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BREAKSPEAR HOUSE, BREAKSPEAR ROAD NORTH, HAREFIELD, HILLINGDON, GREATER LONDON
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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BREAKSPEAR HOUSE, BREAKSPEAR ROAD NORTH, HAREFIELD, HILLINGDON, LONDON

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SUMMARY
Dendrochronological analysis of 18 of the 21 samples obtained exclusively from the floor frames of Breakspear House, no other timbers being suitable, has produced four site chronologies, three of which can be dated.
The first site chronology comprises six samples and has an overall length of 121 rings. These rings are dated as spanning the years AD 1574–1694. A second site chronology of 73 rings overall length, comprises two samples, spanning AD 1517–89. A third site chronology, of two samples and 88 rings overall length, is undated. The fourth site chronology comprises three samples with an overall length of 114 rings, spanning the years AD 1497–1610.
Interpretation of the sapwood on the dated samples indicates that the first-floor frame includes one timber felled in the period AD 1620–45, along with two others that are clearly broadly coeval but could possibly have been felled earlier, at the same time, or later. The second-floor frame contains some timbers felled in the last decade of the seventeenth century. Again other timbers are broadly coeval, although one could have been felled in the late-seventeenth or early-eighteenth century, whilst another could have been felled a few decades earlier in the seventeenth century.

CONTRIBUTORS
Alison Arnold and Robert Howard

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INTRODUCTION

Breakspear House is a large, Grade I listed, red-brick mansion of two storeys with attics, standing in its own grounds approximately one kilometre to the south-east of Harefield Village, west London, in the county of Middlesex (TQ 060 896, Figs 1 and 2). According to a recent archaeological assessment and building survey (Compass Archaeology Ltd 2009), the present building is thought not to be the first known house on the site, an earlier one possibly dating from *c* 1514–59, when documentary records refer to a Thomas Ashby being in residence at '*Breakspears'*. The Ashby family held the estate until 1769, at which time it passed to Joseph Partridge through his earlier marriage to Elisabeth Ashby. It continued in the Partridge family until 1857. From 1857 to 1886 the house was in the ownership of William Drake, still a descendant of the Ashby family, passing to a further descendant, Alfred Tarleton in 1886. The Tarleton family continued in residence until 1951. After this the house was converted into a residential care home for the elderly, as which it continued until 1987. It was then vacated and, although finding occasional use as a film set, has been standing empty ever since. The fabric of both Breakspear House itself, its nearby dovecote, and other associated buildings, have experienced such deterioration since 1987 that that they are now on English Heritage's Buildings At Risk register.

When Breakspear House was originally listed in 1950, it was identified as dating to the early- to mid-seventeenth century, whilst a later survey identified parts of the Entrance Hall and Dining Room as being of later-sixteenth century date (Lee 2000). The most recent evaluation (Compass Archaeology Ltd 2009), however, reassesses the evidence and suggests that only the eastern portion of the present house is potentially of seventeenth-century date (Fig 3), the major part of it belonging to the period 1820 to 1857, when extensive remodelling was undertaken. Further additions and alterations were made in the twentieth century. The 2009 survey suggests that these later alterations may reuse older timbers reset in new positions.

SAMPLING

Sampling and analysis by dendrochronology of timbers at Breakspear House were requested by Kim Stabler, Archaeology Advisor in English Heritage's Greater London Archaeological Advisory Service, and Will Reading, Historic Building and Areas Advisor in English Heritage's London Region Office, in an attempt to more fully understand the history of the building and to determine the extent of survival of the historic fabric. It was hoped that this analysis would inform the historic buildings appraisal being undertaken in advance of potential redevelopment, and inform the associated listed building consent as appropriate.

A thorough pre-sampling assessment was made of the potential of the timbers throughout the building for tree-ring analysis. This showed that only the main beams and joists of the eastern parts of both the first- and second-floor frames might be suitable. The panelling of the entrance hall and dining room appeared to be all fake, possibly dating from their use as a film set. The roof structure comprised modern softwood timbers in the eastern section and very fast grown oak timbers with too few rings for analysis in the western section. The spindles, rails, and posts of the staircase were considered unsuitable due to their size and decorative nature. There were no other timbers to either walls or ceilings, or any that formed lintels to doors or windows, which might have been sampled.

Thus, from the limited number of areas containing suitable timbers (ie the eastern parts of the first- and second-floor frames,) a total of 21 oak samples was obtained by coring. Each sample was given the code HFD-B (for Harefield, site 'B') and numbered 01–21. The location of samples was noted at the time of coring and marked on the drawings made and provided by Compass Archaeology Ltd. These are reproduced here as Figure 4. In respect of sample locations, given the difficulty of lifting floorboards in some areas, the exact layout of the main beams in some rooms is not always clear (Figs 5a/b). Further details relating to the samples can be found in Table 1.

ANALYSIS

Each of the 21 samples obtained was prepared by sanding and polishing. It was seen at this time that three samples, HFD-B03, B18, and B19, had less than the minimum of 50 rings here deemed necessary for reliable dating, and these samples were rejected from this programme of analysis. The annual growth-ring widths of the remaining 18 samples were, however, measured, the data of these measurements being given at the end of this report.

The data of the 18 measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), allowing three separate groups, accounting for 10 measured samples, to be formed at a high minimum value of t=6.4 (see section on intra-site cross-matching below). The samples of each group cross-match as shown in Figures 6–9. The cross-matching samples of each group were combined at their indicated offset positions to form site chronologies HFDBSQ01–SQ03.

Each of these three site chronologies was then compared to an extensive corpus of reference material for oak, this process resulting in the satisfactory dating of two of these site chronologies. Site chronology HFDBBQ01, comprising six samples with an overall length of 121 rings, was found to match repeatedly and consistently with a series of reference chronologies for oak, when the date of its first ring is AD 1574 and the date of its last measured ring is AD 1694. The evidence for this dating is given in Table 2.

Site chronology HFDBSQ02, comprising two samples with an overall length of 73 rings, was found to match repeatedly and consistently with a series of reference chronologies when the date of its first ring is AD 1517 and the date of its last measured ring is AD 1589. The evidence for this dating is given in Table 3.

The third site chronology HFDBSQ03, also comprising two samples, with an overall length of 88 rings, failed to date, although it was compared to an extensive corpus of reference material including not only that held by the Nottingham Tree-ring Dating Laboratory but also that held, for example, at the Sheffield University Dendrochronology Laboratory.

The eight remaining measured but ungrouped single samples were then compared individually to the full corpus of reference material, this process indicating dates for three of these samples, HFD-B01, B10, and B21. It was seen at this time that these three samples not only shared overlapping date spans, but in fact could be combined at the relative positions indicated by their individual dating, at a minimum value of t=3.9. Given these facts, the samples were combined to form a fourth site chronology, HFDBSQ04, with an overall length of 114 rings. This site chronology was also compared to the reference material for oak, indicating a satisfactory cross-match when the date of its first ring is AD 1497 and the date of its last measured ring is AD 1610. The evidence for this dating is given in Table 4. The five other measured but ungrouped samples all remain undated.

This analysis may be summarised as follows:

Site chronology	Number of samples	Number of rings	Date span AD (where dated)
HFDBSQ01	6	121	1574–1694
HFDBSQ02	2	73	1517–89
HFDBSQ03	2	88	undated
HFDBSQ04	3	114	1497–1610
Ungrouped	5	---	undated
Unmeasured	3	---	---

INTERPRETATION

Analysis by dendrochronology of 18 measured samples from this building has produced four site chronologies, three of which can be dated. Interpretation of the sapwood on the samples of the three dated site chronologies would suggest the probability that, as intimated by the structural evidence, timbers of different phases of felling are to be found at this site.

Site chronology HFDBSQ01

The most recent material detected in this analysis appears to be represented by the six samples, all from the second floor, of site chronology HFDBSQ01 (Fig 6). Two samples in this site chronology, HFD-B05 and B08, retain complete sapwood (ie the last ring produced by the tree represented before it was felled) and in both cases this last, complete, sapwood ring, and thus the felling of the trees, is dated to AD 1694.

Another sample, HFD-B12, in site chronology HFDBSQ01, retains the heartwood/sapwood boundary, this being dated to AD 1678. Using a 95% confidence limit of 15–40 rings for the amount of sapwood the tree represented might have had would give it an estimated felling date in the range AD 1693–1718. The heartwood/sapwood boundary is only a few years later than the two timbers felled in AD 1694, discussed above, and this felling date range brackets the known felling date. It is therefore potentially coeval but, in the absence of complete sapwood, it is also possible that it represents a slightly later felling phase. It is of note that this timber is not jointed, or structurally integral, to the others represented in this group, and is associated with two timbers (samples HFD-B11 and B13) that are undated.

Two further samples in site chronology HFDBSQ01, HFD-B06 and B07, do not retain the heartwood/sapwood boundary. Normally, the felling date of the timbers represented could not, thus, be determined, except to say that, with last measured heartwood ring dates of AD 1663 and AD 1658, and allowing for the usual minimum of 15 sapwood rings, this is unlikely to be before AD 1678 and AD 1673, respectively and hence clearly broadly coeval with the other material in this group. In this case, however, the potential same-tree derivation for the timbers represented by samples B07 and B08 (see below), would suggest, that B07 at least was felled in AD 1694 as well.

The sixth sample in this first site chronology, HFD-B04, has an apparently anomalously early heartwood/sapwood boundary date of AD 1640, which, using the same sapwood estimate as above would imply a felling date in the range AD 1655–80, which does not include the known felling date, AD 1694, identified above and the estimated felling date range of HFD-B12. Thus, either HFD-B04 was indeed felled slightly earlier or it had a higher number of sapwood rings than usual. Given the level of cross-matching between the samples of this site chronology (see below), and that in a group of 21 samples we might expect to find one with sapwood ring numbers outside the 95% confidence interval, the latter explanation seems perhaps more likely. However this supposition cannot be proven, so whilst it is clearly broadly coeval with this late-seventeenth century group, it is clearly possible for it to represent a separate, slightly earlier, felling phase in the seventeenth century.

Site chronology HFDBSQ04

The earliest definite felling period is represented by sample HFD-B21 in site chronology HFDBSQ04 (Fig 9), this sample having a heartwood/sapwood boundary date of AD 1605. Using the same sapwood estimate as above, 15–40 rings, would give the timber represented an estimated felling date in the range AD 1620–45.

Two other samples in site chronology HFDBSQ04, HFD-B01 and B10, are broadly coeval with HFD-B21, but do not retain the heartwood/sapwood boundary and thus, the felling date of the timbers represented cannot be determined. However, with last measured heartwood ring dates of AD 1599 and AD 1589, this is unlikely to be before AD 1614 and AD 1604, respectively, allowing for the usual minimum of 15 sapwood rings.

Site chronology HFDBSQ02

Likewise, the felling date of the timbers represented by samples HFD-B14 and B20, in site chronology HFDBSQ02 (Fig 7), cannot be determined, although they are broadly coeval with the samples incorporated into site sequence HFDBSQ04. With last measured heartwood ring dates of AD 1587 and AD 1589, and using the usual minimum of 15 sapwood rings, it is unlikely that these timbers were felled before AD 1602 and AD 1604, respectively.

Site chronology HFDBSQ03

The two samples, HFD-B11 and B13, of site chronology HFDBSQ03 (Fig 8) cannot be dated. However, although undated, given that the heartwood/sapwood boundary on the two samples is at identical positions, it seems likely that the two timbers represented were felled at the same time. Indeed, given the level of cross-matching between these samples (see below), it is probable that the two timbers have been derived from a single tree.

DISCUSSION

Whilst it is not easy to relate the tree-ring results clearly and directly to the construction of the building, it is possible to make some overall comments. The information derived from the tree-ring dating suggests that timbers of at least two, and possibly more, episodes of felling are represented in the floor-framing in the eastern section of Breakspear House. No timbers earlier than the early- to mid-seventeenth century have been detected, which suggests that no timbers from an earlier, older, house on the site here have been reused.

The latest clearly identified phase of felling is represented by samples HFD-B05, B07, and B08, in site chronology HFDBSQ01, from timbers felled in AD 1694. However, within the group of six timbers that form site chronology HFDBSQ01, it remains a possibility that, whilst they are all likely to be broadly coeval, at least one timber could have been felled slightly earlier in the seventeenth century and one could have been felled slightly later in the seventeenth century or early in the eighteenth century. It may be noted from Table 1 that all these samples are from the second floor frame.

The earliest clearly identified phase of felling is represented by sample HFD-B21, from the first-floor frame, in site chronology HFDBSQ04, which has an estimated felling date in the range AD 1620–45. The timbers represented by samples HFD-B01 and B10, from the second-floor frame and also in site chronology HFDBSQ04, and by samples HFD-B14 and B20, from the first-floor frame, in site chronology HFDBSQ03, are broadly coeval with this early/mid seventeenth-century felling date, although, in the absence of any trace of sapwood, it is possible these could have been felled slightly earlier or, indeed, sometime later.

Thus, the first-floor frame includes one timber (B21) which was felled in the earlier-seventeenth century, and which may represent the construction date of this frame. Two other timbers from this frame, however (B14 and B20), could possibly have been felled earlier, at the same time, or might not have been felled till some later time, and it is possible that these timbers have been reused/reset in later programmes of work.

The second-floor frame contain some timbers felled in the late-seventeenth century, with one (B12) possibly felled as late as the early eighteenth century, but also includes at least three timbers (B01, B04, and B10) which could possibly have been felled earlier.

A bar diagram showing all the samples in the three dated site chronologies is given in Figure 10.

The intra-site cross-matching of some samples, particularly those of site chronology HFDBSQ01, is such as to suggest that the timbers represented may have been derived from a single woodland source, some samples cross-matching with each other with values in excess of t=9.0. This adds weight to the possibility that the timbers represented by HFDBSQ01 are coeval, it being relatively unlikely that timbers which were originally growing very close to each other in the same woodland, but which had been felled at different times, would come to be used in the same building.

Indeed, the level of cross-matching between some samples, HFD-B07 and B08 for example, at a value of t=16.3, is sufficiently high to suggest the possibility that the two timbers represented are derived from the same tree. Such an interpretation is supported by the probability that, although the greater part of both beams were hidden beneath floorboards, and their visual surface characteristics could not be fully compared, they both appeared to be half-trees. In this instance such an observation is of more than passing interest, in that sample B07, being one of those without the heartwood/sapwood boundary and representing a timber theoretically of uncertain felling date, can now be potentially dated as a timber cut, like its other half, which has complete sapwood, in AD 1694.

Further pairs of timbers, such as undated samples HFD-B11 and B13, which cross-match with each other with a value of t=15.4, and dated samples HFD-B14 and B20, which cross-match with each other with a value of t=15.2, may also be derived from single trees. In each case, the likelihood of the pairs of timbers being derived from single trees is again supported by the fact that the beams appear to be half-trees, though again, being largely hidden beneath floorboards, they could not be visually compared.

Where this source woodland was cannot be identified precisely by dendrochronology (eg Bridge 2000). However, as may be seen from Tables 2–4, which lists a short selection of the reference chronologies used to date each site sequence, the majority of better cross-matches tend to be with reference chronologies from north of London. Clearly, as has been noted before, the area exploited for timber for use in London was extensive.

One site sequence, HFDBSQ03, comprising two samples, and five further individual samples, or just over 27% of those obtained and measured, remain ungrouped and undated. None of these samples show any obvious problems with their annual growth rings, such as distortion, compression, or erratic growth, which would make cross-matching and dating difficult, and only one sample, HFD-B15, has a number of rings which, although above the minimum of 54, is towards the lower end of the required figure. All other single samples have sufficient rings and show no peculiarities.

Bearing in mind the extensive nineteenth-century alterations here, and the possible reuse of material, it is possible that these undated timbers are from a time and/or place that is not yet particularly well-represented in the reference material, there being fewer chronologies for London and the south-east from the mid-seventeenth century onwards . It is also possible that each timber is from a different source, making each one, in effect, a singleton. Such timbers are often more difficult to date than well-replicated groups of data.

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TABLES

Table 1: Details of tree-ring samples from Breakspear House, Harefield, Hillingdon, London

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	2nd floor					
HFD-B01	Main beam	88	no h/s	1512	------	1599
HFD-B02	Main beam	65	no h/s	------	------	------
HFD-B03	Main beam	nm	---	------	------	------
HFD-B04	Main beam	71	8	1578	1640	1648
HFD-B05	Main beam	121	21C	1574	1673	1694
HFD-B06	Main beam	54	no h/s	1610	------	1663
HFD-B07	Main beam	79	no h/s	1580	------	1658
HFD-B08	Main beam	118	24C	1577	1670	1694
HFD-B09	Main beam	90	6	------	------	------
HFD-B10	Main beam	79	no h/s	1511	------	1589
HFD-B11	Main beam	88	16	------	------	------
HFD-B12	Main beam	69	11	1621	1678	1689
HFD-B13	Main beam	86	16	------	------	------
	1st floor					
HFD-B14	Main beam	71	no h/s	1517	------	1587
HFD-B15	Main beam	54	5	------	------	------
HFD-B16	Common joist	86	4	------	------	------
HFD-B17	Main beam	71	24C	------	------	------
HFD-B18	Common joist	nm	---	------	------	------
HFD-B19	Common joist	nm	---	------	------	------
HFD-B20	Main beam	61	no h/s	1529	------	1589
HFD-B21	Main beam	114	5	1497	1605	1610

*h/s = the heartwood/sapwood ring is the last ring on the sample
h/s = the heartwood/sapwood ring is the last ring on the sample
nm = sample not measured
C = complete sapwood is retained on the sample; the last measured ring date is the felling date of the tree represented

Table 2: Results of the cross-matching of site sequence HFDBSQ01 and relevant reference chronologies when the first-ring date is AD 1574 and the last-ring date is AD 1694

Reference chronology	Span of chronology	*t*-value	Reference
Old Clarendon Building, Oxford	AD 1539–1711	9.5	(Worthington and Miles 2006)
Hill Hall, Theydon Mount, Essex	AD 1525–1681	9.4	(Bridge 1999)
Wren Wing, Easton Neston, Northamptonshire	AD 1468–1686	8.6	(Arnold *et al* 2008)
De Grey Mausoleum, Flitton, Bedfordshire	AD 1510–1726	8.5	(Arnold *et al* 2003)
The Vyne (south range), Hampshire	AD 1543–1653	7.2	(Miles *et al* 1998)
Newington House, Oxfordshire	AD 1540–1678	7.0	(Haddon-Reece *et al* 1987)
St Hugh's' Choir, Lincoln Cathedral	AD 1575–1724	6.8	(Laxton *et al* 1984)
Old Barn, Shottery, Stratford upon Avon, Warwickshire	AD 1591–1735	6.6	(Howard *et al* 1996)

Table 3: Results of the cross-matching of site sequence HFDBSQ02 and relevant reference chronologies when the first-ring date is AD 1517 and the last-ring date is AD 1589

Reference chronology	Span of chronology	*t*-value	Reference
White Tower, Tower of London, London	AD 1463–1616	6.3	(Miles 2007)
Cressing Temple farmhouse, Essex	AD 1514–1608	6.2	(Tyers 1995)
Moyns Park, Essex	AD 1431–1606	5.9	(Tyers 1999)
Lodge Farm, Kingston Lacy, Dorset	AD 1470–1568	5.8	(Groves 1994)
Manor Farm (stables), Stanton St John, Oxfordshire	AD 1480–1646	5.7	(Miles and Worthington 1998)
Flore's House, Oakham, Rutland	AD 1408–1591	5.7	(Hurford *et al* 2008)
Wigborough Manor, South Petherton, Somerset	AD 1447–1584	5.6	(Miles *et al* 1997a)
Stoneleigh Abbey, Stoneleigh, Warwickshire	AD 1646–1813	5.3	(Howard *et al* 2000)

Table 4: Results of the cross-matching of site sequence HFDBSQ04 and relevant reference chronologies when the first-ring date is AD 1497 and the last-ring date is AD 1610

Reference chronology	Span of chronology	*t*-value	Reference
Old Clarendon Building, Oxford	AD 1539–1711	8.4	(Worthington and Miles 2006)
The Vyne (garden house), Hampshire	AD 1459–1630	8.4	(Miles *et al* 1997b)
Upper House farmhouse, Nuffield, Oxfordshire	AD 1404–1627	7.6	(Haddon–Reece *et al* 1989)
Aston Hall, Aston, Birmingham	AD 1457–1624	7.1	(Howard 2005 unpubl)
Kenilworth Castle Gatehouse, Warwickshire	AD 1473–1561	6.6	(Arnold and Howard 2007)
Swaylands Barn, Penshurst, Kent	AD 1515–1616	6.6	(Arnold *et al* 2001)
Cressing Temple farmhouse, Essex	AD 1514–1608	6.3	(Tyers 1995)
Manor Farm (south-west wing), Stanton St John, Oxfordshire	AD 1533–1637	6.2	(Miles and Worthington 1998)

FIGURES

Figure 1: Map to show the location of Breakspear House (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, © Crown Copyright)

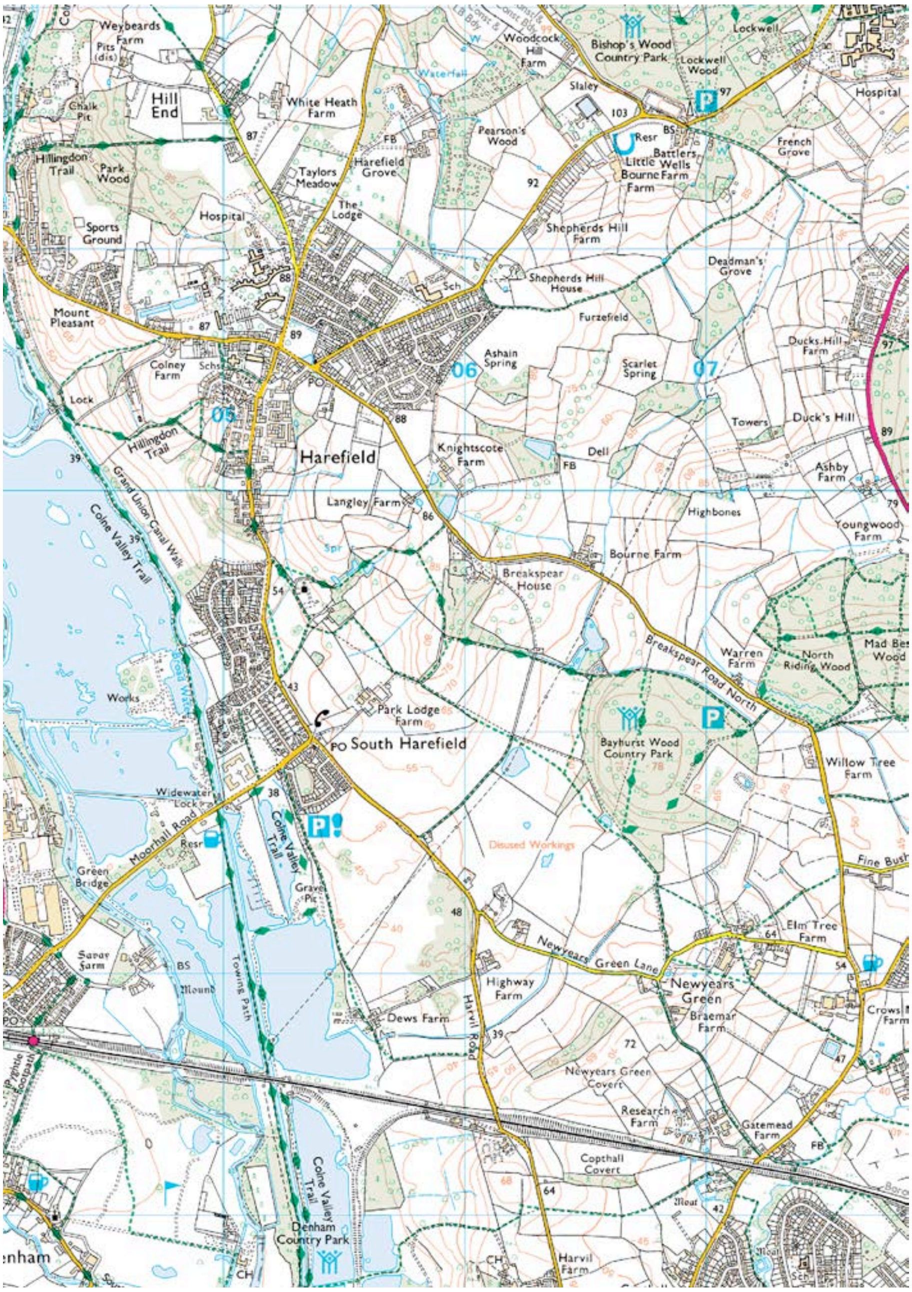


Figure 2: Map to show the location of Breakspear House (based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, ©Crown Copyright)

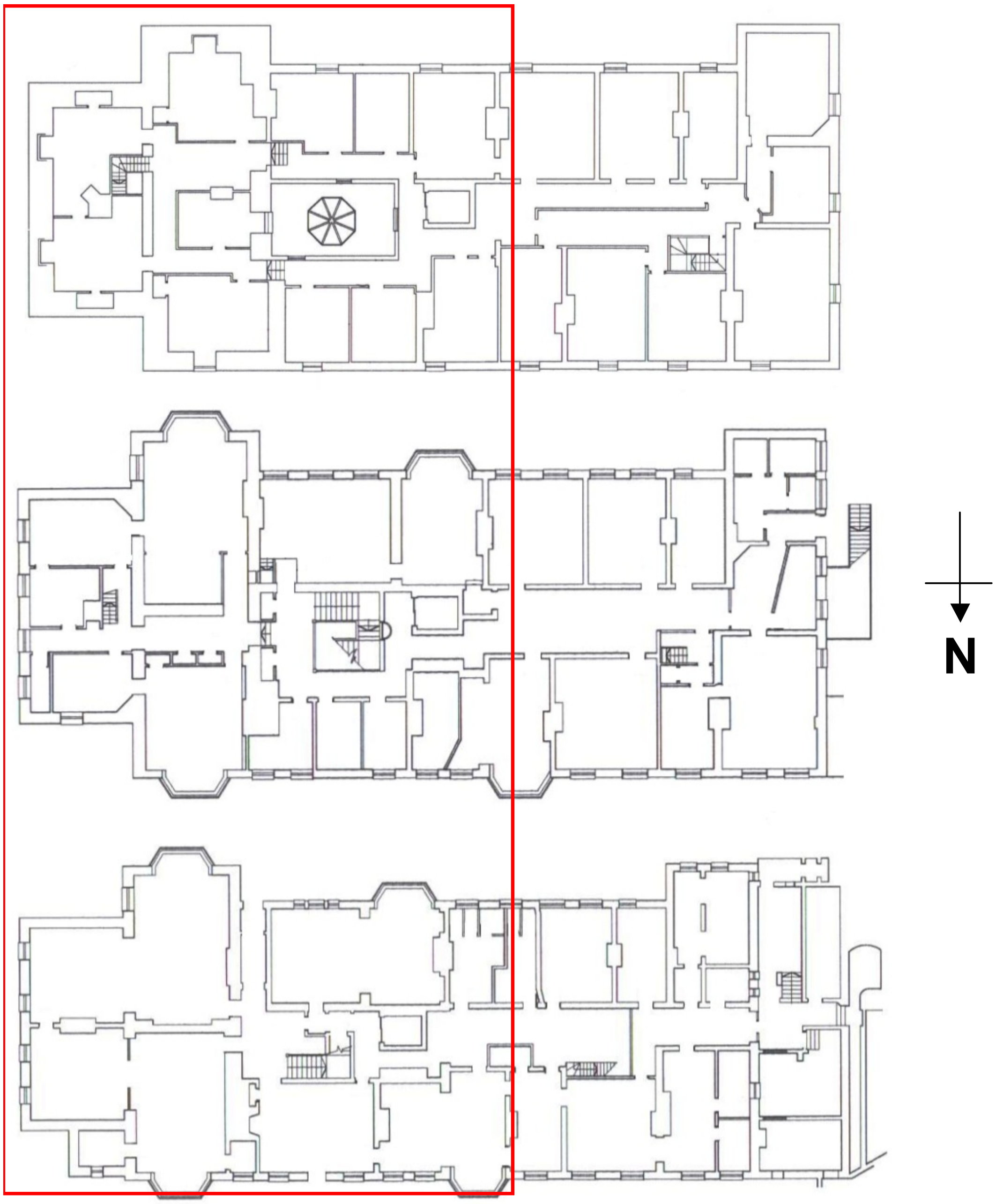


Figure 3: Basic plan of Breakspear House at second-, first-, and ground-floor level (top to bottom), with the supposedly older, seventeenth-century, portion outlined in red (after Compass Archaeology Ltd, 2009)

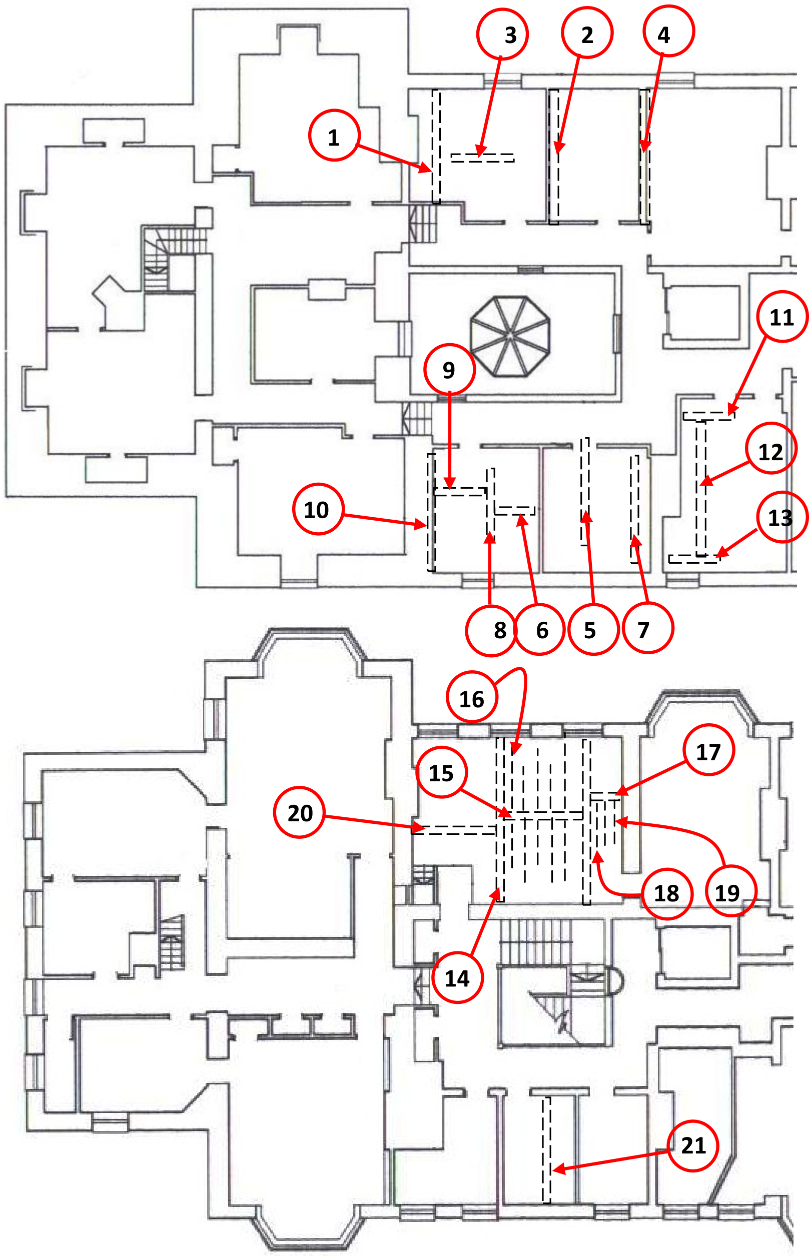
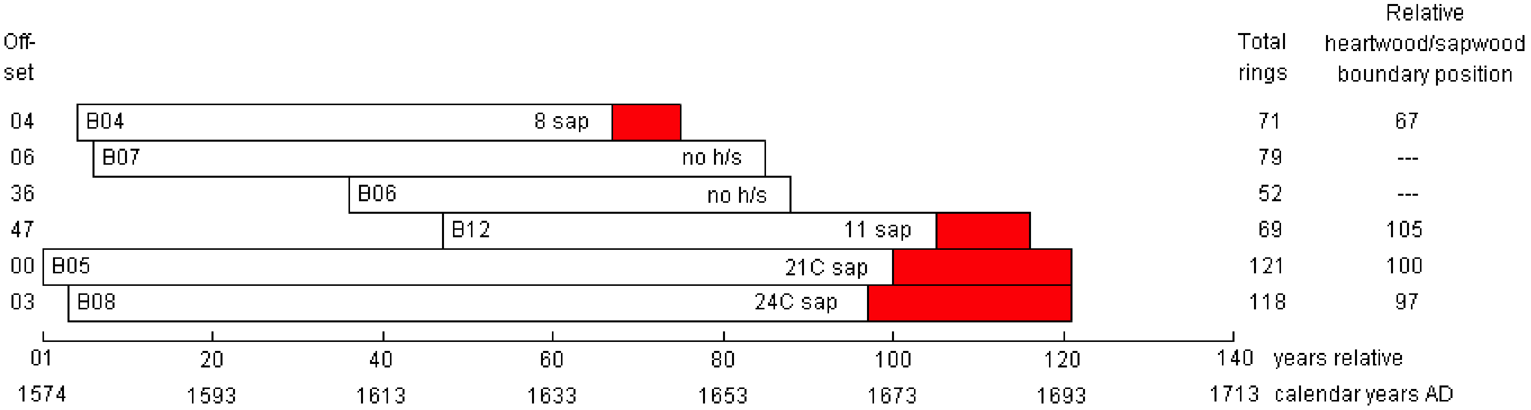
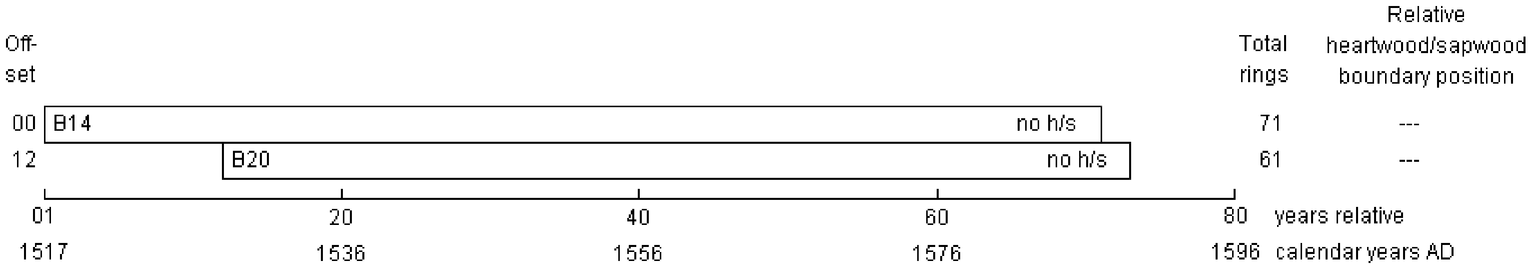


Figure 4: Plan at second- and first-floor levels (top and bottom) to show approximate position of sampled floor-frame timbers (after Compass Archaeology Ltd, 2009)

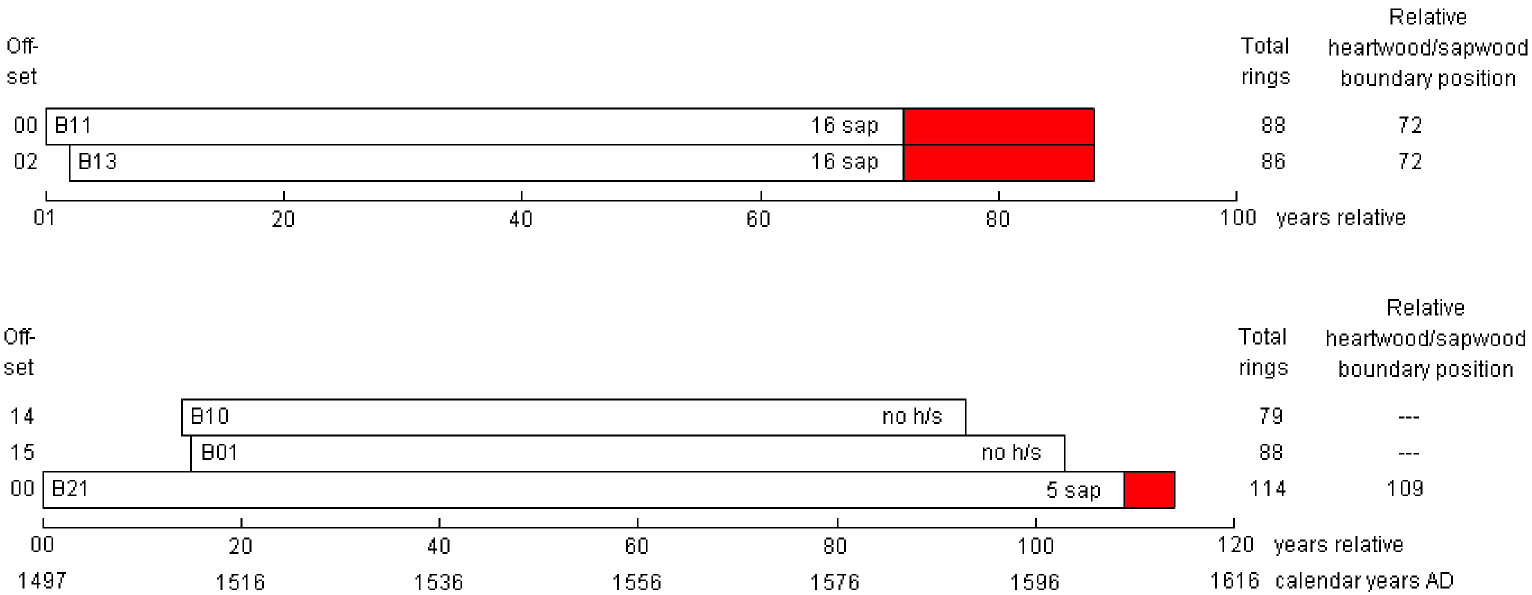
Figure 5a/b: Views to show the occasional limited nature of access to floor frames





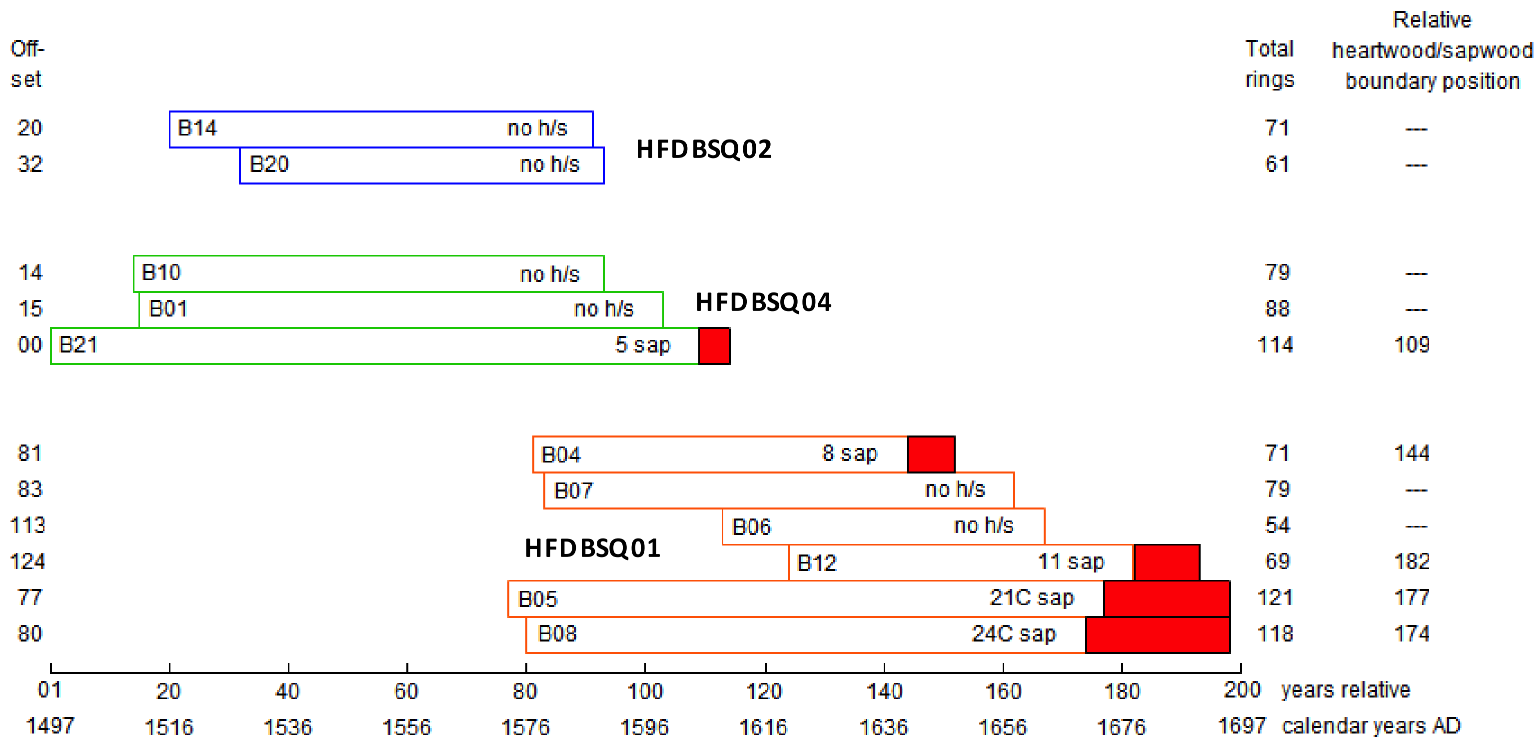
White bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary
C = complete sapwood, the last measured ring date is the felling date of the tree represented

Figures 6 and 7: Bar diagram of the samples in site chronology HFDBSQ01 (top) and SQ02 (bottom)



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

Figures 8 and 9: Bar diagram of the samples in site chronology HFDBSQ03 (top) and SQ04 (bottom)



White bars = heartwood rings, shaded area = sapwood rings
h/s = heartwood/sapwood boundary
C = complete sapwood, the last measured ring date is the felling date of the tree represented

Figure 10: Bar diagram of all dated samples in last measured ring date order

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

HFD-B01A 88
277 235 251 183 183 139 185 209 146 81 128 108 94 112 89 109 104 116 81 152
96 78 76 69 86 85 101 134 133 157 110 180 133 141 92 125 69 79 64 74
52 75 83 113 75 68 81 95 74 86 123 94 96 84 73 97 112 112 144 120
81 114 74 95 85 117 91 103 138 117 96 115 134 133 160 125 95 144 103 139
110 114 173 181 166 162 181 121
HFD-B01B 88
294 255 252 196 199 147 255 161 165 97 146 106 107 105 95 105 100 120 80 158
87 85 67 73 87 87 103 131 138 166 115 189 129 144 83 125 65 84 68 83
46 68 89 106 77 76 77 86 110 58 123 90 89 79 75 100 103 118 127 121
77 107 73 103 85 118 96 100 155 130 88 114 129 128 156 125 99 140 109 128
119 111 170 184 152 148 157 134
HFD-B02A 65
386 489 350 346 426 315 281 358 276 509 384 300 215 202 102 127 139 142 183 144
163 188 179 172 165 182 184 206 192 168 164 142 112 139 149 231 172 154 80 102
83 97 67 50 52 71 53 76 47 70 46 42 31 30 35 37 67 69 85 89
73 86 72 74 143
HFD-B02B 65
370 521 354 350 424 329 294 361 283 508 366 293 207 196 123 143 138 147 170 148
160 184 199 169 158 178 193 206 188 162 178 150 110 135 151 245 171 154 77 97
88 101 71 49 55 65 58 69 46 72 54 38 34 30 25 47 60 76 83 83
73 81 64 68 147
HFD-B04A 71
210 235 298 175 158 219 190 343 296 241 264 232 188 188 231 179 203 222 194 193
153 142 143 193 201 170 270 199 293 194 168 129 157 150 166 231 136 148 240 235
179 182 143 196 212 191 159 220 208 217 222 184 153 165 217 182 132 142 136 151
136 132 212 228 155 155 182 236 270 222 286
HFD-B04B 71
240 220 248 182 162 221 198 345 307 245 289 249 168 184 202 183 221 239 197 192
143 137 147 225 204 177 260 201 281 203 183 129 140 156 173 236 136 157 217 249
160 193 137 194 213 182 169 227 206 208 222 186 151 172 217 184 128 153 141 157
143 111 213 204 157 176 233 193 240 238 270
HFD-B05A 121
279 309 290 298 178 321 361 302 348 438 321 506 390 198 336 381 195 312 243 273
307 296 314 281 274 248 232 208 169 147 236 229 290 222 263 196 271 209 268 287
102 133 192 211 112 171 128 225 275 184 175 264 187 214 219 159 170 183 156 152
95 112 108 133 126 110 271 298 237 252 272 233 222 212 339 202 175 143 169 135
120 182 147 193 199 129 142 166 201 188 213 120 106 148 170 111 125 125 173 141
150 102 80 147 178 115 146 104 155 176 120 98 146 153 171 157 129 132 151 157
150
HFD-B05B 121
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312 293 326 262 266 255 232 203 171 140 258 225 279 216 262 197 250 221 259 269
115 135 183 208 126 172 124 219 280 197 156 253 183 209 223 166 163 172 183 141
112 117 107 127 134 102 265 307 243 247 264 262 218 215 339 195 164 140 175 124
108 202 153 213 196 124 140 161 201 181 184 133 120 148 174 103 114 131 173 143
140 118 89 146 165 122 136 113 165 153 104 102 130 178 169 133 124 128 157 162
142

HFD-B06A 54
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89 99 178 191 132 157 140 199 287 176 208 215 214 225 267 291 231 193 401 208
146 141 132 112 127 216 188 235 254 210 267 253 194 243
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81 103 173 187 122 158 159 202 298 156 194 232 208 225 283 288 241 213 383 184
149 151 142 97 124 232 188 232 264 200 264 279 200 240
HFD-B07A 79
248 220 180 182 114 203 165 124 196 159 135 161 141 136 225 176 158 173 168 151
146 161 151 135 203 194 219 150 155 106 123 104 127 223 174 155 290 190 216 214
130 138 219 146 125 215 171 216 148 139 123 131 134 217 120 124 132 142 169 151
212 205 237 246 335 246 288 287 319 212 192 169 195 150 136 249 199 239 249
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240 237 167 207 118 211 191 127 182 160 129 176 133 203 230 164 172 177 171 147
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116 155 213 148 144 201 156 206 163 143 124 143 164 216 108 130 126 142 175 149
198 218 225 244 319 255 297 276 314 201 217 158 169 167 134 252 194 234 251
HFD-B08A 118
219 226 251 238 240 175 188 163 269 198 123 195 154 161 223 168 203 233 222 193
229 226 205 172 175 177 145 223 156 275 216 200 155 160 128 138 253 150 166 298
184 197 221 138 129 171 102 129 148 142 160 136 109 113 117 141 176 131 115 151
152 182 149 220 248 224 253 285 275 286 285 333 202 205 171 181 153 146 227 176
174 228 162 190 227 198 237 168 141 162 162 176 163 175 144 173 172 149 137 107
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217 241 242 271 236 154 199 153 285 170 132 218 173 142 214 177 216 277 210 190
216 256 188 181 171 174 153 218 177 287 197 221 161 173 130 136 246 179 173 305
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159 169 169 218 238 241 236 276 299 294 293 333 209 202 175 162 166 154 188 176
173 215 173 194 215 183 269 183 148 147 164 141 172 167 162 182 166 146 141 96
143 157 138 115 111 132 162 107 111 136 127 148 158 147 113 109 99 142
HFD-B09A 90
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160 137 100 121 129 153 126 146 137 121 143 105 127 158 151 145 216 271 219 161
191 142 148 175 79 57 77 82 99 80 120 109 129 99 86 85 84 97 112 149
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282 231 273 226 317 170 149 125 123 210 142 198 126 120 137 141 127 140 133 113
95 91 161 136 94 138 202 145 167 168 161 197 203 158 229 167 142 198 324
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195 200 213 223 333 281 288 356 449 391 395 314 329 303 346 257 331 332 366 259
277 230 281 224 318 170 134 122 138 210 180 193 125 115 134 130 126 134 133 133

98 95 149 136 101 138 180 151 172 161 156 151 205 153 210 202 138 183 347
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205 156 178 210 153 97 98 85 188 203 271 167 176 108 160 244 64 48 125 148
220 276 294 236 199 273 206 274 236 150 52 73 160 175 161 192 132 196 199 226
56 44 38 45 68 82 180 248 176 235 96 91 107 133 150 114 142 49 60 80
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223 155 185 210 183 54 83 85 186 207 274 173 169 110 164 232 66 68 126 151
209 246 296 263 192 252 200 261 247 155 61 84 142 177 164 169 142 172 173 204
60 33 49 53 57 86 169 267 176 228 97 90 99 132 162 103 153 50 51 83
67 116 85 124 123 156 134 132
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268 286 352 319 296 282 220 328 221 249 175 151 142 147 220 186 153 217 117 149
184 169 255 183 173 157 149 209 169 172 133 197 201 197 138 103 191 231 161 288
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183 372 239 156 183 177 184 245 256
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376 286 178 261 184 198 207 105 38 76 126 167 155 188 146 232 188 236 48 36
38 39 51 66 143 252 192 243 76 76 134 152 169 124 155 66 59 32 81 52
80 97 175 111 138 105
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63 156 185 211 255 262 330 332 357 225 226 230 221 189

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79 70 102 111 168 174 115 195 227 113 85 83 42 44 42 34 56 57 55 82
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126 172 268 327 499 624
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80 81 81 116 99 39 37 29 33 40 54 49 51 72 70 69 97 112 79 123
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120 133 133 181 79 79 78 97 100 108 111
HFD-B17B 71
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143
HFD-B20B 61
192 215 211 156 128 154 212 220 187 207 206 223 269 260 262 288 359 281 276 309
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208 253 208 156 175 153 171 162 152 121 149 191 112 131 122 116 168 149 129 166
146
HFD-B21A 114
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153 174 155 103 87 89 117 208 181 155 171 194 101 79 225 130 106 134 111 128
128 124 155 177 195 108 129 123 147 144 141 179 185 172 176 144 191 204 253 153
116 104 180 173 252 201 182 166 113 85 81 101 134 114 115 78 57 36 38 34
29 44 46 46 57 55 79 110 102 100 89 59 64 82 89 89 91 100 117 108
78 89 82 85 91 82 122 179 192 212 166 165 103 148
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141 128 139 190 197 144 151 149 173 178 143 180 197 179 172 140 186 207 257 155
111 110 167 164 239 206 194 154 106 83 89 110 146 109 119 71 67 33 38 35
30 37 54 45 61 51 87 94 105 105 80 70 65 83 91 87 91 97 120 101
87 87 82 93 84 80 117 173 201 215 156 169 112 143

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 Building* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1988). 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

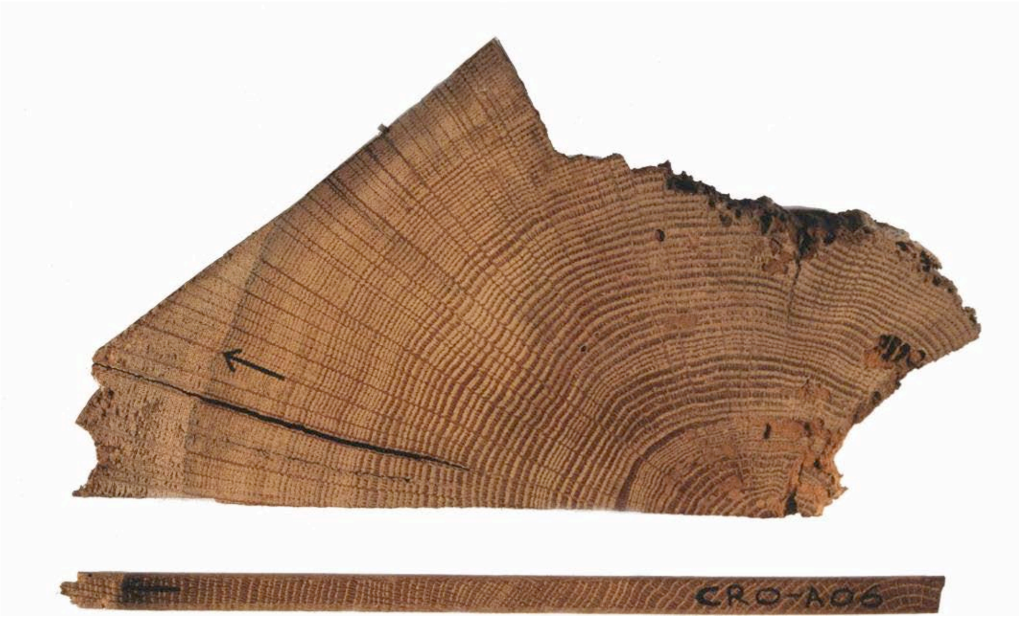


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

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

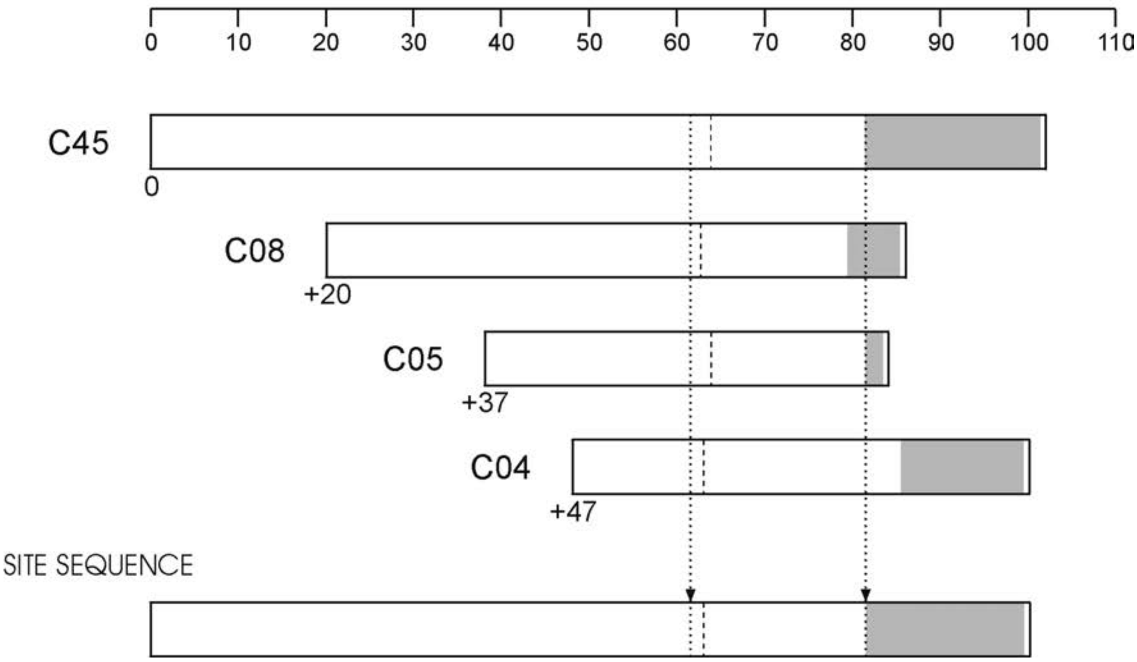


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

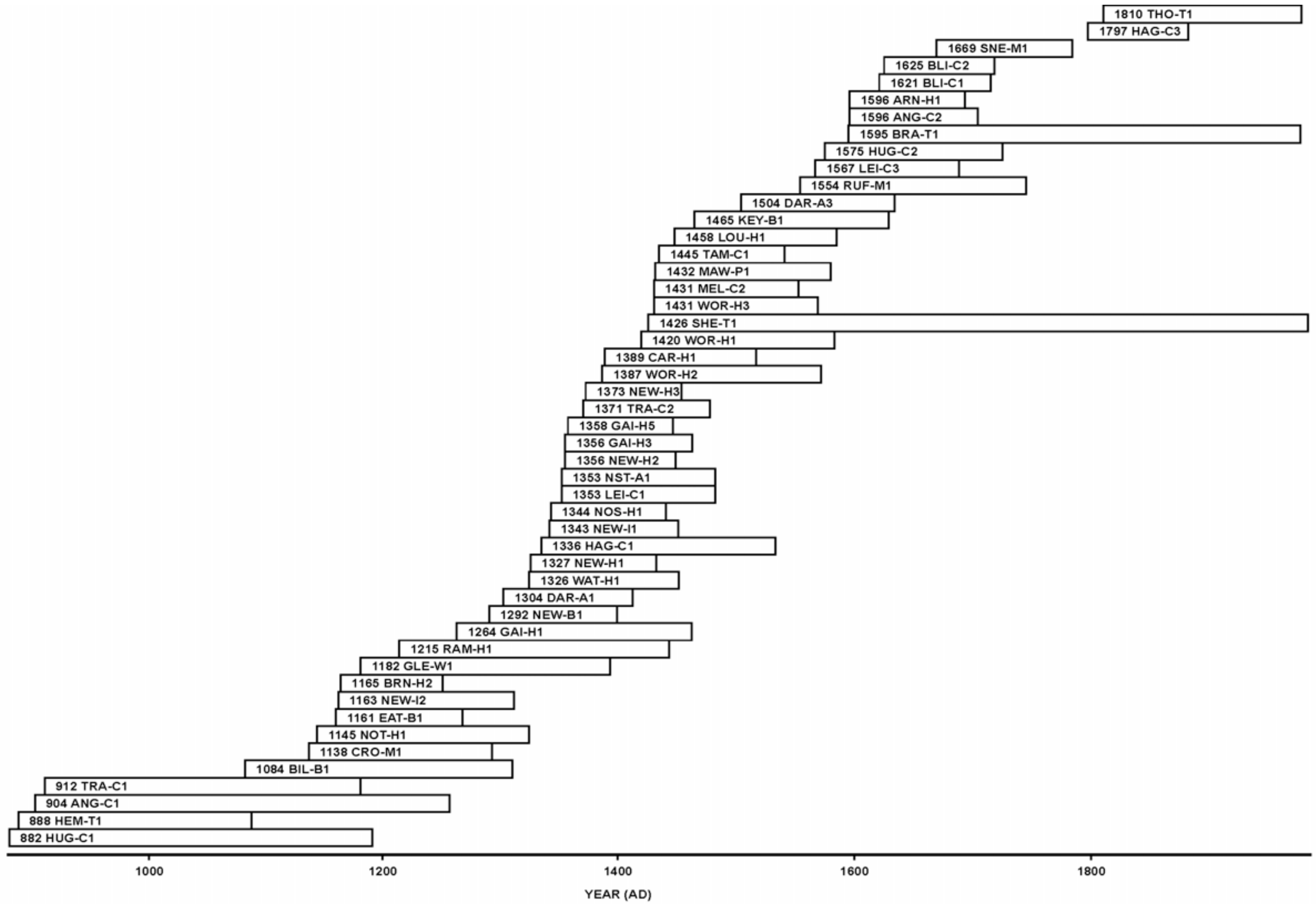
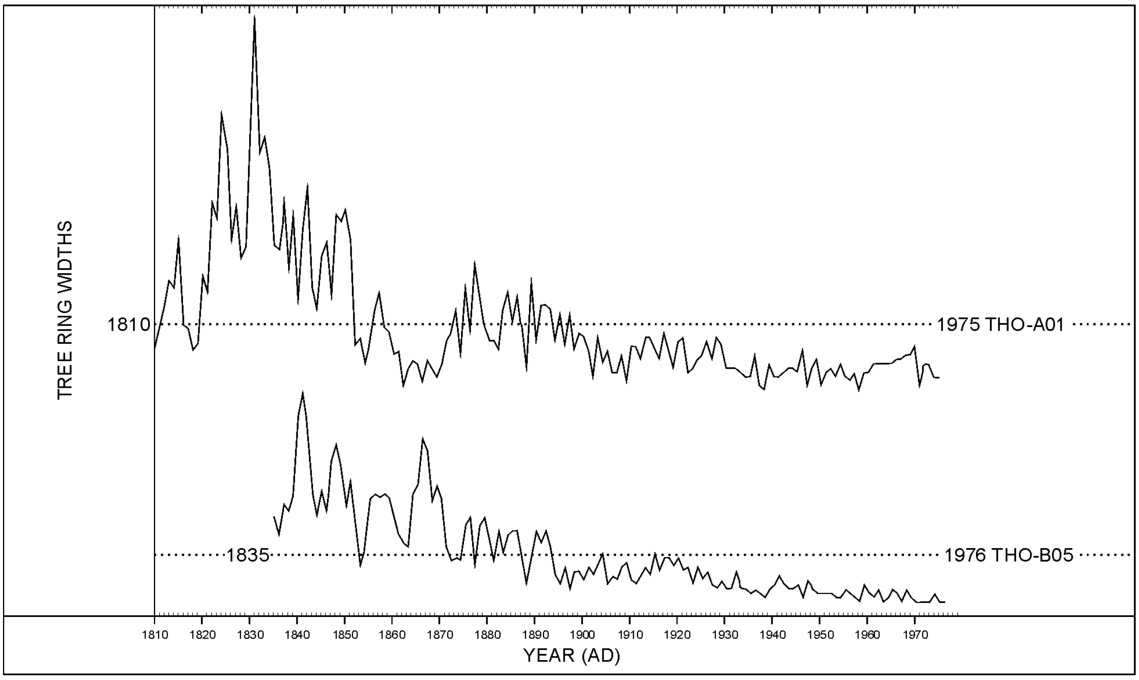


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

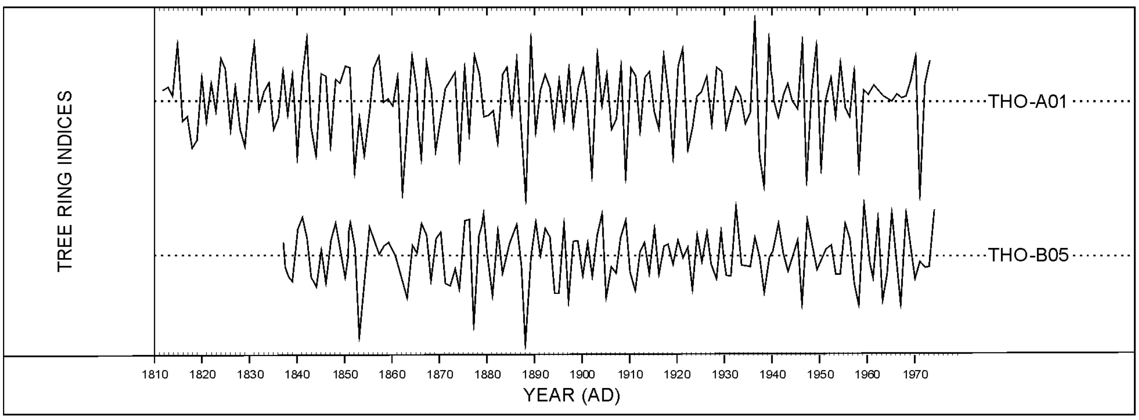


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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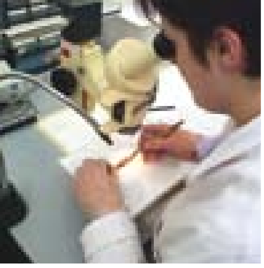
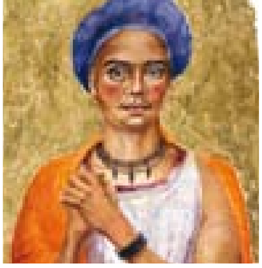



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