Research Department Report Series 37/2006

Tree-Ring Analysis of Timbers from Abbey House, Whitby Abbey, Whitby, North Yorkshire

Alison Arnold, Robert Howard, Cliff Litton, and Cathy Tyers

ISSN 1749-8775

The Research Department Report Series, incorporates reports from all the specialist teams within the English Heritage Research Department: Archaeological Science; Archaeological Archives; Historic Interiors Research and Conservation; Archaeological Projects; Aerial Survey and Investigation; Archaeological Survey and Investigation; Architectural Investigation; Imaging, Graphics and Survey, and the Survey of London. It replaces the former Centre for Archaeology Reports Series, the Archaeological Investigation Report Series, and the Architectural Investigation Report Series.

Many of these are interim reports which make available the results of specialist investigations in advance of full publication. They are not usually subject to external refereeing, and their conclusions may sometimes have to be modified in the light of information not available at the time of the investigation. Where no final project report is available, readers are advised to consult the author before citing these reports in any publication. Opinions expressed in Research Department reports are those of the author(s) and are not necessarily those of English Heritage.

Research Department Report Series 37/2006

Tree-Ring Analysis of Timbers from Abbey House, Whitby Abbey, Whitby, North Yorkshire

Alison Arnold, Robert Howard, Cliff Litton, and Cathy Tyers

Summary

A total of 27 cores samples was obtained from timbers of Abbey House at Whitby Abbey, North Yorkshire. Twelve of these samples were from pine timbers forming the roof of the main range, while a further ten samples came from pine timbers forming the roof of a short connecting range between the main range and the Banqueting Hall. Five samples were obtained from oak timbers in the ground floor of the main range.

The analysis of these samples produced four pine site chronologies, comprising one group of seven samples and three groups of two samples each. These site chronologies range in length from 63 rings to 135 rings. Despite being compared to an extensive range of reference chronologies for pine none of the pine site chronologies could be dated.

There was no cross-matching between any of the oak samples and attempts to cross-match them individually with oak reference chronologies produced no satisfactory results. This analysis forms part of the on-going dendrochronological research programme on conifer timbers funded by English Heritage.

Keywords

Dendrochronology
Standing Building

Authors' Addresses

Robert Howard: Nottingham Tree-Ring Dating Laboratory, 20 Hillcrest Grove, Sherwood, Nottingham, NG5 1FT. Telephone: 0115 9603833. Email:roberthoward10@hotmail.com

Cliff Litton: Department of Mathematics, University of Nottingham, University Park, Nottingham, NG7 2RD. Telephone: 0115 951 4960. Email:cdl@maths.nottingham.ac.uk

Alison Arnold: Nottingham Tree-Ring Dating Laboratory, 20 Hillcrest Grove, Sherwood, Nottingham, NG5 1FT. Telephone: 0115 9603833. Email:alisonjarnold@hotmail.com

Cathy Tyers: Sheffield Dendrochronology Laboratory, Archaeological Research School, University of Sheffield, West Court, 2 Mappin St, Sheffield, S1 4DT. Telephone: 0114 276 3146. Email: c.m.groves@sheffield.ac.uk

Introduction

The Abbey at Whitby, built, it is believed, upon the site of a possible Roman signal station, was founded in AD 657 by St Hilda, abbess of Hartlepool, following a vow by King Oswy after his victory over Penda, King of Mercia in AD 655. The abbey, which was for men as well as women, soon gained an international reputation, and it was here in AD 664 that the Synod was held at which the two branches of early English Christianity, the Celtic and Roman churches, debated the dating of Easter. The Synod decided in favour of the Roman tradition. This first abbey was destroyed by Danish raiders in AD 867.

The re-establishment of an abbey at Whitby, along with its monastic building, was undertaken in the late-eleventh century during the pilgrimage of Aldwin of Winchcombe, and of Elfwy and Reinfred from Evesham. So great were the numbers of pilgrims visiting the abbey that by the early-thirteenth century the Romanesque church had become inadequate and the building of a new abbey was started. It is the remains of this abbey that now stand as a spectacular ruin, imposing and stark, on its windswept hilltop overlooking the town at the mouth of the river Esk and North Sea below.

Although mostly ruinous, there are a few intact buildings remaining within the abbey grounds. In particular a group to the south-east of the Abbey form what is known as 'Abbey House', which stands, supposedly, on the site of the prior's kitchen (NZ 903 112, Figures 1 and 2). This substantial range was built after the Dissolution of the monasteries by Richard Chomley, between AD 1583 – 93, and rebuilt or remodelled by the first Sir Hugh Chomley between AD 1633 – 6. Between AD 1672 – 82 the second Sir Hugh Chomley added the large Banqueting Hall in front of, or to the north of, the original range. Some time later, the exact date is uncertain, a short cross-wing range was built connecting the original and later buildings at their western ends. Abbey House is Grade I listed building.

Sampling

Sampling and analysis by tree-ring dating of timbers from two ranges of Abbey House were commissioned by English Heritage, the initial purpose of this being to inform listed building consent. These parts of the building have until recently been used by Countrywide Holidays and were undergoing archaeological recording as part of a lottery bid to convert the building into a youth hostel. There are no plans under this scheme for any works to the Banqueting Hall range, and thus no request for tree-ring sampling of timbers in this area. The assessment ascertained that the timbers associated with the roofs of these two ranges were conifers. An English Heritage funded research project is currently investigating the viability of dendrochronological analysis of conifer timbers imported into England. Consequently as the roof timbers were considered a potentially valuable source of data this site was incorporated into the research programme.

Of particular interest to this programme of analysis are the timbers of the east – west orientated main range, and those of the short connecting range at the west end of the main range which link it to the Banqueting Hall. Within the roof of the main range are a series of what appear to be principal rafter with collar trusses (the apexes of the trusses and any common rafters are hidden from view behind or above a closed ceiling), there being at least one purlin, though sometimes two purlins, to each slope. An illustrative example of a truss is given in Figure 3a. These trusses are made of pine (*Pinus* spp.), and given the possibility that they may date to the post-Dissolution construction phase, would represent an unusual example of the early use of such timber in England.

The basement of the main range also contains a small number of oak (*Quercus* spp.) timbers. These too could date to the late-sixteenth century construction phase but there is a possibility that they might represent the reuse of earlier material from one of the Abbey's construction phases.

Also of interest to this analysis are the roof timbers of the short north – south range connecting the main house and the Banqueting Hall. The roof here comprises four 'half'-trusses, each composed of a single principal rafter supported by a diagonal strut rising from a short 'tiebeam'. The half-trusses are set against a vertical wall at their 'inner' end. An illustration of a truss from this roof is shown in Figure 3b. These timbers are again of pine and are believed to date to some time in the eighteenth century.

From this material a total of 27 core samples were obtained. Each sample obtained was given the code WIT-B (for Whitby, site 'B') and numbered 01 – 27. Twelve samples, WIT-B01 – B12, were obtained from the pine roof of the main range, with a further ten samples, WIT-B13 – B22, being obtained from the pine timbers of the connecting range. Five samples, WIT-B23 – B27, were obtained from the oak timbers of the basement.

The positions of these samples are marked on plans provided by English Heritage or made at the time of sampling. These are reproduced here as Figures 4a – d. All the pine roof timbers appeared to form composite roof-trusses and as such all appeared to be integral to each other, all being jointed and pegged. The oak timbers of the basement, on the other hand, are probably separate timbers, there being no pegged joints visible between them. Details of the samples are given in Table 1. In this Table, all frames or trusses, and individual timbers, are identified and numbered from either north to south, or from east to west, as appropriate.

The Laboratory would like to take this opportunity to particularly thank Craig and Sarah Pattinson, managers of the adjacent Youth Hostel for their help, hospitality, and interest during sampling. We would also like to thank Dr Adam Menuge, Senior Investigator and Team Leader of English Heritage's Yorkshire region who helped interpret the possible phasing of the roofs. Various dendrochronologists from Scandinavia and countries around the Baltic Sea have kindly either carried out cross-dating procedures or made reference data available. Reference data has also been obtained from the International Tree-Ring Data Bank based in Boulder, Colorado, funded by the National Geophysical Data Center (part of the World Data Center). Tim Lawrence (Kew Gardens), Rowena Gale (wood anatomist), and Alex Wiedenhoeft (Center for Wood Anatomy Research, Wisconsin, USA) provided valuable advice concerning the identification of pine species.

Analysis

Each of the 27 samples obtained was prepared by sanding and polishing. It was seen at this time that six samples, WIT-B01, B02, B05, B09, B10, and B13, all pine samples, had less than the minimum of 54 rings required for reliable tree-ring dating and all such short samples were rejected from the programme of analysis. The annual growth-ring widths of the remaining 21 samples were, however, measured, the data of these measurements being given at the end of the report.

The growth-ring widths of all 16 measured pine samples were compared with each other by the Litton/Zainodin grouping procedure (see appendix) in one sub-set programme of analysis, the growth-ring widths of the five measured oak samples being compared with each other as a separate sub-set. The species were analysed separately as the oaks are likely to have been obtained from a local woodland source, where as the pines are likely to have been imported. At a minimum value of t=4.5, four groups of cross-matching pine samples, accounting for 13 measured pine samples, could be formed, (there being no satisfactory cross-matching between any of the oak samples).

The cross-matching samples of each group were then combined at their indicated positions to form site chronologies WITBSQ01 – SQ04. The relative positions of the constituent samples in these four site chronologies are shown in the bar diagrams, Figures 5 – 8. Each pine site chronology was compared with the other three, and with the remaining three measured but ungrouped pine samples. There was, however, no further satisfactory cross-matching.

Taking into account the expected date of the two roofs under investigation, it was anticipated that they were most likely to be imported from northern Europe. Documentary evidence relating to importation of conifers implies that the main range roof timber is likely to be Scandinavian origin where as the connecting range roof is most likely to be either Scandinavian or Baltic region origin (eg Groves 2000; Groves 2004). Each of the four pine site chronologies plus the remaining individual measured but ungrouped pine samples was therefore compared with an extensive range of European pine reference chronologies. There was however, no satisfactory cross-matching. Consequently the site master chronologies were also compared with reference chronologies from Canada and the north-eastern area of the United States of America, but again no consistent conclusive results were obtained. The data from the four site chronologies were sent to various colleagues for further comparisons to be made but, despite these exhaustive checks, no consistent results were obtained for any of the ring sequences, and thus the dendrochronological analysis has been unable to provide precise calendar dates for any of the timbers.

The oak samples were also compared individually with an extensive series of reference chronologies from both the British Isles and, taking into account the presence of imported pine, elsewhere in Europe but again there was no satisfactory cross-matching. These samples must also remain undated.

Conclusion

Analysis by dendrochronology has produced four pine site chronologies, one of seven samples and three of two samples each. Despite being compared to an extensive range of reference chronologies both the pine material from the roofs, and the oak material from the ground floor, remains undated.

Pine samples

The failure to produce reliable dendrochronological dates for any of the pine timbers from either of roofs is clearly disappointing, particularly in the light of the recent successes with various conifer assemblages (Groves 2002; Groves and Locatelli 2005; Arnold *et al* forthcoming). This could be the result of the use of timber from multiple diverse sources but intra-site cross-matching, at least for the connecting range roof, suggests this is unlikely to be the case (see below). Intra-site cross-matching, particularly for the main range roof, is likely to have been adversely affected by the relative shortness of the rings sequences. All samples from this roof have less than 90 rings. A significant percentage of timbers from successfully analysed sites have far more than 100 rings and indeed at 107 Jermyn Street it was noticeable that none of the samples analysed which had less than 100 rings were successfully dated (Groves and Locatelli 2005). The site chronologies produced are all relatively short and none are particularly well-replicated thus reducing the chances of successful dating. However as the conifer research project progresses and reference data becomes more extensive it may prove possible to provide dates for the Whitby Abbey material.

Despite the lack of dating it is noticeable that of the four site chronologies created from the Whitby material, the one with the most samples is made up of entirely of material from the roof of the connecting range. This would suggest that all the timbers used in this element of

Abbey House are from the same locality or woodland. Judging by the similarity of the relative positions of the heartwood/sapwood boundaries it is likely that these timbers were all felled at the same time, and that this roof is, as might be suspected from the structural evidence, of one phase of construction.

The material from the main range produces less satisfactory internal cross-matching, with three groups of two samples each being formed of this material. As noted above this could possibly be due to the samples from this roof having low numbers of rings (Table 1). This prevents the dendrochronological analysis confirming or refuting whether the timbers used represent a single phase of construction.

Whilst there are clear differences between the groups of pine timbers of the two roofs which could be taken as further evidence that they do indeed represent different phases of construction, the lack of conclusive dating evidence means that, from a dendrochronological perspective, this remains unproven.

Oak samples

The lack of cross-matching and dating amongst the oak timbers is again possibly due in some cases to low numbers of rings, and also, according to the actual date of the material, possibly due to insufficient relevant reference material. Given that there is little evidence for jointing between some of these timbers, and that they are possibly reused, it is possible that each timber has a different felling date and is from a different place. While single samples can on occasion be dated individually, it is often more difficult than with a group of cross-matching timbers where the data is well replicated.

Bibliography

Arnold, A J, Howard, R E, and Tyers, C, forthcoming *Dendrochronological analysis of conifer timbers from Millers House and House Mill, Three Mills Lane, Bromley by Bow, London*, English Heritage Res Dept Rep Series, **-**

Groves, C, 2000 Belarus to Bexley and beyond: dendrochronology and dendroprovenancing of conifer timbers, *Vernacular Architect*, **31**, 59–66

Groves, C, 2002 *Dendrochronological Analysis of Conifer Timbers from Danson House and Danson Stables, Bexley, Kent*, Centre for Archaeol Rep, **69/2002**

Groves, C, 2004 *Dendrochronological Analysis of Conifer Timbers from the Giltspur Street Compter, City of London (KEW98)*, Centre for Archaeol Rep, **20/2004**

Groves, C and Locatelli, C, 2005 *Tree-Ring Analysis of Conifer Timbers from 107 Jermyn Street, City of Westminster, London*, Centre for Archaeol, **67/2005**

Table 1: Details of samples from Whitby Abbey, Whitby, North Yorkshire

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Main range roof timbers (pine)					
WIT-B01	East principal rafter, truss 3	nm	---	------	------	------
WIT-B02	West principal rafter, truss 3	nm	---	------	------	------
WIT-B03	Collar, truss 3	71	h/s	------	------	------
WIT-B04	West purlin, truss 3 – 4	84	h/s	------	------	------
WIT-B05	East purlin, truss 3 – 4	nm	---	------	------	------
WIT-B06	East principal rafter, truss 2	63	h/s	------	------	------
WIT-B07	Collar, truss 2	62	h/s	------	------	------
WIT-B08	East purlin, truss 1 – 2	64	h/s	------	------	------
WIT-B09	West purlin, truss 2 – 3	nm	---	------	------	------
WIT-B10	West principal rafter, truss 5	nm	---	------	------	------
WIT-B11	West purlin, truss 4 – 5	63	h/s	------	------	------
WIT-B12	West purlin, truss 6 – 7	87	h/s	------	------	------
	Connecting range roof timbers (pine)					
WIT-B13	Strut, truss 1	nm	---	------	------	------
WIT-B14	Principal rafter, truss 1	100	h/s	------	------	------
WIT-B15	Purlin, truss 1 – 2	127	h/s	------	------	------
WIT-B16	Strut, truss 2	114	h/s	------	------	------
WIT-B17	Principal rafter, truss 2	116	h/s	------	------	------
WIT-B18	Purlin, truss 3 – 4	126	h/s	------	------	------

Table 1: continued

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	Connecting range roof continued					
WIT-B19	Principal rafter, truss 3	113	no h/s	------	------	------
WIT-B20	Strut, truss 3	100	h/s	------	------	------
WIT-B21	Principal rafter, truss 4	63	no h/s	------	------	------
WIT-B22	Strut, truss 4	79	no h/s	------	------	------
	Main range ground-floor timbers (oak)					
WIT-B23	East wall plate	87	22	------	------	------
WIT-B24	West wall plate	73	21	------	------	------
WIT-B25	North west corner post	105	h/s	------	------	------
WIT-B26	West support post	62	h/s	------	------	------
WIT-B27	Central bridging beam	139	11	------	------	------

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

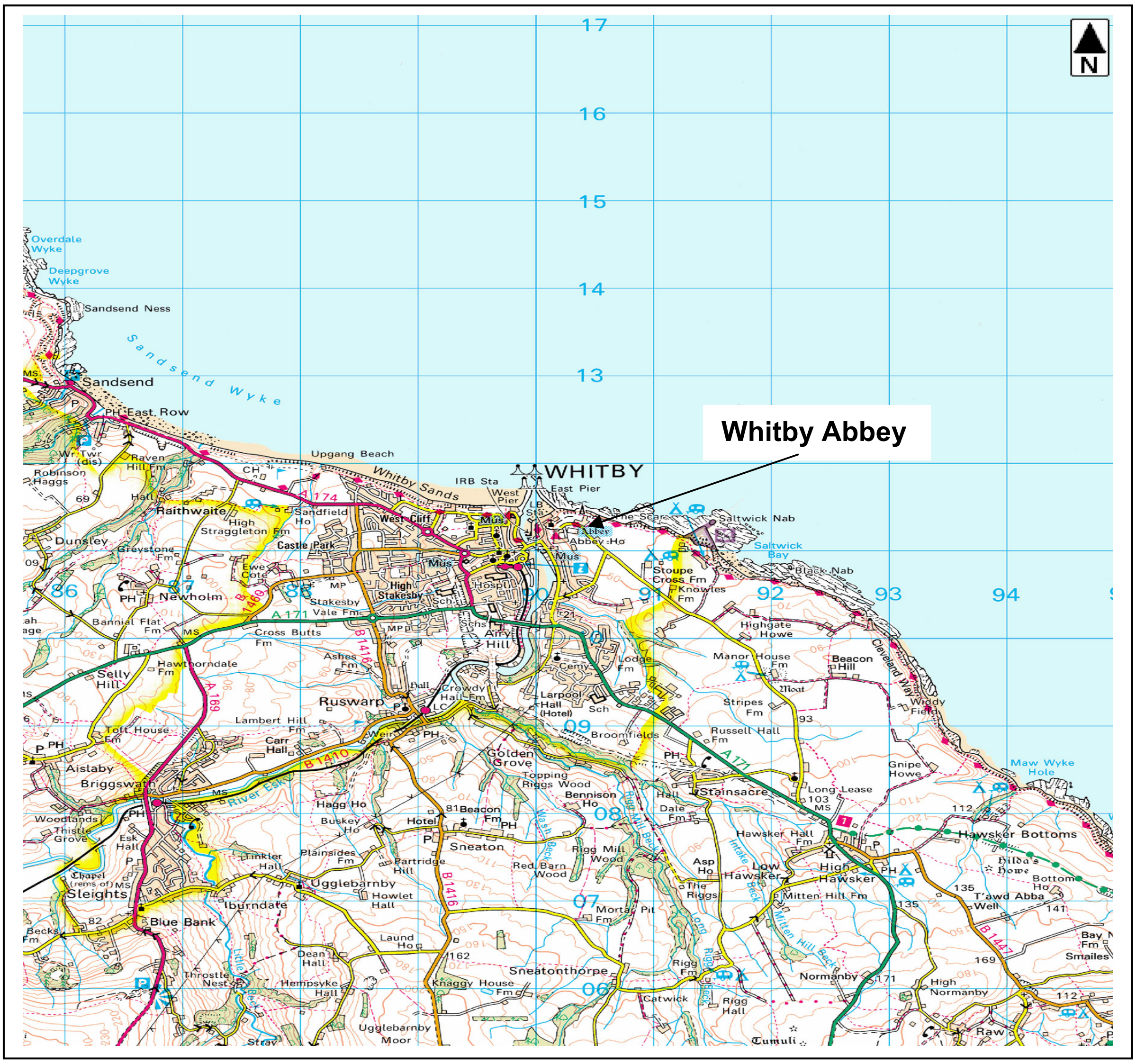


Figure 1: Map to show general location of Whitby Abbey

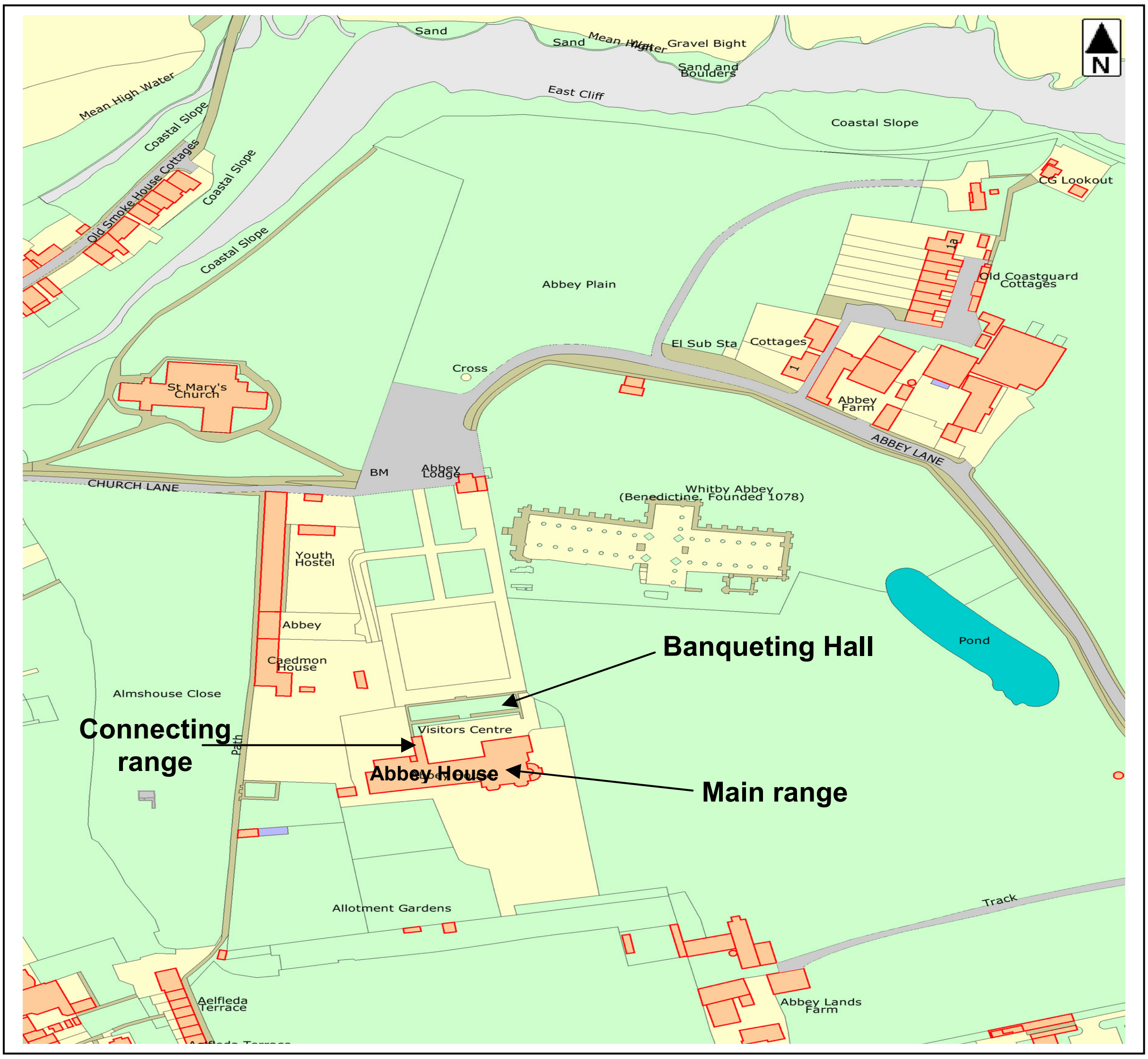


Figure 2: Map to show location of Abbey House within the Abbey precincts

Figure 3a (top): View of a truss from the roof of the main range

Figure 3b (bottom): View of a truss from the roof of the connecting range

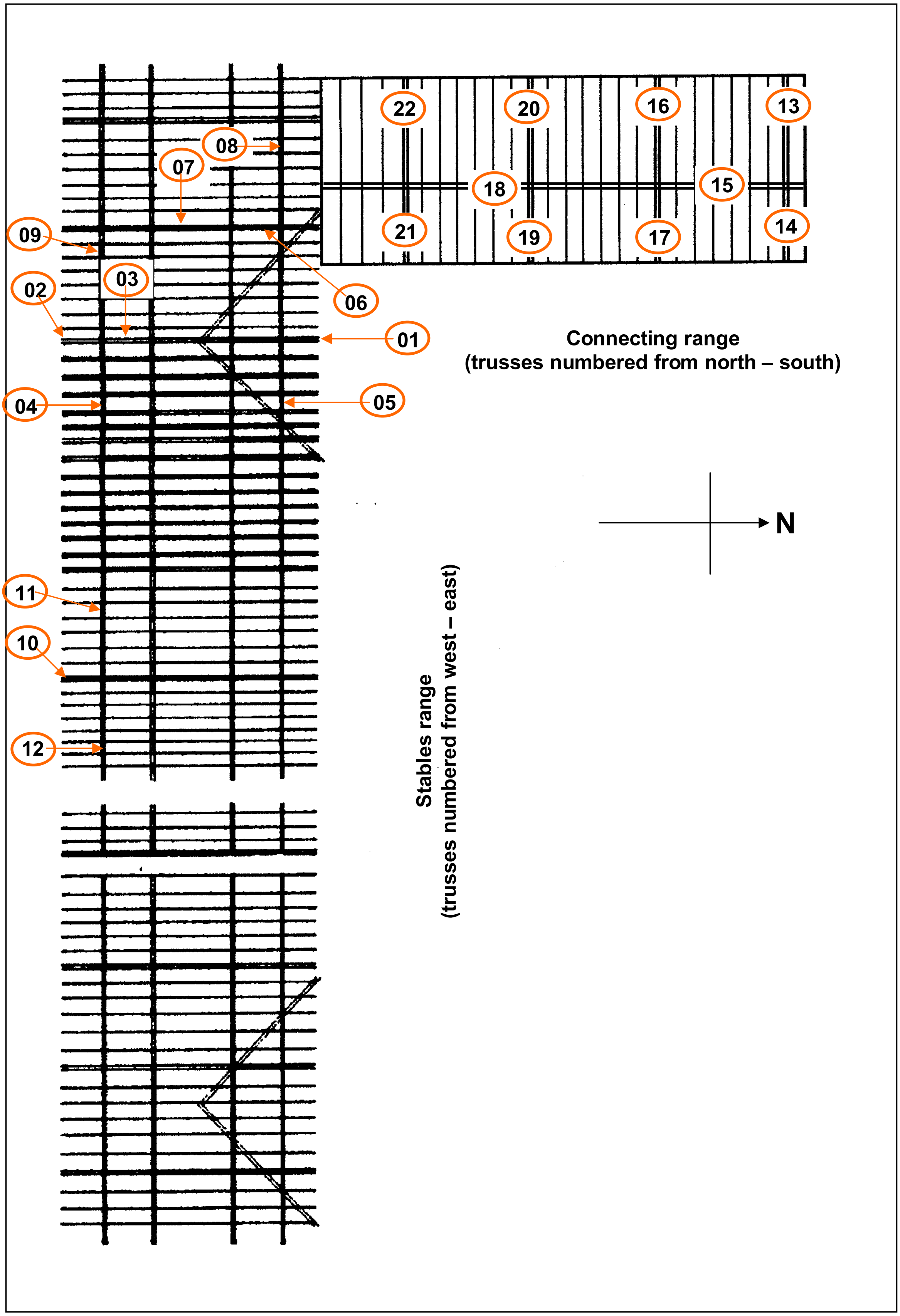
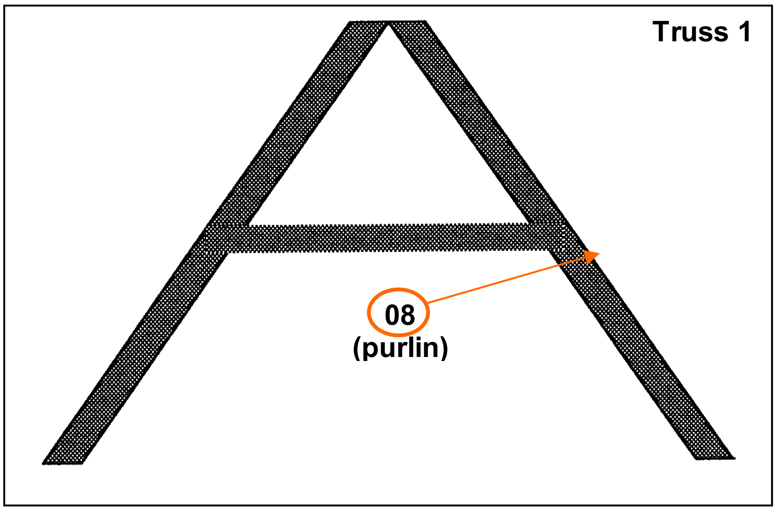
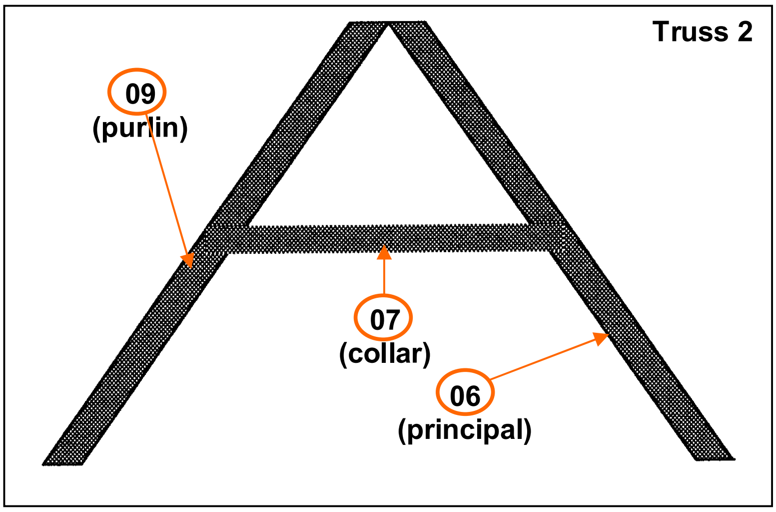


Figure 4a: Plan to show location of samples from the roofs of the main and connecting ranges





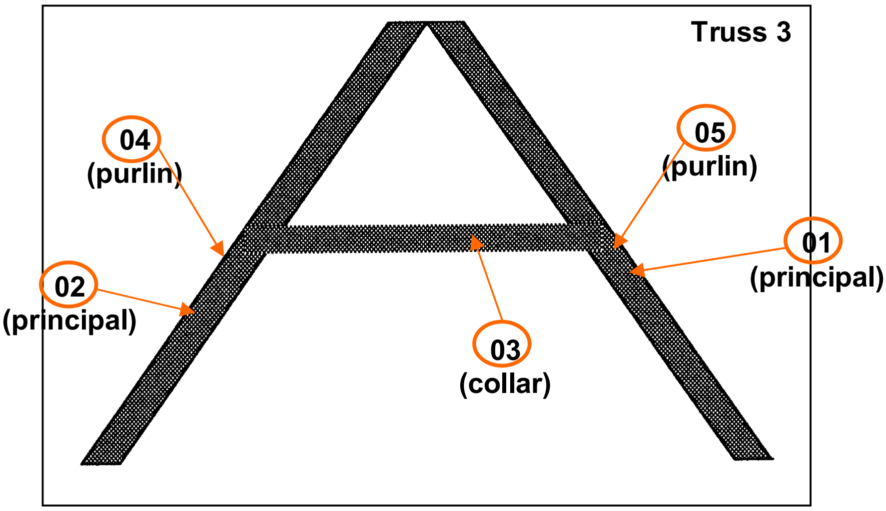
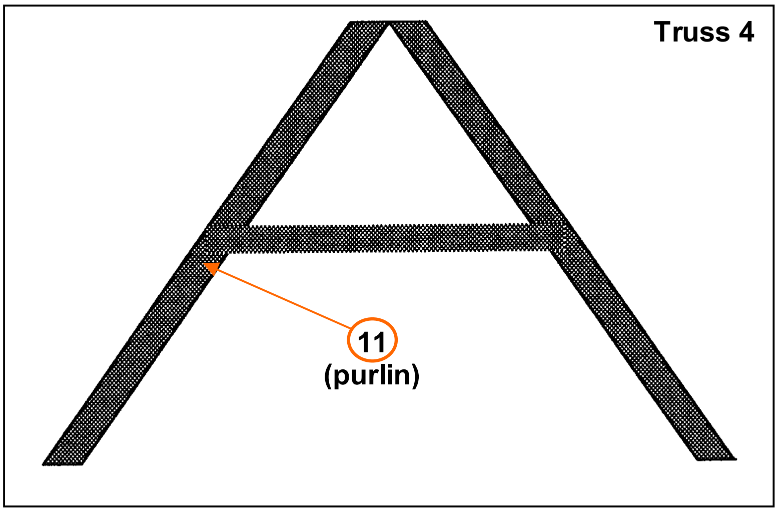
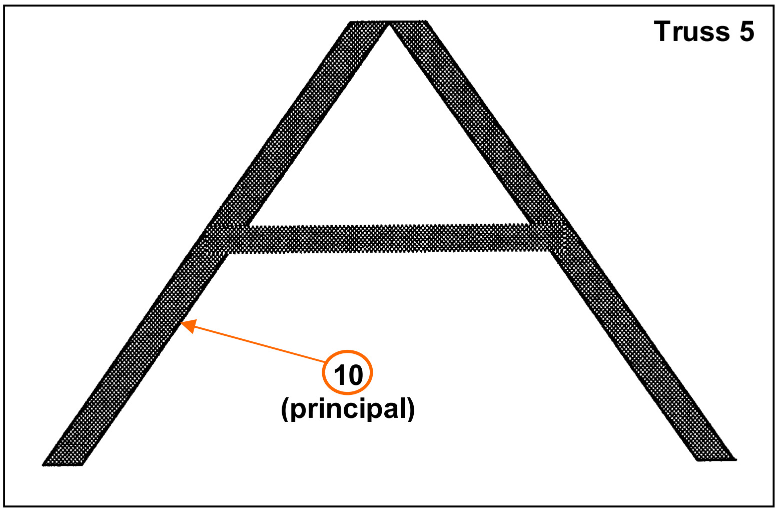


Figure 4bi: Main or stables range roof trusses to show sample locations (viewed from east looking west)





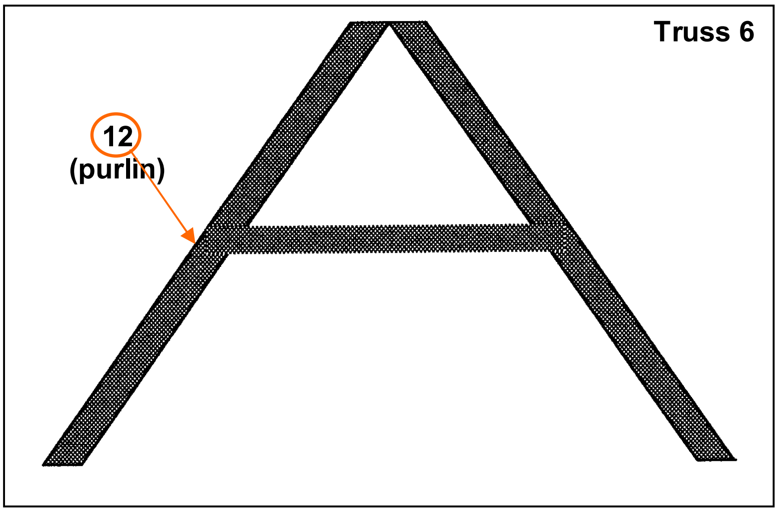


Figure 4bii: Main or stables range roof trusses to show sample locations (viewed from east looking west)

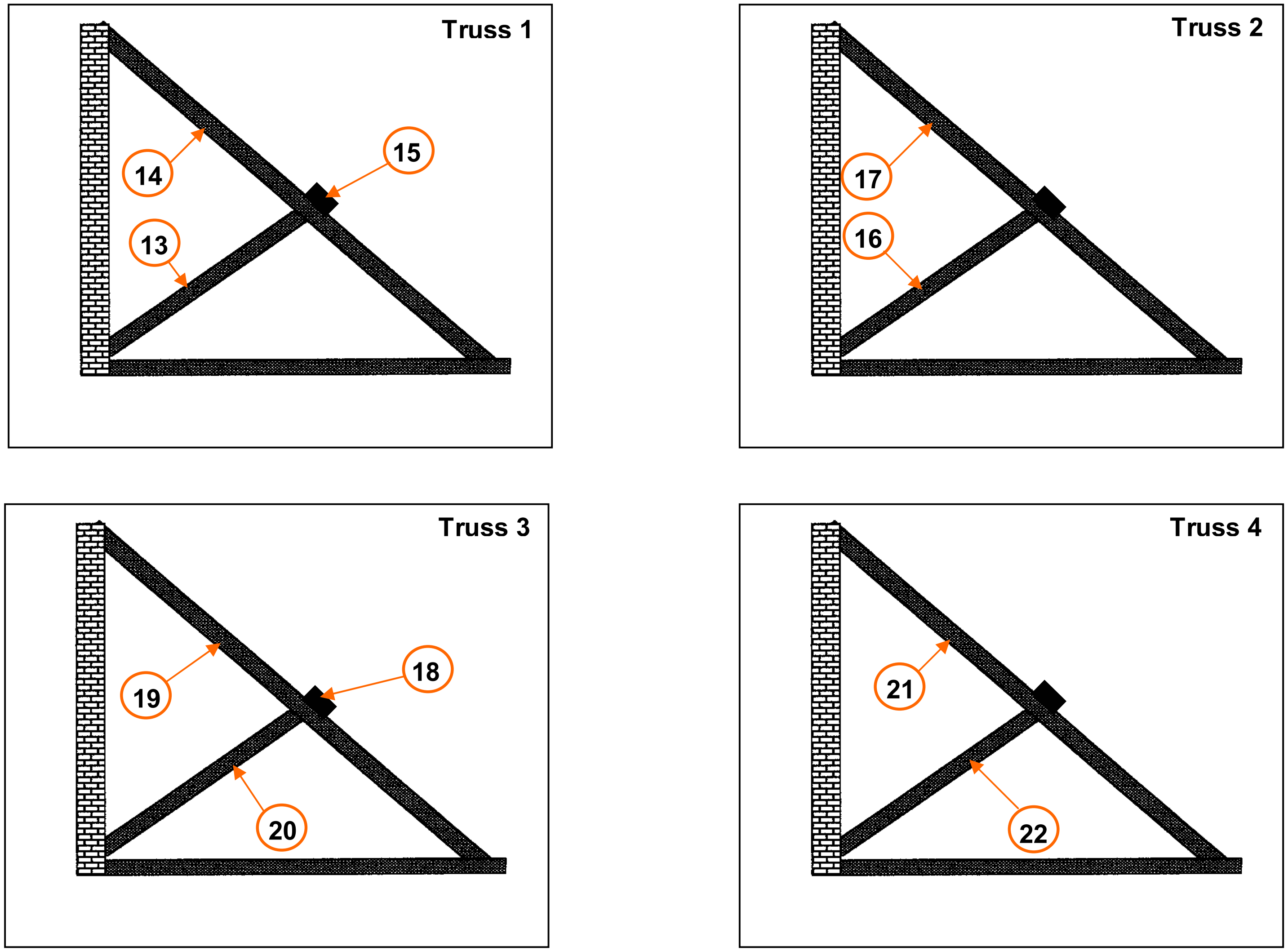


Figure 4c: Roof trusses of the connecting range showing sample positions (trusses viewed from the south looking north)

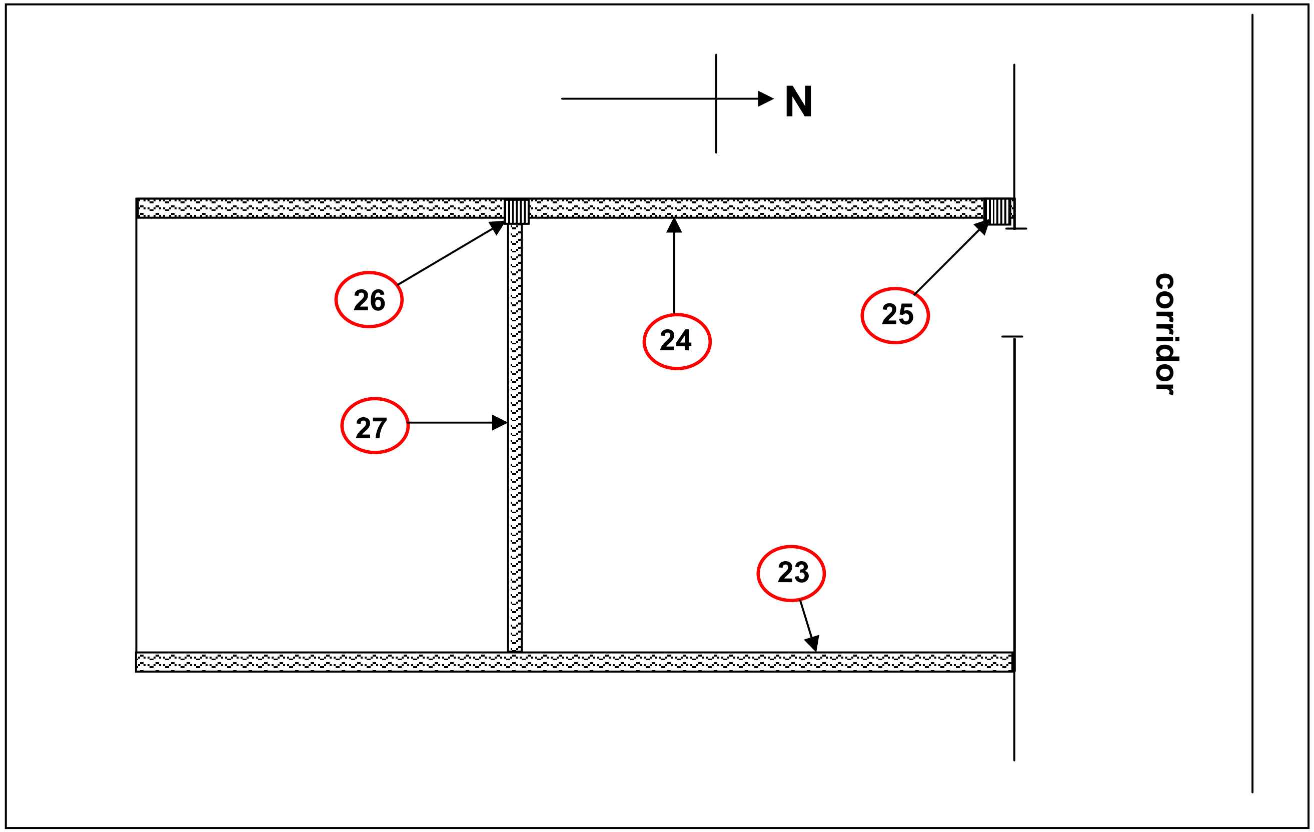


Figure 4d: Plan of the basement to show location of samples from the oak timbers

Figure 5: Bar diagram of the samples in site chronology WITBSQ01

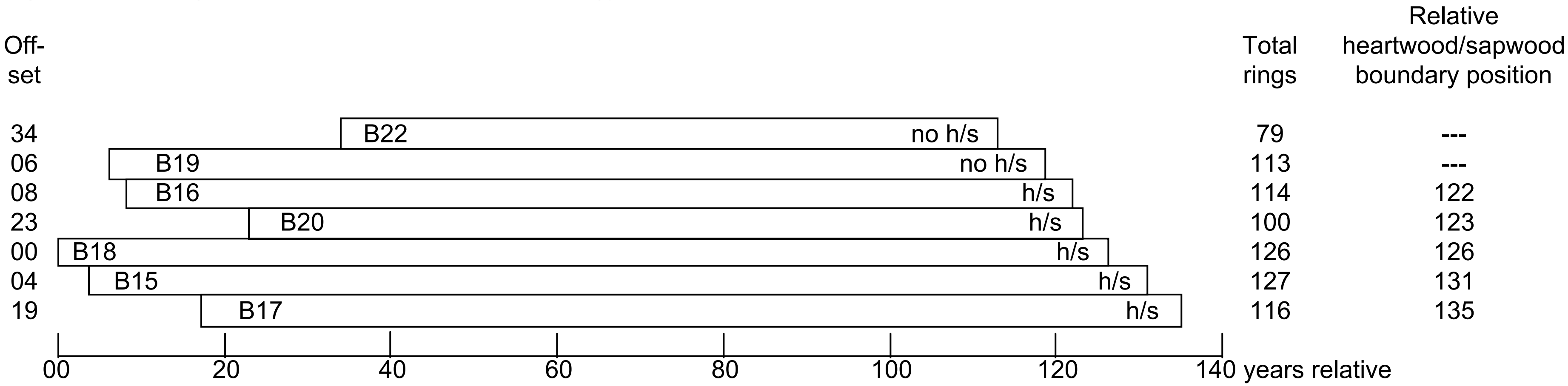
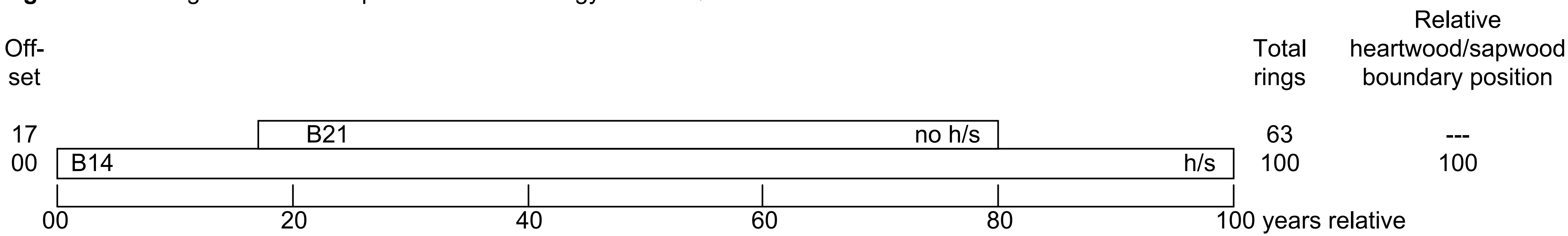


Figure 6: Bar diagram of the samples in site chronology WITBSQ02



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

Figure 7: Bar diagram of the samples in site chronology WITBSQ03

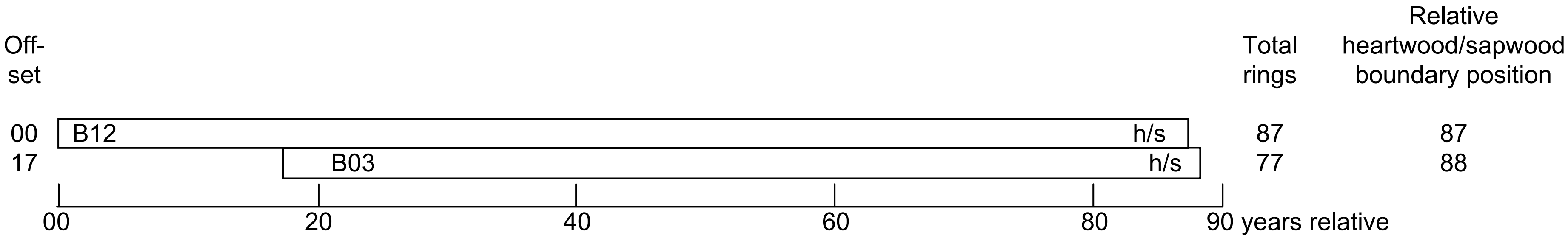
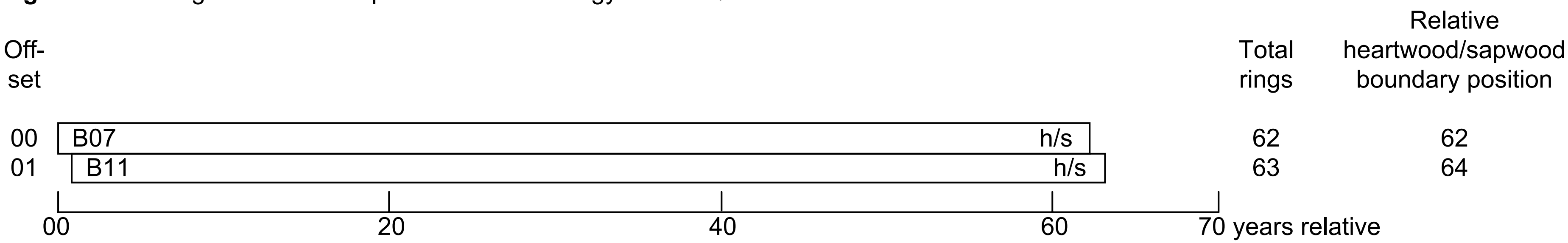


Figure 8: Bar diagram of the samples in site chronology WITBSQ04



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

Data of measured oak samples – measurements in 0.01 mm units

WIT-B23A 87
246 159 348 160 100 192 149 169 285 232 161 160 217 166 203 188 195 182 202 171
159 159 137 95 66 38 48 38 59 69 90 138 120 109 134 123 104 99 133 100
90 93 99 125 110 132 114 137 101 109 125 122 125 150 135 74 80 72 125 104
103 107 121 152 125 80 110 161 124 94 82 80 106 90 94 93 85 90 87 48
63 45 58 52 77 58 78
WIT-B23B 87
285 148 329 223 140 213 142 185 295 228 172 155 219 173 192 189 193 176 206 195
147 163 149 89 62 41 43 38 57 66 90 148 102 122 135 129 109 102 123 107
96 90 110 110 130 124 110 151 107 109 128 118 127 169 123 100 63 76 107 109
130 92 129 152 113 97 102 139 115 118 82 84 116 95 97 88 88 92 55 60
74 48 64 55 72 57 80
WIT-B24A 73
183 220 248 215 148 162 149 271 252 254 196 151 91 74 98 161 214 167 176 128
89 134 122 139 164 251 196 189 167 159 220 194 147 146 181 160 126 89 116 176
149 142 135 128 150 210 185 156 170 224 212 260 211 179 176 147 120 128 148 192
169 213 176 159 201 181 144 144 112 132 160 110 135
WIT-B24B 73
195 213 237 241 250 144 146 265 250 287 186 151 66 81 81 160 206 158 167 121
89 121 144 160 191 291 166 191 148 189 227 193 145 138 205 157 124 103 114 190
157 150 133 143 149 223 169 177 167 235 212 232 208 158 188 157 125 118 125 217
176 205 174 161 193 171 154 143 106 138 152 115 140
WIT-B25A 105
165 188 251 240 169 136 85 107 141 132 165 142 122 130 111 123 132 117 40 40
24 44 55 61 61 85 89 125 82 97 93 55 55 83 93 64 112 114 91 96
114 93 79 57 44 22 47 97 88 117 135 94 118 69 40 72 89 80 107 124
162 152 200 213 182 145 154 83 54 121 179 162 133 131 156 107 127 76 60 77
48 57 74 61 63 65 102 83 92 45 52 114 142 141 123 211 169 84 41 60
54 73 118 162 126
WIT-B25B 105
174 192 252 245 171 146 89 104 145 135 160 141 124 139 110 115 169 49 45 51
30 48 65 63 41 98 92 77 102 117 104 45 59 85 94 73 116 113 105 92
124 72 92 55 34 36 42 89 88 108 104 114 105 85 51 80 90 78 85 145
159 155 201 218 204 189 170 85 61 127 197 157 149 118 158 106 133 71 60 74
56 55 76 56 69 60 103 60 79 60 44 84 133 128 133 207 169 91 43 37
52 88 126 164 126
WIT-B26A 62
433 513 361 478 321 199 120 251 255 242 379 246 294 106 163 172 230 188 147 204
91 216 120 117 96 100 79 44 26 36 55 49 59 64 45 115 139 167 154 103
90 99 128 147 166 140 179 207 107 83 149 180 141 150 125 132 131 136 123 164
167 152
WIT-B26B 62
426 517 350 496 326 206 117 252 255 240 380 236 296 122 157 167 243 192 146 217
104 217 115 136 81 114 53 53 31 41 45 62 65 51 55 95 144 158 160 99
93 96 131 155 163 132 194 203 106 100 145 164 160 137 151 119 136 97 121 170
171 156

WIT-B27A 139
54 61 60 61 84 69 87 90 102 137 91 107 155 112 111 135 59 116 78 53
50 83 81 73 74 103 83 75 83 105 143 100 122 118 95 85 134 101 105 117
101 164 78 113 134 95 58 86 100 133 151 132 118 159 106 146 145 120 103 153
84 72 107 68 114 53 38 83 116 91 139 99 97 106 123 105 112 125 103 116
136 119 90 139 99 105 124 132 100 107 113 95 105 103 81 66 106 89 75 130
73 86 92 82 78 44 53 56 91 89 86 104 118 134 94 85 97 78 86 97
120 111 61 63 88 130 79 92 73 73 98 79 99 126 116 102 91 71 64
WIT-B27B 139
63 59 78 56 94 73 82 91 95 137 132 95 157 119 114 128 61 110 89 57
70 93 61 84 74 116 80 70 107 96 139 104 118 96 126 102 145 115 100 117
110 177 86 126 138 95 57 90 95 133 157 149 107 155 121 140 139 125 118 145
84 91 100 86 106 59 43 76 127 83 137 102 94 101 133 104 105 138 86 116
155 113 97 130 97 109 143 123 84 118 106 111 84 111 82 85 101 89 69 124
79 90 86 71 65 64 44 60 85 82 93 100 107 136 78 88 81 84 97 99
126 107 60 73 77 123 98 74 74 84 100 86 89 130 113 108 92 69 82

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 1 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 1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction 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 2 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 to 10 samples per phase are usually taken. Sometimes we take many more, especially if the construction is complicated. One reason for taking so many samples is that, in general, some will fail to give a date. There may be many reasons why a particular sequence of ring widths from a sample of timber fails to give a date even though others from the same building do. For example, a particular tree may have grown in an odd ecological niche, so odd indeed that the widths of its rings were determined by factors other than the local climate! In such circumstances it will be impossible to date a timber from this tree using the master sequence whose widths, we can assume, were predominantly determined by the local climate at the time.

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure 2; it is about 15cm long and 1cm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost 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 1: A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can determined by counting back from the outside ring, which grew in 1976.

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

Figure 3: Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measure 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 4: Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical.

2. ***Measuring Ring Widths***. Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure 2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig 3).

3. ***Cross-matching and Dating the Samples***. Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig 4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t-value* (defined in almost any introductory book on statistics). That offset with the maximum *t*-value among the *t*-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a *t*-value of at least 4.5, and preferably 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 5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN-C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the *bar-diagram*, as is usual, but the offsets at which they best cross-match each other are shown; eg 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 5. 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 5 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 straight forward 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. Actually it could be the year after if it had been felled in the first three months before any new growth had started, but this is not too important a consideration in most cases. The actual bark may not be present on a timber in a building, though the dendrochronologist who is sampling can often see from its surface that only the bark is missing. In these cases the date of the last ring is still the date of felling.

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called *sapwood* rings, are usually lighter than the inner rings, the *heartwood*, and so are relatively easy to identify. For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure 2, 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 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 2 was taken still had complete sapwood but that none of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 2 cm, 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 and Miles 1997, 50-55). Hence provided 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, figure 8 and pages 34-5 where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storing 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 Fig 6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Fig 6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (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 Fig 7. 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 phenomena 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

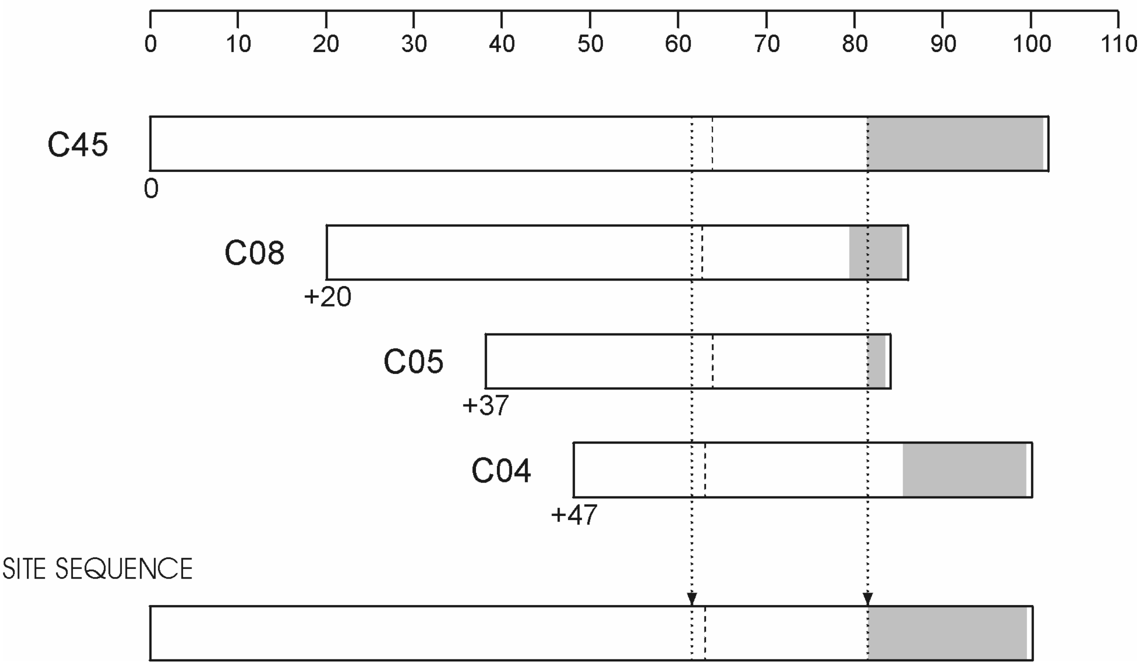


Figure 5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

The *bar diagram* represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (*offsets*) to each other at which they have maximum correlation as measured by the *t*-values.

The *t*-value/offset matrix contains the maximum *t*-values below the diagonal and the offsets above it. Thus, the maximum *t*-value between C08 and C45 occurs at the offset of +20 rings and the *t*-value is then 5.6.

The *site sequence* is composed of the average of the corresponding widths, as illustrated with one width.

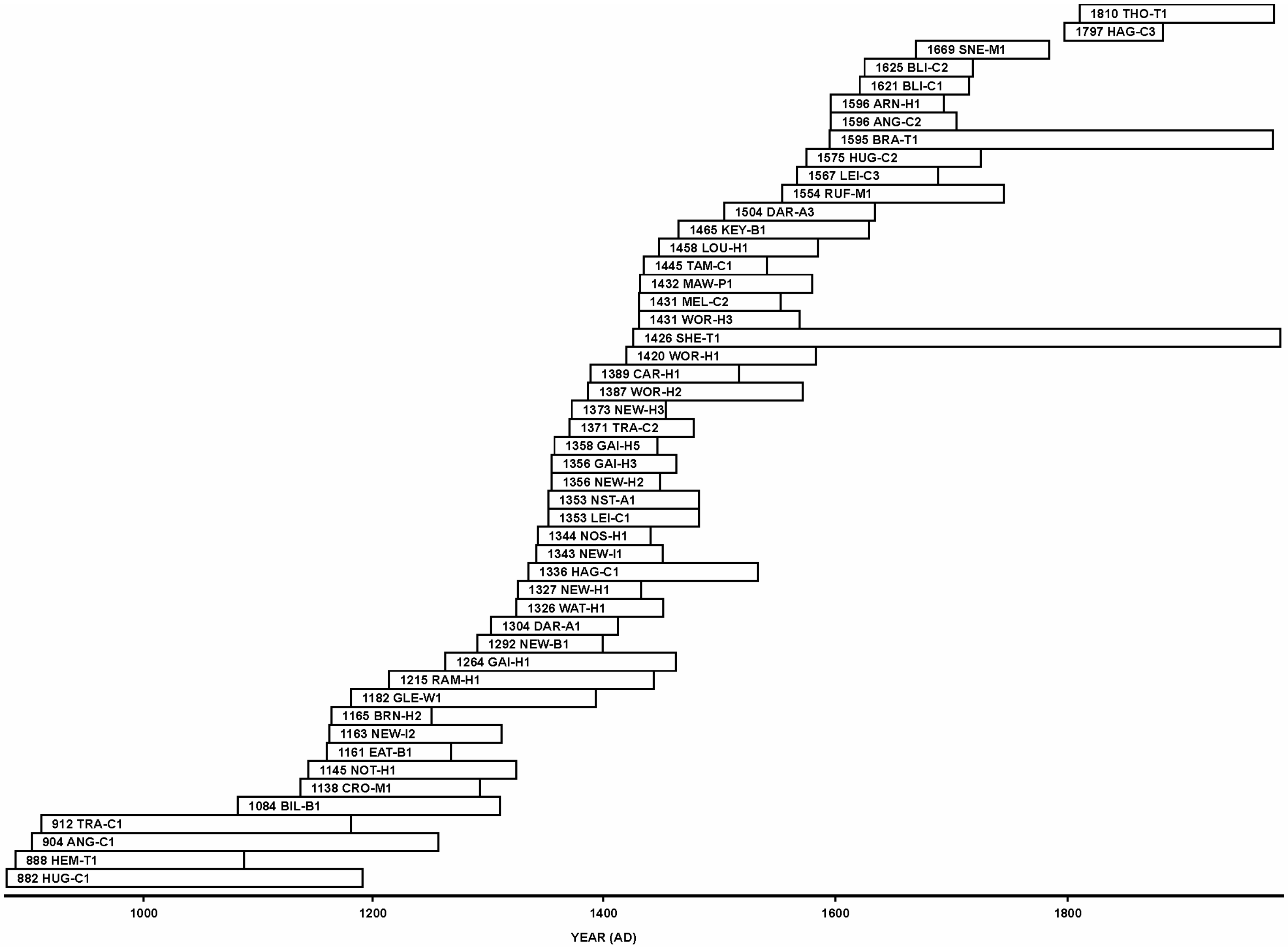
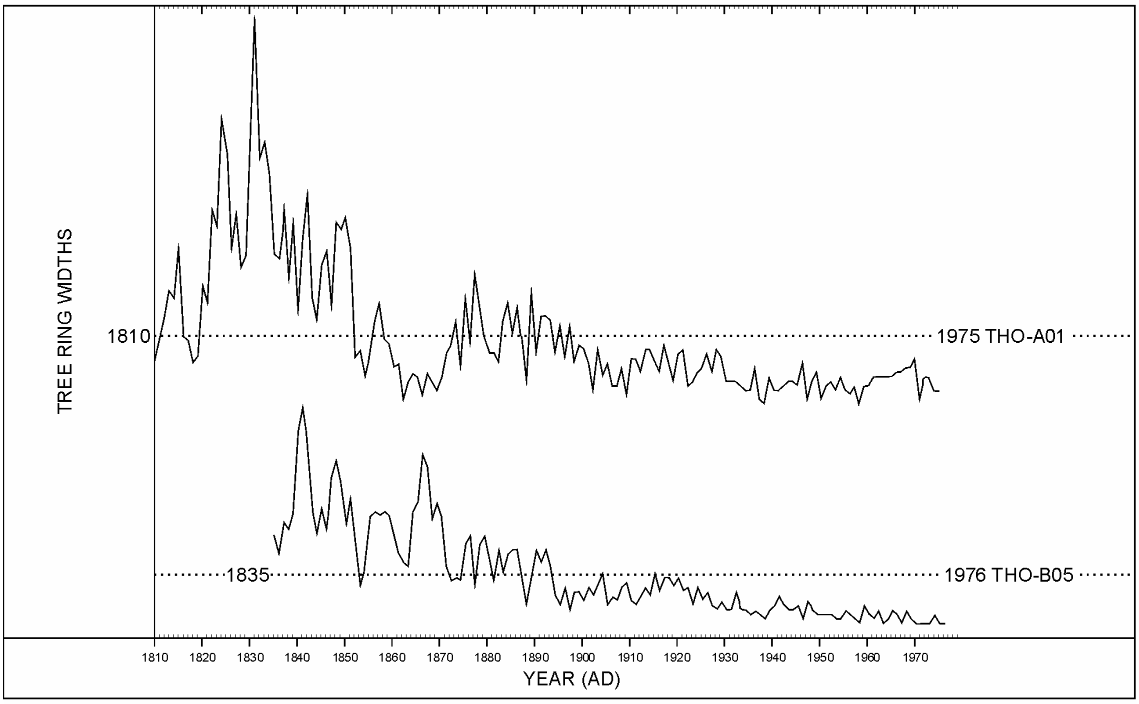


Figure 6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

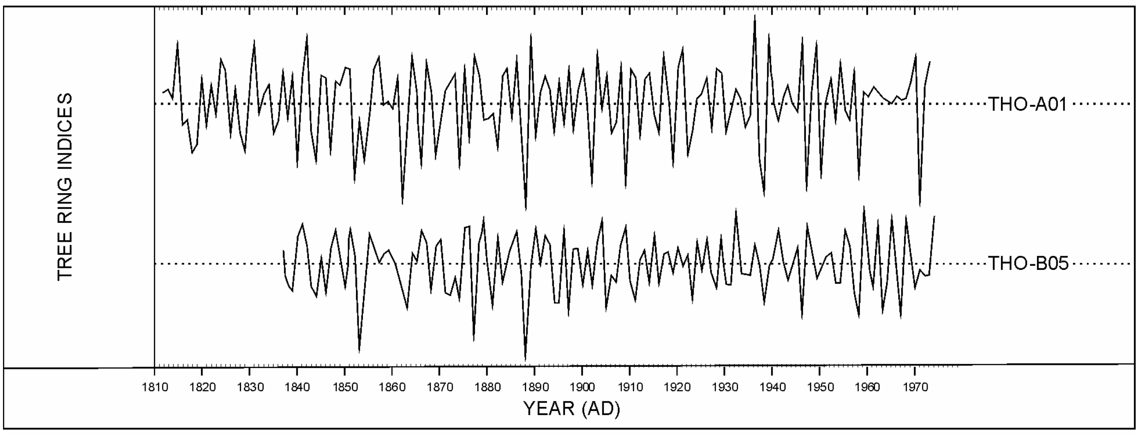


Figure 7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young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

Figure 7 (b): The *Baillie-Pilcher* indices of the above widths. The growth-trends have been removed completely.

REFERENCES

Baillie, M G L, and Pilcher, J R, 1973, A simple cross-dating program for tree-ring research, *Tree-Ring Bulletin*, **33**, 7-14

English Heritage, 1998 *Dendrochronology; Guidelines on Producing and Interpreting Dendrochronological Dates*, London

Hillam, J, Morgan, R A, and Tyers, I, 1987, Sapwood estimates and the dating of short ring sequences, *Applications of tree-ring studies*, BAR Int Ser, **3**, 165-85

Howard, R E, Laxton, R R, Litton, C D, and Simpson, W G, 1984-95, Nottingham University Tree-Ring Dating Laboratory Results, *Vernacular Architecture*, **15-26**

Hughes, M K, Milson, S J, and Legett, P A, 1981 Sapwood estimates in the interpretation of tree-ring dates, *J Archaeol Sci*, **8**, 381-90

Laxon, R R, Litton, C D, and Zainodin, H J, 1988 An objective method for forming a master ring-width sequence, *P A C T*, **22**, 25-35

Laxton, R R, and Litton, C D, 1988 *An East Midlands Master Chronology and its use for dating vernacular buildings*, University of Nottingham, Department of Archaeology Publication, Monograph Series III

Laxton, R R, and Litton, C D, 1989 Construction of a Kent Master Dendrochronological Sequence for Oak, AD 1158 to 1540, *Medieval Archaeol*, **33**, 90-8

Laxon, R R, Litton, C D, and Howard, R E, 2001 *Timber; Dendrochronology of Roof Timbers at Lincoln Cathedral*, English Heritage Research Transactions, **7**

Litton, C D, and Zainodin, H J, 1991 Statistical models of Dendrochronology, *J Archaeol Sci*¸**18**, 29-40

Miles, D W H, 1997 The interpretation, presentation and use of tree-ring dates, *Vernacular Architecture*, **28**, 40-56

Pearson, S, 1995 *The Medieval Houses of Kent, An Historical Analysis*, London

Rackham, O, 1976 *Trees and Woodland in the British Landscape*, London