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KENWOOD HOUSE, HAMPSTEAD LANE, LONDON BOROUGH OF CAMDEN
TREE-RING ANALYSIS OF TIMBERS FROM WOOD POND

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

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Summary

Seven samples were taken from timbers recovered during works undertaken to strengthen the dam between Wood Pond and Thousand Pound Pond. Three of these samples contained recurring bands of very narrow rings which prevented accurate measurement. Dendrochronological analysis was undertaken on the remaining three oak samples and one conifer sample. This resulted in two of the oak samples grouping and being combined to form KENHSQ01, a site sequence of 90 rings.

Attempts to date KENHSQ01, the ungrouped oak sample, and the conifer sample were unsuccessful, and all timbers remain undated.

Keywords

Dendrochronology
Watching Brief

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Introduction

During work being undertaken to strengthen the western face of the eighteenth-century dam between Wood Pond and Thousand Pound Pond at Kenwood House, London (TQ27218719; Figs 1 and 2), contractors discovered a substantial timber structure. During the course of this strengthening work a number of timbers were removed, although others were left *in situ*. An elm water pipe was encountered and also removed. English Heritage, which has guardianship of the property, commissioned the Museum of London Archaeology Service (MoLAS) to undertake an archaeological watching brief to assess and record the *ex-situ* timbers and to observe the continuing works, assessing and recording any further discoveries.

The timbers

The *in-situ* timbers were found on the western edge of the bank or dam between Wood Pond and Thousand Pound Pond, and are thought to form part of the base of the structure from which the *ex-situ* timbers had been removed, which started within the bank or dam between the ponds and extended westwards into Wood Pond. The timbers noted are thought to be elements of two diagonally-braced trusses set on horizontal sill beams. Several of these *ex-situ* timbers appear to be in pairs of similar pieces, and it is thought that some of them would have been joined together. These timbers were divided into two groups of structural elements, designated 'Assemblies' A and B. 'Assembly A' (Fig 3) had been fixed to a sill beam, one of the *in-situ* timbers noted during the watching brief. The matching assembly, 'Assembly B' (Fig 4), had presumably been attached to a second sill that was not seen, but is thought to also remain *in-situ*. The timbers which had been removed from the structure were pit-sawn and many had wood merchants' batch marks and/or carpenter's marks. This suggests a date most likely to be in the late seventeenth or eighteenth century.

Although the structure is thought to be seventeenth or eighteenth century in date, what purpose it served is uncertain. Various suggestions have been put forward for it. It may have been a sluice or other water-management structure, possibly removed during the AD 1750s when the grounds were landscaped for the first Lord Mansfield. Alternatively, it could be part of a folly or other structure built as part of this or later landscaping.

The elm water pipe was found 30 to 40m north of the *in-situ* timbers and may be part of a system connecting Wood Pond and Thousand Pound Pond, thought to potentially date to the late-eighteenth century. The timbers associated with it consist of a bored elm water pipe and two softwood stakes. The elm pipe is of a type relatively common in central London that dates from the sixteenth to the nineteenth century. The presence of conifer stakes also suggests a post-medieval date.

The above summary and details of the archaeological findings are taken from the report on the watching brief (Elsden and Goodburn 2006).

Tree-ring dating was commissioned and funded by English Heritage. It was hoped that the production of precise dating evidence for these timbers would assist in the interpretation of the structure.

Acknowledgements

The Laboratory would like to thank Damian Goodburn of MoLAS for sampling the timbers. Thanks are also given to MoLAS for allowing us to see their draft report from which the above site description and Figures 3 and 4 are taken (Elsden and Goodburn 2006). We would also like to thank Cathy Tyers of the English-Heritage-funded Sheffield University Dendrochronological Laboratory for her advice regarding the problematic samples and for her invaluable comments on early drafts of this report.

Sampling

Seven of the *ex-situ* timbers were sampled for dendrochronological analysis by MoLAS using a chainsaw. Each of these sliced samples have been given the code KEN-H (for Kenwood House) and numbered 01–07. Six of these samples were from oak timbers of Assemblies 'A' and 'B' (KEN-H01–06) with the seventh sample being from one of the softwood stakes related to the elm water pipe (KEN-H07). Further details relating to the samples can be found in Table 1.

Analysis and Results

Firstly, the samples were cut up into more manageable sections suitable for analysing under a microscope, *c* 50mm wide and *c* 50mm thick, before being frozen. Once completely frozen the samples were prepared using a woodworking plane and a scalpel. At this point it was seen that three of the oak samples (KEN-H03, KEN-H05, and KEN-H06) contained recurring bands of very narrow growth rings. Despite careful preparation, it was not possible to accurately determine the ring boundaries, so these samples were discarded prior to measurement. The growth-ring widths of the remaining three oak samples and the single conifer sample were then measured; the data of these measurements are given at the end of the report. The three oak samples were compared with each other by the Litton/Zainodin grouping procedure (see appendix).

At a least value of t=6.0, two samples matched each other and were combined at the relevant offset positions to form KENHSQ01, a site sequence of 90 rings (Fig 5). This site sequence was then compared against a series of relevant reference chronologies for oak but could not be matched, and thus remains undated. One of these samples (KEN-H01) has complete sapwood, with the last ring on the sample representing tree growth in the year the tree was felled. As this ring is 23 years earlier than the last measured ring on sample KEN-H04 (which has incomplete sapwood, and would have been felled 10–25 years after the date of its last measured ring), dendrochronology shows that these two timbers are from trees with significantly different felling dates.

Attempts to date the ungrouped oak sample, KEN-H02, and the single conifer sample, KEN-H07, were also unsuccessful, and these remain undated.

Discussion

The dendrochronological analysis has demonstrated that there are at least two different felling dates associated with the oak timbers from Assembly A and Assembly B. These separate fellings are several decades apart, but with such little dendrochronological evidence to go on it is not possible to say whether this means the structure incorporated reused timbers or was modified or repaired at some point during its lifetime. It is unfortunate that, in this instance, the dendrochronological analysis has been able to add so little to the overall interpretation of either the main structure or the system which the elm water pipe was associated with.

The inability to provide absolute dating evidence for any of the measured samples is likely to be due to a number of contributory factors. It is acknowledged that the longer and better replicated a site sequence is, the greater the chance for success, whatever the species. KENHSQ01 consists of only two timbers and is relatively short, whereas KEN-H02 and KEN-H07 are both unreplicated individual timber ring sequences.

Additionally, it may be that these timbers are from an area and/or period of history for which we do not have reference material against which to cross-match the samples. The availability of conifer reference chronologies from a relevant source region is in this instance probably better than that of native oak reference chronologies for this period and region. A further factor that is likely to have had a detrimental effect on the dating potential of the oak samples is the fact that they all show at least some disruption to their ring sequences, which will have the effect of masking the general climatic signal that is needed for successful dating. This was most marked in the oak samples that were rejected before measurement, which had suffered a series of periodic and severe growth retardation events. It seems more likely that these traumas are the result of non-climatic influences, potentially in the form of anthropogenic factors, such as woodland management regimes.

Bibliography

Elsden, N, J and Goodburn, D, M, 2006 *Wood Pond, Kenwood House, Hampstead Lane, London NW3 7JR: A report on the watching brief*, Museum of London Archaeology Service report

Table 1: Details of tree-ring samples from Wood Pond, Kenwood House, Hampstead Lane, London

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Oak samples 'Assembly A'						
KEN-H01	Major brace (timber 1)	67	20C	----	----	----
KEN-H02	Light pegged and nailed brace (timber 2)	72	13C	----	----	----
KEN-H03	Strut (timber 6)	NM	--	----	----	----
'Assembly B'						
KEN-H04	Major post (timber 4)	82	05	----	----	----
KEN-H05	Lapped and nailed brace (timber 5)	NM	--	----	----	----
KEN-H06	Major post (timber 7)	NM	--	----	----	----
Conifer sample Elm Water Pipe						
KEN-H07	Stake (timber 10)	116	56	----	----	----

*NM = not measured
C = complete sapwood retained on sample, last measured ring is the felling date

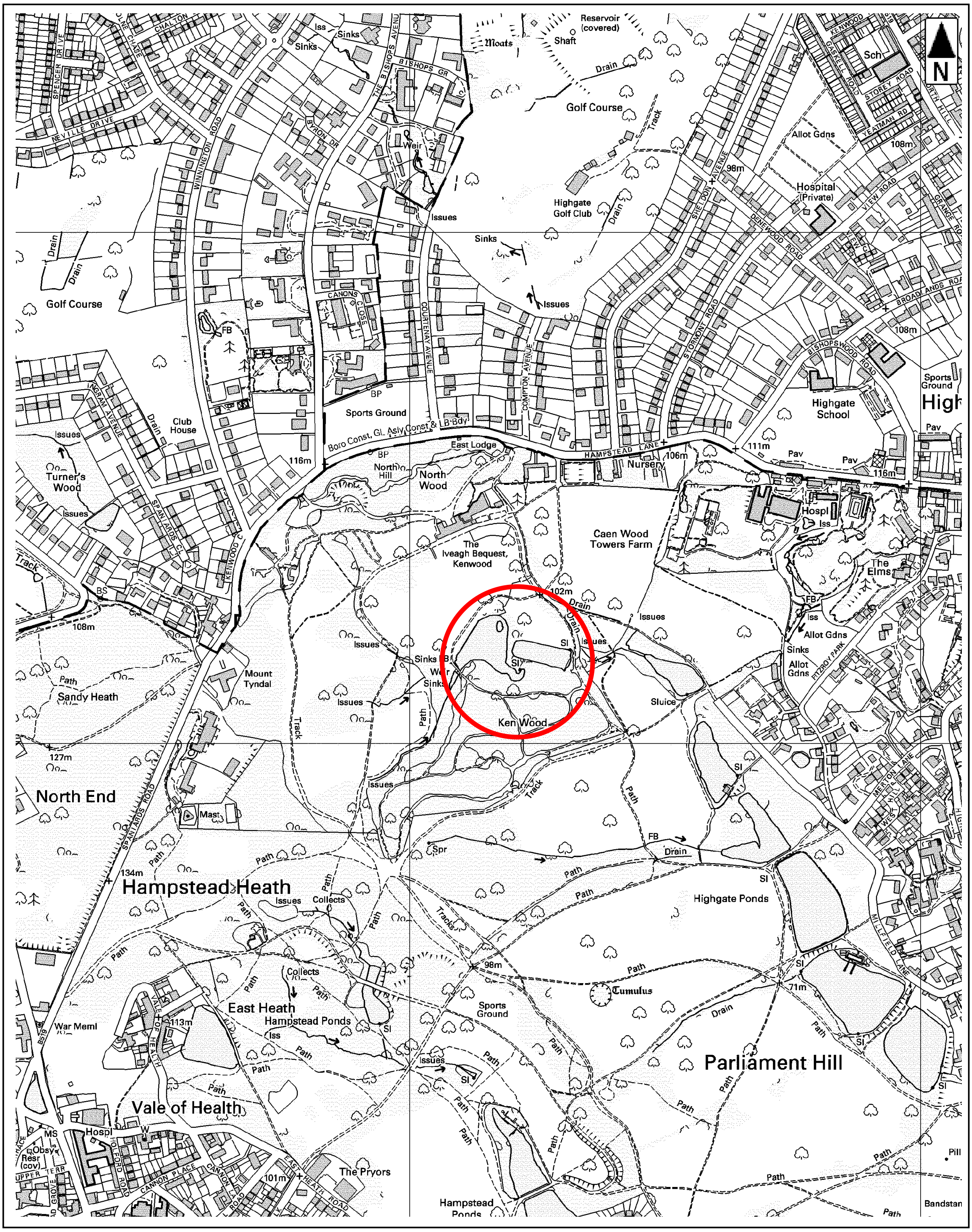


Figure 1: Map to show the location of the ponds (circled in red) within the surrounding area

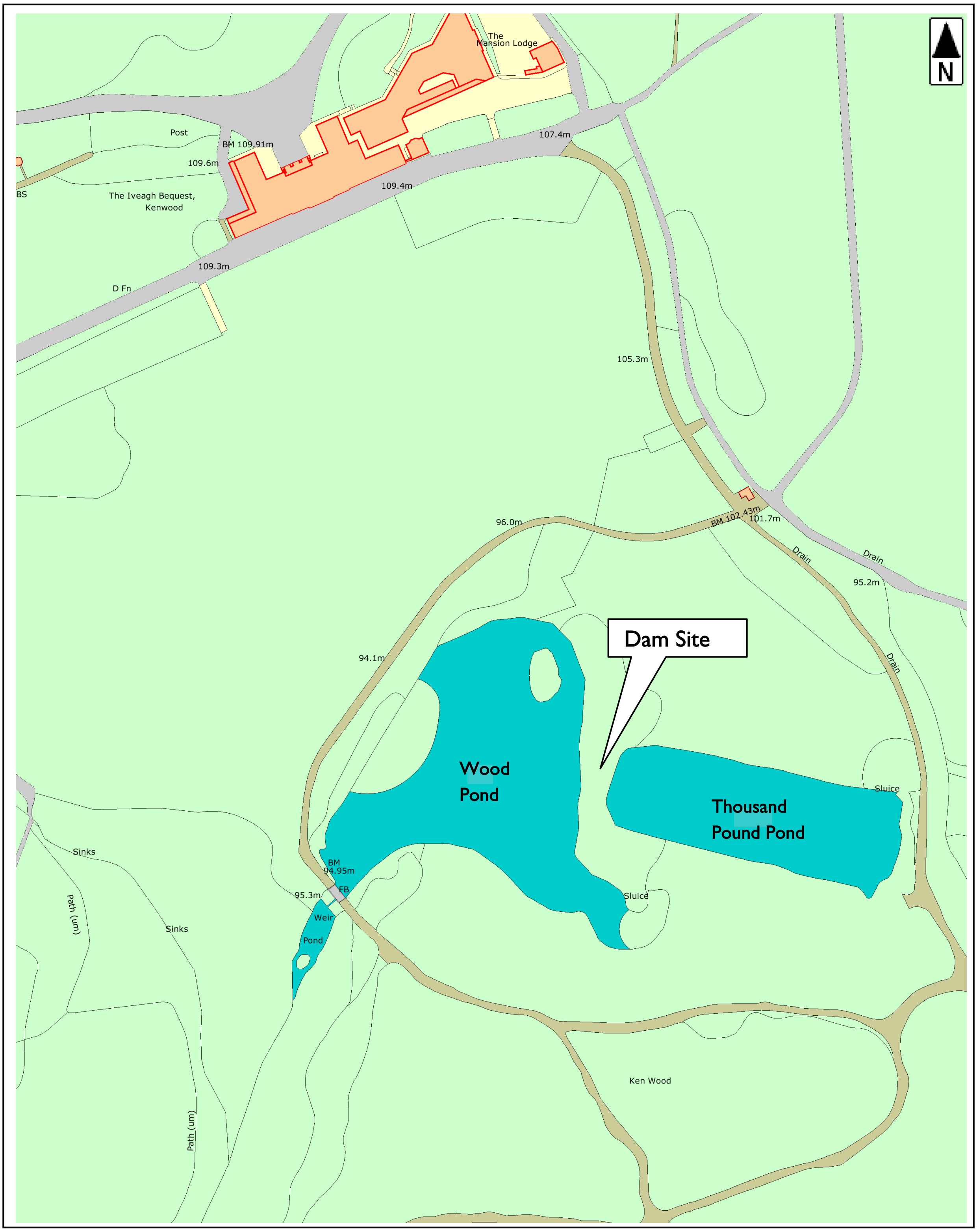


Figure 2: Map to show Wood and Thousand Pound Ponds the dam site

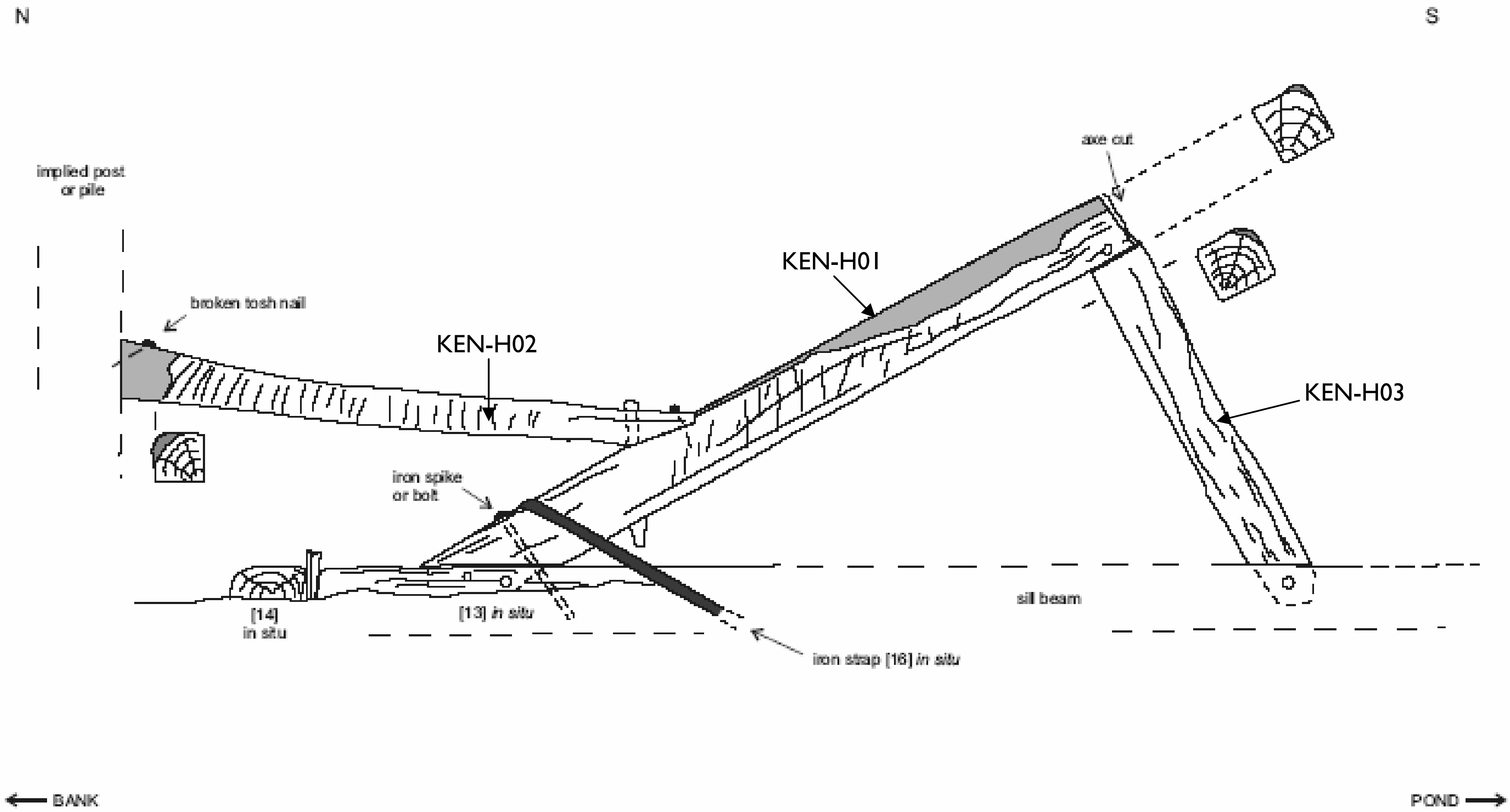


Figure 3: Reconstructed elevation of refitting timbers, forming 'Assembly A': part of a truss-like structure, showing the location of samples KEN-H01–3 (Elsden and Goodburn 2006)

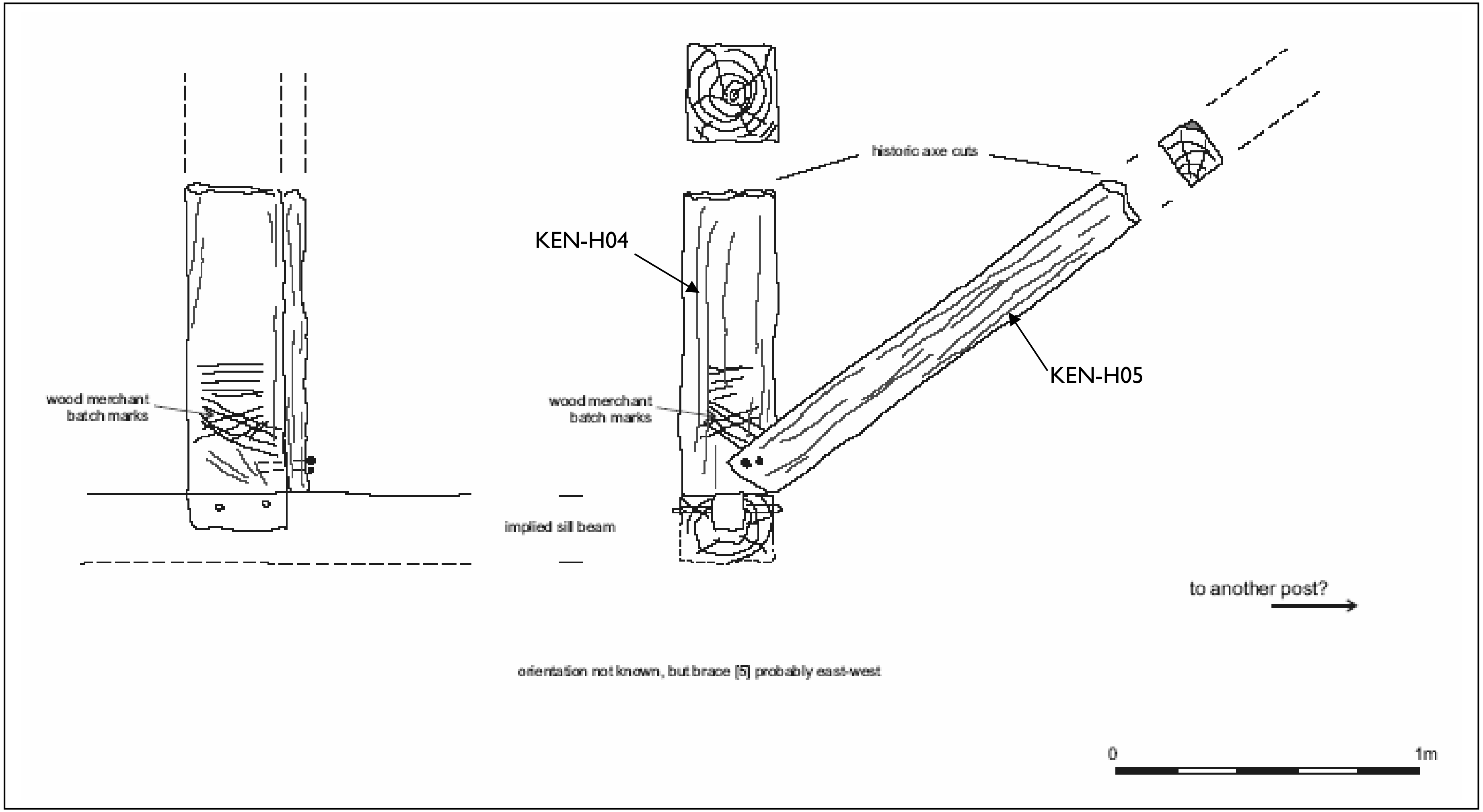
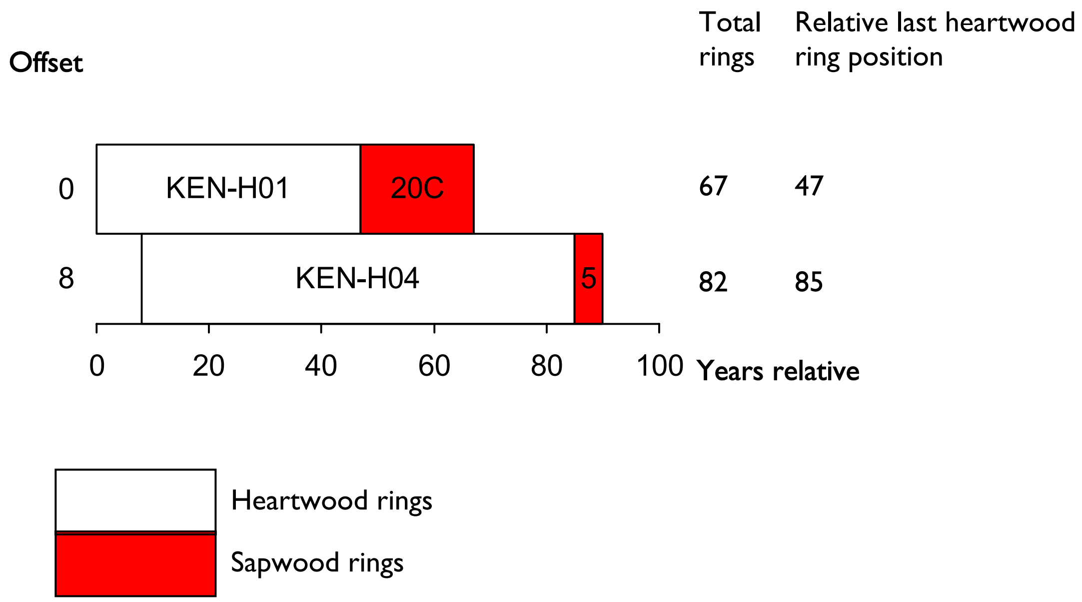


Figure 4: Reconstructed elevation of refitting timbers, forming 'Assembly B': a substantial post and diagonal cross-brace (probably orientated at right angles to figure 3), showing the location of samples KEN-H04 and KEN-H05 (Elsden and Goodburn 2006)



C = complete sapwood retained on sample, last measured ring is the felling date.

Figure 5: Bar diagram of samples in undated site sequence KENHSQ01

Data of measured samples – measurements in 0.01mm units

KEN-H01A 67
331 496 594 624 501 474 579 587 276 347 401 450 428 330 252 205 265 438 479 274
339 353 347 335 221 378 400 287 142 212 256 245 219 297 280 400 261 148 190 104
153 140 115 93 93 91 100 130 176 197 157 187 206 287 145 91 87 236 189 223
263 150 107 85 110 161 136
KEN-H01B 67
311 468 613 624 555 477 563 639 290 349 405 412 408 325 255 221 260 358 494 258
313 351 349 357 200 376 378 295 150 209 286 278 211 285 298 372 268 157 185 119
136 161 94 111 91 91 98 127 151 195 145 194 185 262 152 95 75 216 164 234
284 149 88 78 114 175 89
KEN-H02A 72
203 219 120 152 198 163 192 194 195 242 182 213 135 178 141 103 90 139 105 147
137 109 80 93 89 149 157 93 112 205 200 169 170 176 235 235 218 196 175 173
235 187 153 164 136 197 198 266 226 273 334 293 226 158 170 179 150 139 120 289
238 203 194 203 183 199 194 226 235 223 198 198
KEN-H02B 72
204 227 141 148 199 172 187 202 206 251 188 209 157 178 135 112 82 132 102 128
138 103 95 84 95 153 154 83 121 219 211 154 169 189 258 226 202 218 188 152
231 183 158 149 141 195 203 242 229 257 313 285 256 156 169 188 151 137 131 293
243 211 191 203 190 201 198 231 235 216 217 194
KEN-H04A 82
109 56 180 154 129 221 267 302 217 282 242 229 179 350 338 314 370 454 380 189
126 185 402 360 345 352 387 379 199 165 133 146 125 293 243 233 314 207 133 187
176 206 183 253 250 380 261 143 147 347 281 268 197 142 91 80 129 226 228 167
97 110 81 101 144 150 128 93 193 171 83 84 193 160 192 222 302 391 588 522
249 373
KEN-H04B 82
87 59 174 144 129 217 255 299 222 283 251 234 197 330 338 303 379 375 438 206
123 194 406 381 356 357 379 343 222 182 141 136 169 246 240 241 290 168 163 187
171 211 192 262 208 409 230 157 152 347 294 250 204 148 101 74 110 216 254 160
94 109 83 105 152 159 122 109 186 182 99 101 206 160 199 224 310 388 577 528
247 391
KEN-H07A 116
184 107 116 136 98 117 133 93 103 113 93 106 87 80 78 122 128 100 92 78
85 75 90 91 102 75 85 93 92 92 72 92 99 88 94 116 106 110 102 93
70 85 99 83 81 89 53 56 75 69 80 72 75 47 65 74 71 78 58 50
64 49 57 55 58 47 43 41 46 40 38 31 36 29 24 24 25 28 37 27
23 39 38 40 34 34 38 50 53 51 47 39 34 37 68 51 44 38 38 28
40 31 36 36 46 56 42 48 40 32 35 40 40 43 36 44
KEN-H07B 58
111 91 109 117 112 111 136 107 113 100 110 91 99 68 84 107 114 103 89 83
82 78 88 96 92 80 98 92 93 98 90 102 90 91 103 96 98 98 98 89
74 92 99 91 82 78 54 58 65 62 65 77 70 53 55 73 79 57

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 be 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 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 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 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

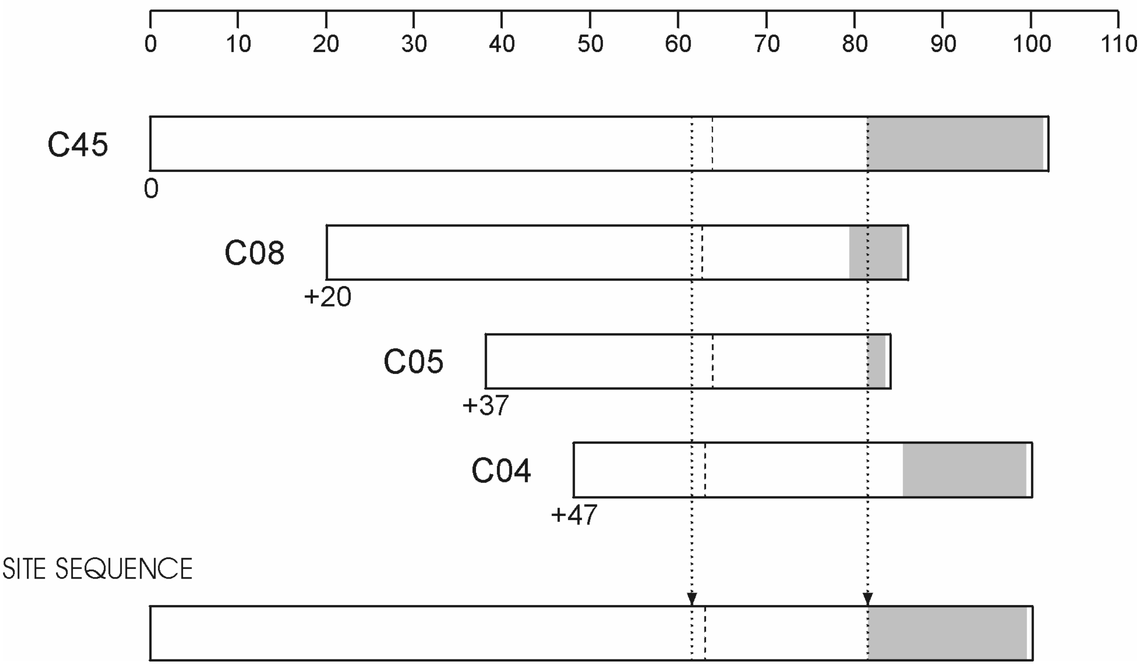


Figure 5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

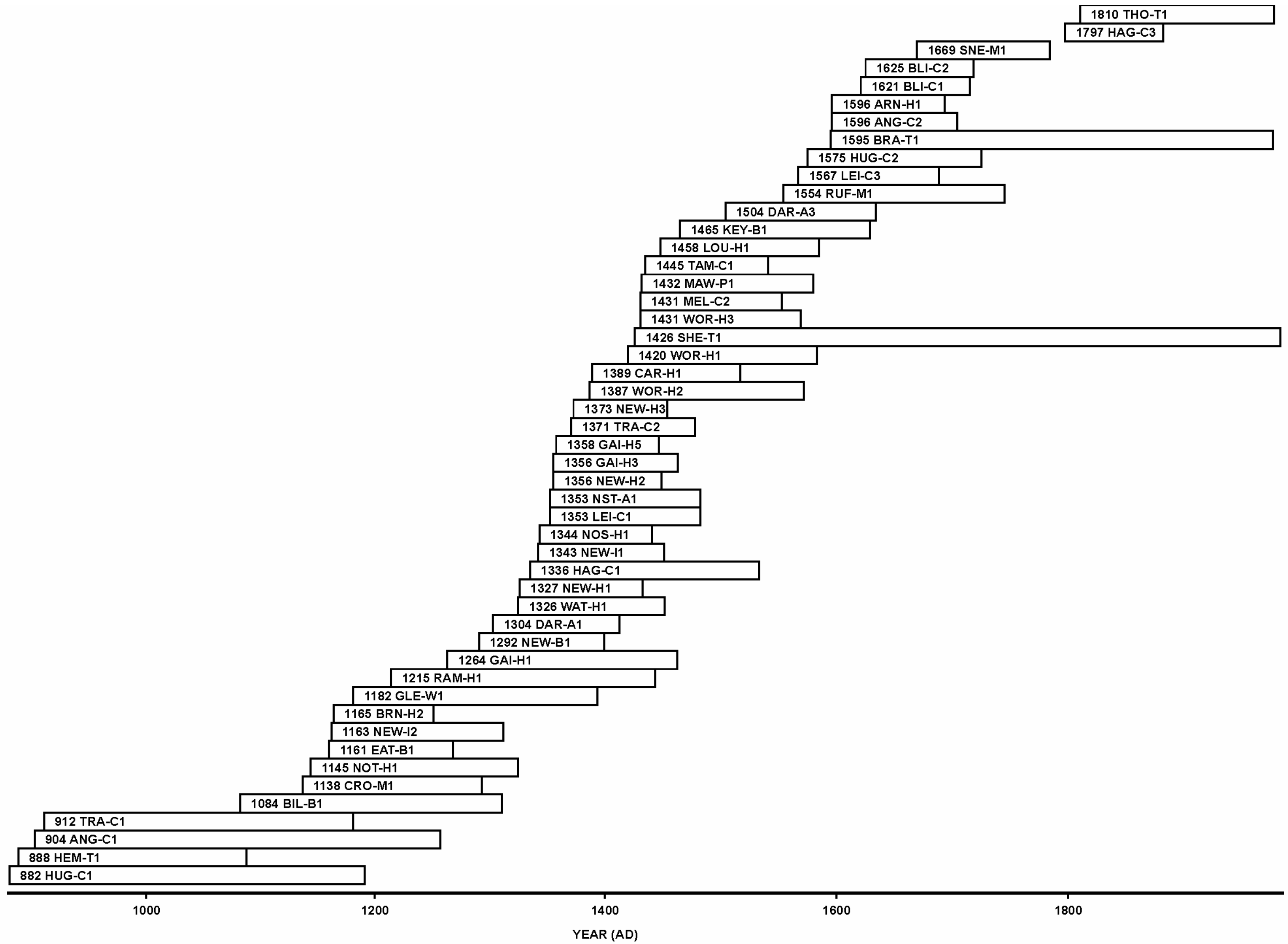
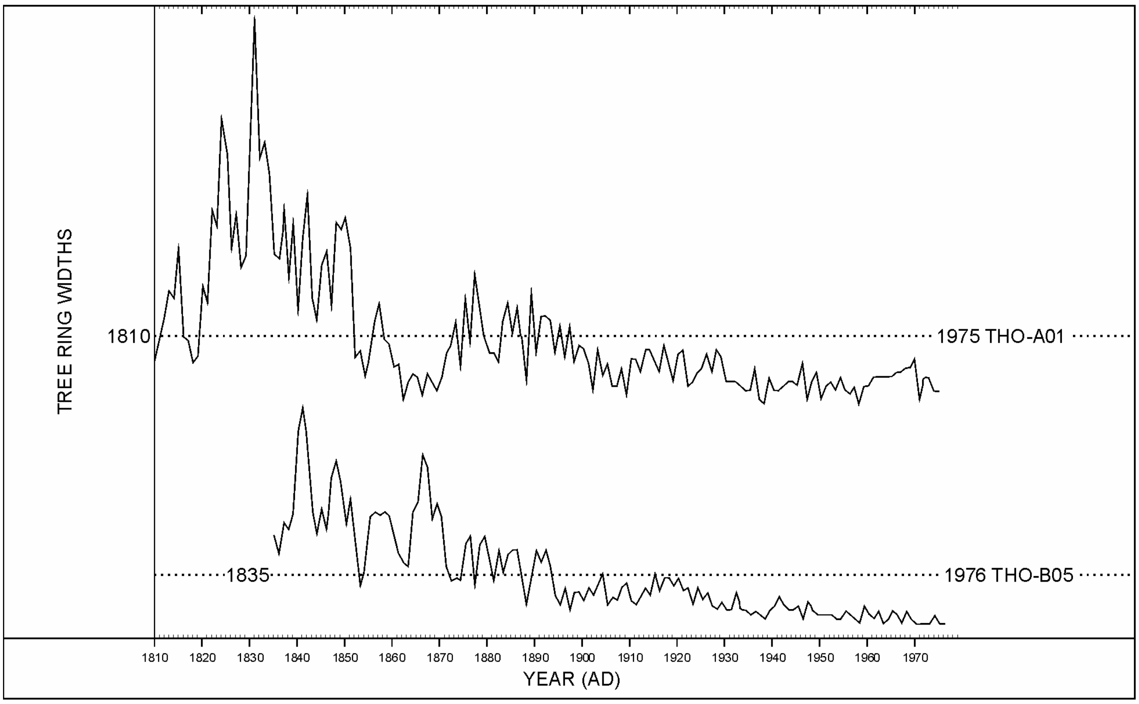


Figure 6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

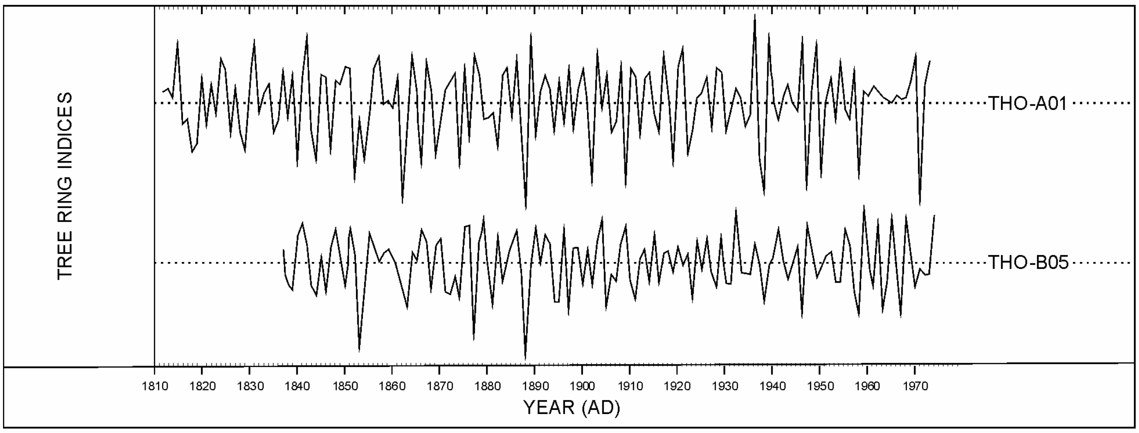


Figure 7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young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

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