 193 289 295 272 267 260 167 259 193 160 265 120 220 145 128 134
101 227 209 168 179 170 259

WLM-C24A 42
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423 398
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425 398
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210 182 195 226
WLM-C25B 64
221 138 207 245 336 309 259 203 141 134 176 193 327 173 298 214 184 186 222 161
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209 192 189 237
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112 93 160 165 81 87 81 118 149 163 114 113 121 128
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514 748 660 468 544 423 517 419 571 366 354 478 382 321 193 233 262 232 168 264
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111 104 156 162 94 90 79 114 163 154 103 117 117 132
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328 270 279 289 253 318 325 406
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183 102 125 83 123 110 158 275 225 199 182 224 280 261 329 350 385 302 473 426
375 249 295 295 256 300 353 417
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303 264 164 185 183 314 310 359 245 285 268 240 272 326 156 179 321 387 218 301
392
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388
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285 275 210 131 177
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276 251 214 146 151

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196 169 144 116 141 108 113 96 112 165 222
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247 256 233 211 256 279 390 339 343 263 272 315 231 202 268 289 355 398 395 220
165 146 184 228 309 260 226 326 321 353 246 328 287 245 180 184 171 216 177 303
193 175 143 121 132 115 108 100 112 159 211
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108 112 119 125 137 116 142 132 124 143 105 107 143 168 132 164 210 145 125 114
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112 115 118 114 120 107 173 167 124 131 128 107 110 132 139 146 135 126 128 142
WLM-C33B 80
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126 119 114 123 146 123 144 132 132 159 103 138 148 175 142 160 211 153 125 108
139 154 175 129 141 125 111 117 110 115 113 161 122 110 150 154 151 198 140 107
104 106 124 114 120 111 173 164 131 120 124 109 117 125 148 140 157 121 123 152

DATA OF MEASURED PINE SAMPLES

Measurements in 0.01mm units

WLM-C11A 152
204 179 162 212 167 219 171 134 189 155 165 152 182 125 142 104 92 110 173 204
114 128 135 150 131 155 189 166 167 145 136 100 185 158 194 184 142 124 175 115
157 141 114 104 125 131 113 82 81 82 53 64 73 85 92 87 74 103 79 104
75 76 70 85 95 57 70 79 106 96 84 71 47 48 76 71 84 107 92 87
101 87 75 62 75 81 48 76 76 101 87 74 66 63 50 64 64 70 75 68
100 114 93 73 85 60 64 48 51 64 73 65 54 70 54 68 59 52 67 62
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56 42 41 43 54 51 58 50 46 50 31 34
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117 132 140 146 129 158 175 175 164 143 148 96 179 157 192 189 135 123 171 122
154 139 110 104 121 135 107 87 71 87 53 70 67 89 92 95 70 100 85 101
78 74 65 89 96 57 71 85 101 93 84 76 48 46 79 73 86 100 95 81
103 87 68 60 76 81 56 74 89 94 91 77 71 64 51 63 65 71 68 78
100 109 93 73 89 56 58 45 46 62 82 67 57 70 62 71 71 39 63 59
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WLM-C12A 176
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44 61 78 71 69 50 50 58 63 69 57 56 46 49 53 48 51 47 46 37
31 40 44 42 34 31 43 54 37 59 53 56 55 62 53 68 65 89 78 49
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205 178 239 225 217 185 212 144 140 156 216 205 227 195 168 150 140 134 136 137
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89 106 103 115 100 128 105 141 131 121 114 114 141 86 100 128 164 142 120 112
92 82 71 69 69 84 93 89 75 75 46 65 35 53 44 46 47 41 52 38
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148 206 192 258 285 214 188 186 166 165 150 176 108 103 82 83 100 110 82 115
104 113 134 151 175 256 275 214 185 150 106 96 62 65 43 64 73 68 79 98
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107 87 104 102 138 103 90 94 86 105 122 97 59 52 64 61 36 21 28 23
25 34 40 48 43 43 50 68 60 57 53 49 47 50 50 52 57 52 55 48
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63 93
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152 197 202 268 275 205 182 177 170 160 178 170 114 96 79 85 102 109 79 117
100 117 129 150 169 262 270 212 190 146 106 105 60 73 41 60 75 61 82 101
89 64 76 81 113 85 92 75 67 103 95 114 93 95 67 100 88 67 73 83
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72 104
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42 68
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48 64

WLM-C18A 154
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43 90 90 68 51 65 58 69 47 57 96 72 60 47 65 62 101 137 157 103
99 97 68 75 64 66 34 39 37 57 71 84 88 46 59 71 53 46 62 50
38 49 43 31 32 37 40 25 50 49 48 62 56 57 56
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200 249 251 269 220 101 20 32 45 57 70 73 99 181 232 276 285 271 271 234
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87 118 84 80 117 140 177 236 182 195 129 134 106 106 81 73 67 57 77 158
203 140 134 98 126 81 85 100 139 101 121 81 38 46 72 96 98 87 56 45
40 89 90 75 48 64 58 64 48 62 96 71 57 53 70 59 98 134 160 96
89 90 73 75 59 68 31 40 43 65 73 90 81 50 59 65 59 46 56 51
39 43 58 28 31 36 34 25 51 46 57 50 58 58 59

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Nottingham Tree-ring Dating Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1998). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

If the bark is still on the sample, as in Figure A1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction or soon after. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

The Practice of Tree-Ring Dating at the Nottingham Tree-Ring Dating Laboratory

1. **Inspecting the Building and Sampling the Timbers.** Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer

rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

To ensure that we are getting the date of the building as a whole, or the whole of a phase of construction if there is more than one, about 8–10 samples per phase are usually taken. Sometimes we take many more, especially if the construction is complicated. One reason for taking so many samples is that, in general, some will fail to give a date. There may be many reasons why a particular sequence of ring widths from a sample of timber fails to give a date even though others from the same building do. For example, a particular tree may have grown in an odd ecological niche, so odd indeed that the widths of its rings were determined by factors other than the local climate! In such circumstances it will be impossible to date a timber from this tree using the master sequence whose widths, we can assume, were predominantly determined by the local climate at the time.

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure A2; it is about 150mm long and 10mm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost in coring. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

During the initial inspection of the building and its timbers the dendrochronologist may come to the conclusion that, as far as can be judged, none of the timbers have sufficient rings in them for dating purposes and may advise against sampling to save further unwarranted expense.

All sampling by the Laboratory is undertaken according to current Health and Safety Standards. The Laboratory's dendrochronologists are insured.

Figure A1: A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976

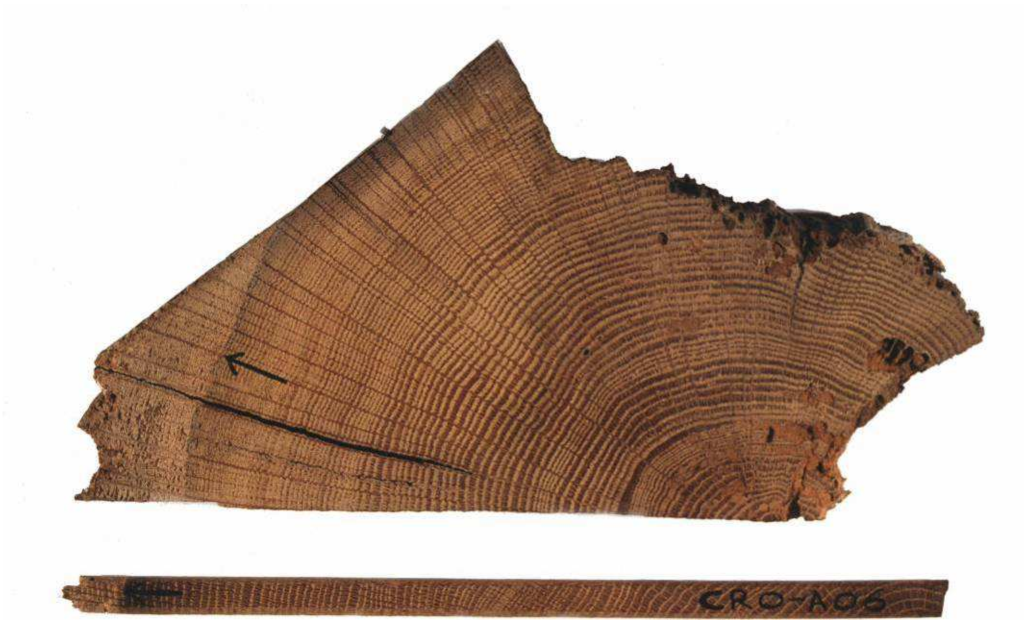


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

Figure A3: Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measured twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis

Figure A4: Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical

2. Measuring Ring Widths. Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure A2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig A3).

3. Cross-Matching and Dating the Samples. Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig A4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t*-value (defined in almost any introductory book on statistics). That offset with the maximum *t*-value among the *t*-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a *t*-value of at least 4.5, and preferably at least 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton and Litton 1988; Laxton *et al* 1988; Howard *et al* 1984–1995).

This is illustrated in Figure A5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN-C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the bar diagram, as is usual, but the offsets at which they best cross-match each other are shown; eg the sequence of ring widths of C08 matches the sequence of ring widths of C45 best when it is at a position starting 20 rings after the first ring of C45, and similarly for the others. The actual t-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the *t*-value between C45 and C08 is 5.6 and is the maximum found between these two among all the positions of one sequence relative to the other.

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

The straightforward method of cross-matching several sample sequences with each other one at a time is called the 'maximal *t*-value' method. The actual method of cross-matching a group of sequences of ring-widths used in the Laboratory involves grouping and averaging the ring-width sequences and is called the 'Litton-Zainodin Grouping Procedure'. It is a modification of the straightforward method and was successfully developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988).

4. **Estimating the Felling Date.** As mentioned above, if the bark is present on a sample, then the date of its last ring is the date of the felling of its tree (or the last full year before felling, if it was felled in the first three months of the following calendar year, before any new growth had started, but this is not too important a consideration in most cases). The actual bark may not be present on a timber in a building, though the dendrochronologist who is sampling can often see from its surface that only the bark is missing. In these cases the date of the last ring is still the date of felling.

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called sapwood rings, are usually lighter than the inner rings, the heartwood, and so are relatively easy to identify. For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure A2, both indicated by arrows. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling.

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. Oak boards quite often come from the Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure A2 was taken still had complete sapwood but that some of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 20mm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

Even if all the sapwood rings are missing on a sample, but none of the heartwood rings are, then an estimate of the felling-date range is possible by adding on the full compliment of, say, 15 to 35 years to the date of the last heartwood ring (called the heartwood/sapwood boundary or transition ring and denoted H/S). Fortunately it is often easy for a trained dendrochronologist to identify this boundary on a timber. If a timber does not have its heartwood/sapwood boundary, then only a *post quem* date for felling is possible.

5. Estimating the Date of Construction. There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998; Miles 1997, 50–5). Hence, provided that all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after (Laxton *et al* 2001, fig 8; 34–5, where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storage before use, or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

6. Master Chronological Sequences. Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Figure A6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Figure A6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. Ring-Width Indices. Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Figure A7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

t-value/offset Matrix

	C45	C08	C05	C04
C45		+20	+37	+47
C08	5.6		+17	+27
C05	5.2	10.4		+10
C04	5.9	3.7	5.1	

Bar Diagram

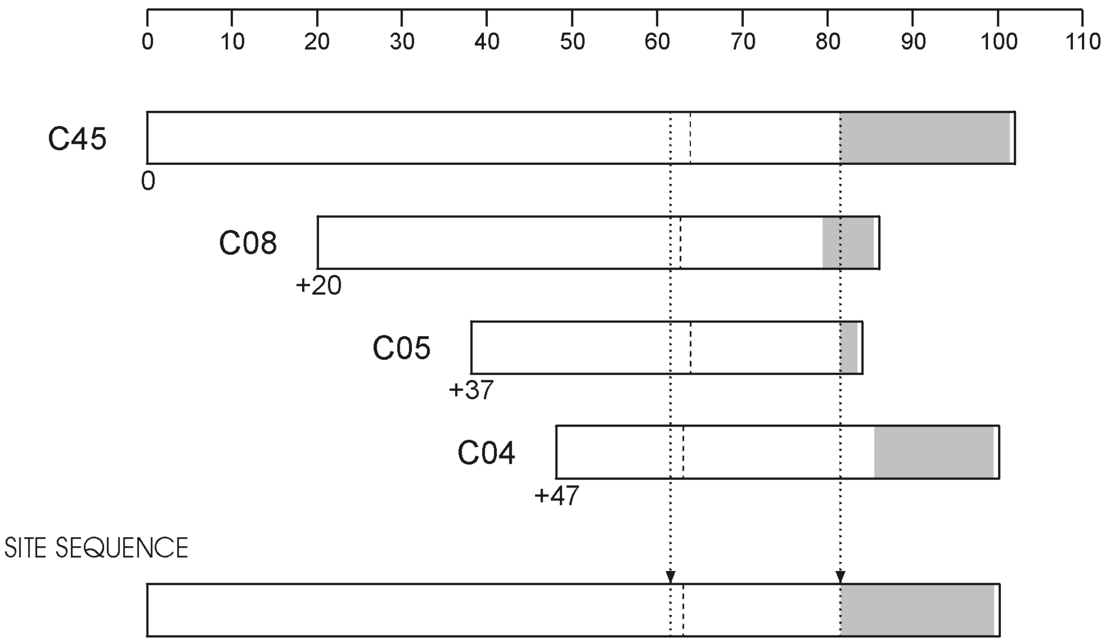


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

The bar diagram represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (offsets) to each other at which they have maximum correlation as measured by the *t*-values. The *t*-value/offset matrix contains the maximum *t*-values below the diagonal and the offsets above it. Thus, the maximum *t*-value between C08 and C45 occurs at the offset of +20 rings and the *t*-value is then 5.6. The site sequence is composed of the average of the corresponding widths, as illustrated with one width.

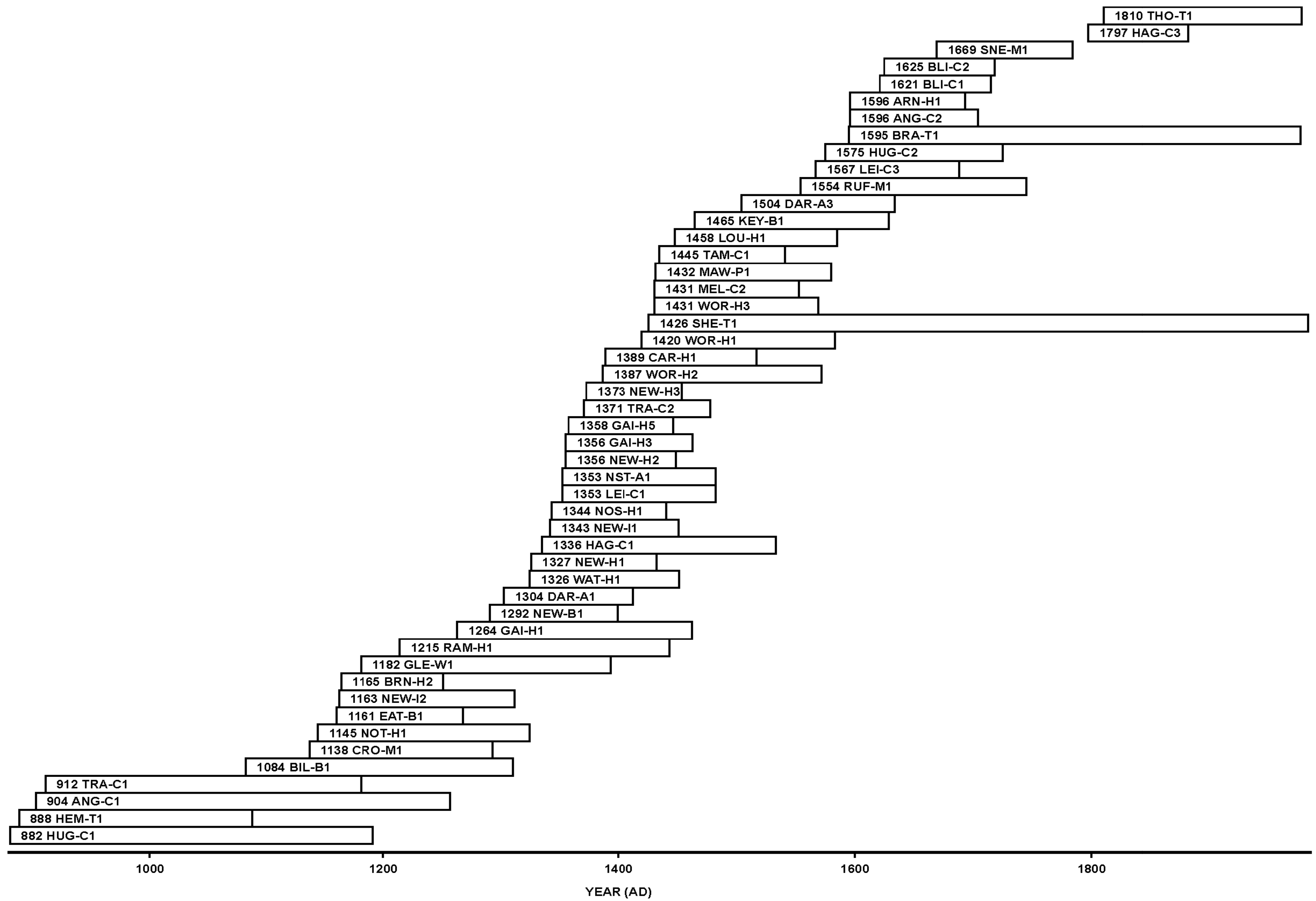
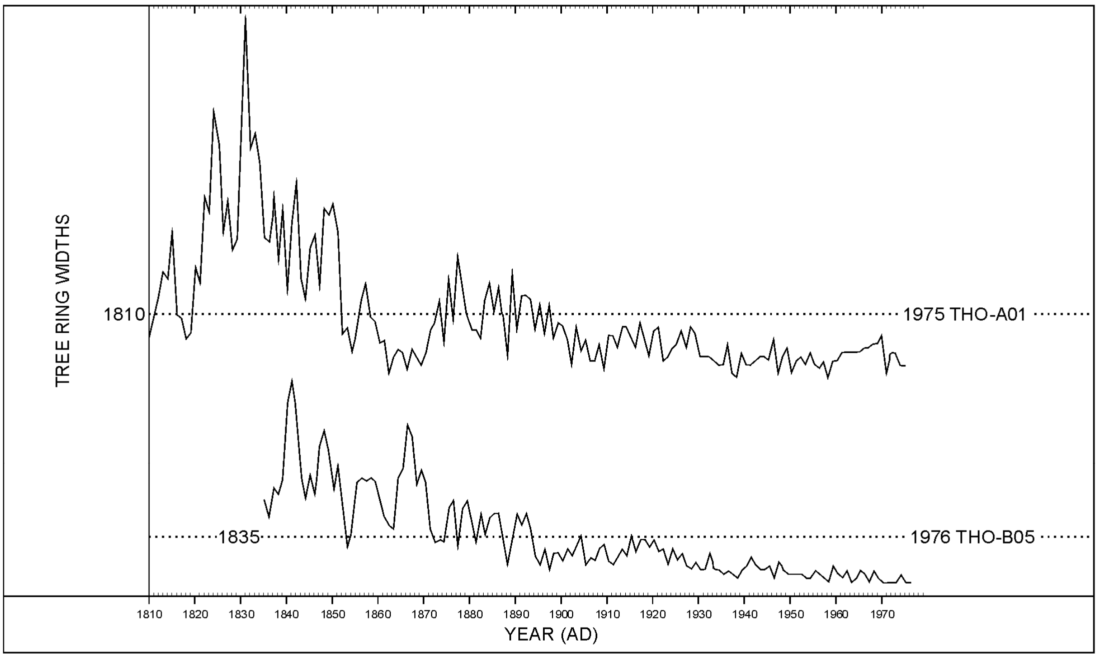


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

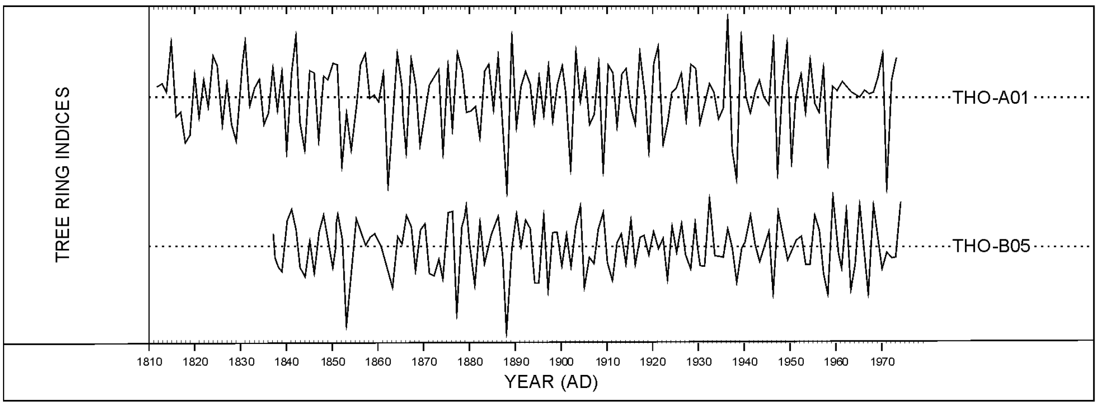


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences

Figure A7 (b): The Baillie-Pilcher indices of the above widths

The growth trends have been removed completely

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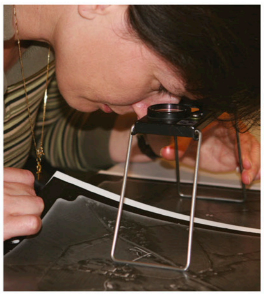

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