

THE WEST TOWER ROOF,
ST CATHERINE'S CHURCH,
LUDHAM, NORFOLK
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard



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Summary

Dendrochronological analysis was undertaken on samples taken from oak timbers of this roof, resulting in the construction of two site sequences.

The first, LUDASQ01, of 78 rings, contains three samples. The second, LUDASQ02, of 61 rings, contains two samples. Neither of these sequences could be matched to any reference chronology. Attempts to individually date the two ungrouped samples were also unsuccessful, and all samples remain undated.

Keywords

Dendrochronology
Standing Building

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Introduction

The parish church of St Catherine's is located in the village of Ludham, Norfolk (TG38811827; Figs 1–3). It is constructed of flint with ashlar dressings and some brickwork. With the exception of the chancel, which is roofed in slate, the majority of the roofs are lead.

The west tower is believed to be fourteenth century, although it is thought to have undergone alterations in the fifteenth century following bequests to new work dated AD 1466. It is a three-stage tower with diagonal west buttresses and side east buttresses, and crenellated parapet. It has lancets to the ringing chamber and a pedimented clock face, dated AD 1762. Its roof is shallow pitched, consisting of tiebeam, wallplates, common rafters, ridgeplate, and purlins (Figs 4–8).

The chancel is also thought to be fourteenth century. It has stepped side buttresses and diagonal buttresses to the east. Inside there is a 5-bay octagonal arcade on high bases with polygonal capitals below double hollow-chamfered arches. The roof is relatively modern, thought to be nineteenth century.

The date of the hammerbeam roof of the nave also probably coincides with the AD 1466 bequests. Alternate hammerbeams rest on polygonal wall posts that drop to corbels carved with angels bearing shields. There are arched braces to ridge pieces and one tier of butt purlins.

Also dating to the fifteenth century are the aisles. Their roofs have arched braces to central purlins, and the outer wall posts rest on head corbels. The north aisle has stepped side buttresses and diagonal ones at the corners.

The two-storey south porch has diagonal buttresses rising to polygonal turrets, an arched doorway in a square surround, and carved spandrels. It has a gabled roof and plain parapet. The north porch also has diagonal buttresses. There is a polygonal stair turret to the north-west.

The church underwent restorations in AD 1861 and AD 1891.

Acknowledgements

The Laboratory would like to thank Nicholas Warns and Barbara Singer of Nicholas Warns Architects Ltd for all their assistance and for providing Figures 3 and 5–8. The description above is based on the building's listing (www.imagesofengland.org.uk).

Sampling and analysis by tree-ring dating was commissioned and funded by English Heritage to inform grant aided repairs to the roof of the tower, which is in a greatly weakened condition due to rainwater entering around a flagpole.

Sampling

A surface examination of the timbers of the tower roof identified them as being relatively fast-grown, with barely enough growth rings to make sampling worthwhile. However, it was decided to undertake sampling of the most promising timbers, all of which were rafters, as the other mostly larger structural elements clearly had too few rings. As a result, eight rafters were sampled, with each sample being given the code LUD-A, and numbered 01–08. The position of samples was noted at the time of sampling and has been marked on Figure 5. Further details relating to the samples can be found in Table 1.

Analysis and Results

At this stage it was seen that four of the samples had less than the usual minimum 54 growth rings this Laboratory requires for analysis. However, in this instance it was decided to accept all samples with 40 or more growth rings in the hope that with a greater number of sample sequences there would be an increased chance of internal cross-matching. In this way, the possibility of producing a well-replicated site sequence (of reasonable length) to match against the reference chronologies would be improved. Only sample LUD-A01 was rejected, as it had less than 40 rings. The remaining seven samples were prepared by sanding and polishing and their growth-ring widths measured; the data of these measurements are given at the end of the report. The samples were compared with each other by the Litton/Zainodin grouping procedure (see appendix).

At a least value of $t=4.5$, five samples had formed two groups. Firstly, three samples matched and were combined at the relevant offset positions to form LUDASQ01, a site sequence of 78 rings (Fig 9). This site sequence was then compared with a large number of relevant reference chronologies for oak, but no consistent match could be found.

Two further samples matched each other and were combined at the relevant offset position to form LUDASQ02, a site sequence of 61 rings (Fig 10). Again, attempts to date this site sequence by comparing it against the reference material proved unsuccessful, and these samples are undated.

Attempts to date the remaining two ungrouped samples by individually comparing them against the reference material were unsuccessful, and these samples are also undated.

Discussion

In this instance tree-ring analysis has not been successful, with none of the seven measured samples being dated and hence no dating evidence being provided for the construction of the west tower roof. This is particularly disappointing in the light of the recent successful analysis at the nearby St Nicholas' Church, Potter Heigham, just to the north-east of Ludham (Fig 1; Arnold and Howard 2007).

There is nothing particularly unusual about the growth patterns of this group of samples; they are neither unduly complacent nor compacted. Therefore, the most likely reason for this lack of dating is the relative shortness of the ring sequences of the samples and site sequences. The longer site sequence, LUDASQ01, only has 78 rings. This, coupled with the lack of replication within both site sequences (only three and two samples), is likely to have added to the difficulty, particularly in a region noted for its problematic nature of dendrochronological analysis and hence the limited network of reference chronologies for the relevant area.

It is unfortunate that, due to the size of this roof, the number of timbers from which to obtain samples was very limited, as this clearly reduced the chances of producing a well-replicated site sequence. If at some point in the future, access to the nave and aisle roofs becomes possible, it might prove useful to undertake sampling of these timbers. This could provide the necessary replication, especially if the west tower roof were to prove to also be fifteenth century and even if it is earlier there is a chance that at least some of its ring sequences may overlap with the nave and aisle roof timbers.

Reference

Howard, R E, and Arnold, A J, 2007 *St Nicholas' Church, Potter Heigham, near Norwich, Norfolk: Tree-Ring Analysis of Timbers*, EH Res Dep Rep Ser, 2/2007

Table 1: Details of tree-ring samples from the West Tower roof, St Catherine's Church, Ludham, Norfolk

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
LUD-A01	South rafter 2	NM	--	----	----	----
LUD-A02	North rafter 4	52	h/s	----	----	----
LUD-A03	South rafter 3	40	h/s	----	----	----
LUD-A04	North rafter 8	44	h/s	----	----	----
LUD-A05	South rafter 11	67	h/s	----	----	----
LUD-A06	North rafter 11	65	--	----	----	----
LUD-A07	South rafter 9	57	h/s	----	----	----
LUD-A08	North rafter 12	67	h/s	----	----	----

*NM = not measured

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

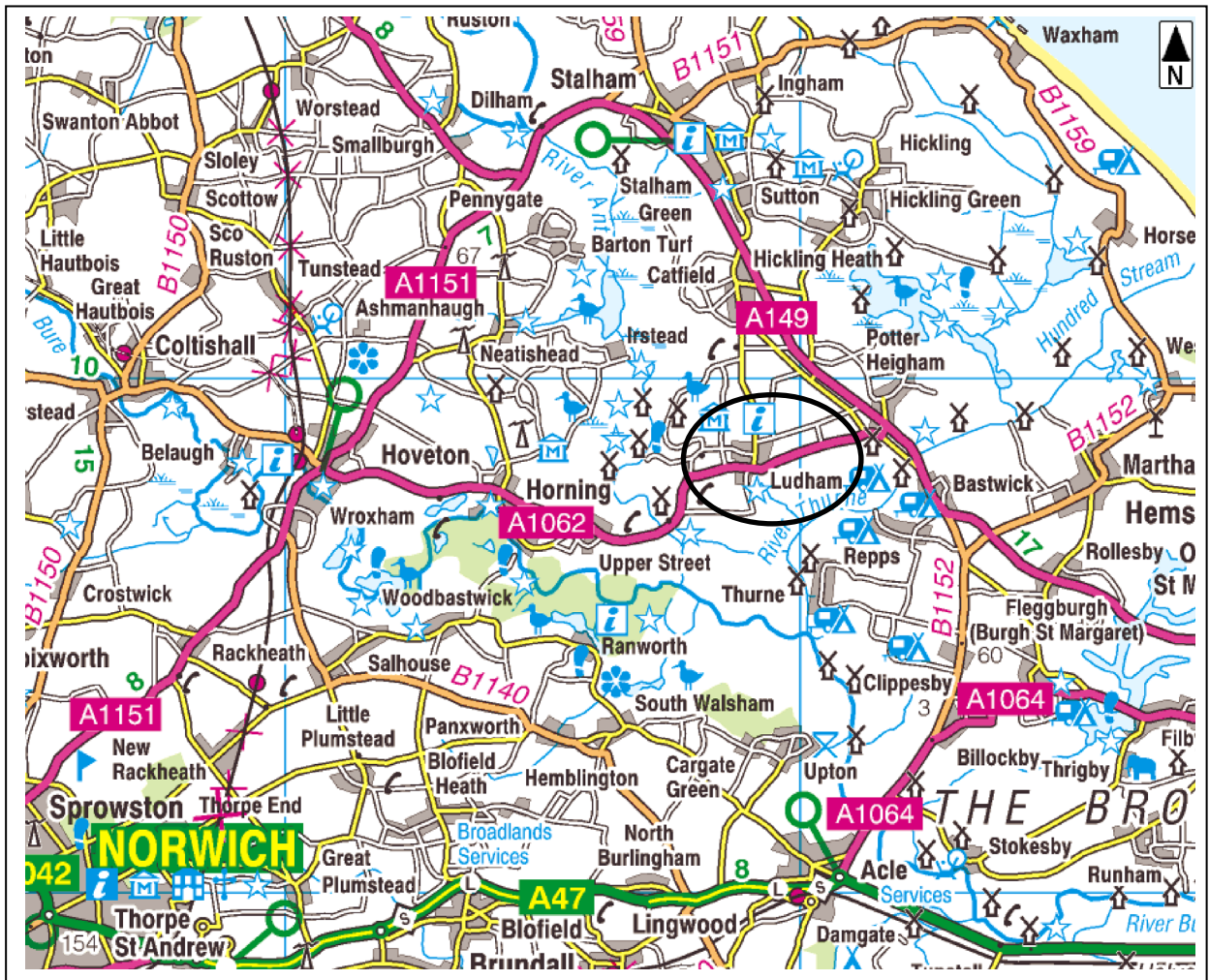


Figure 1: Map to show the location of Ludham, Norfolk,

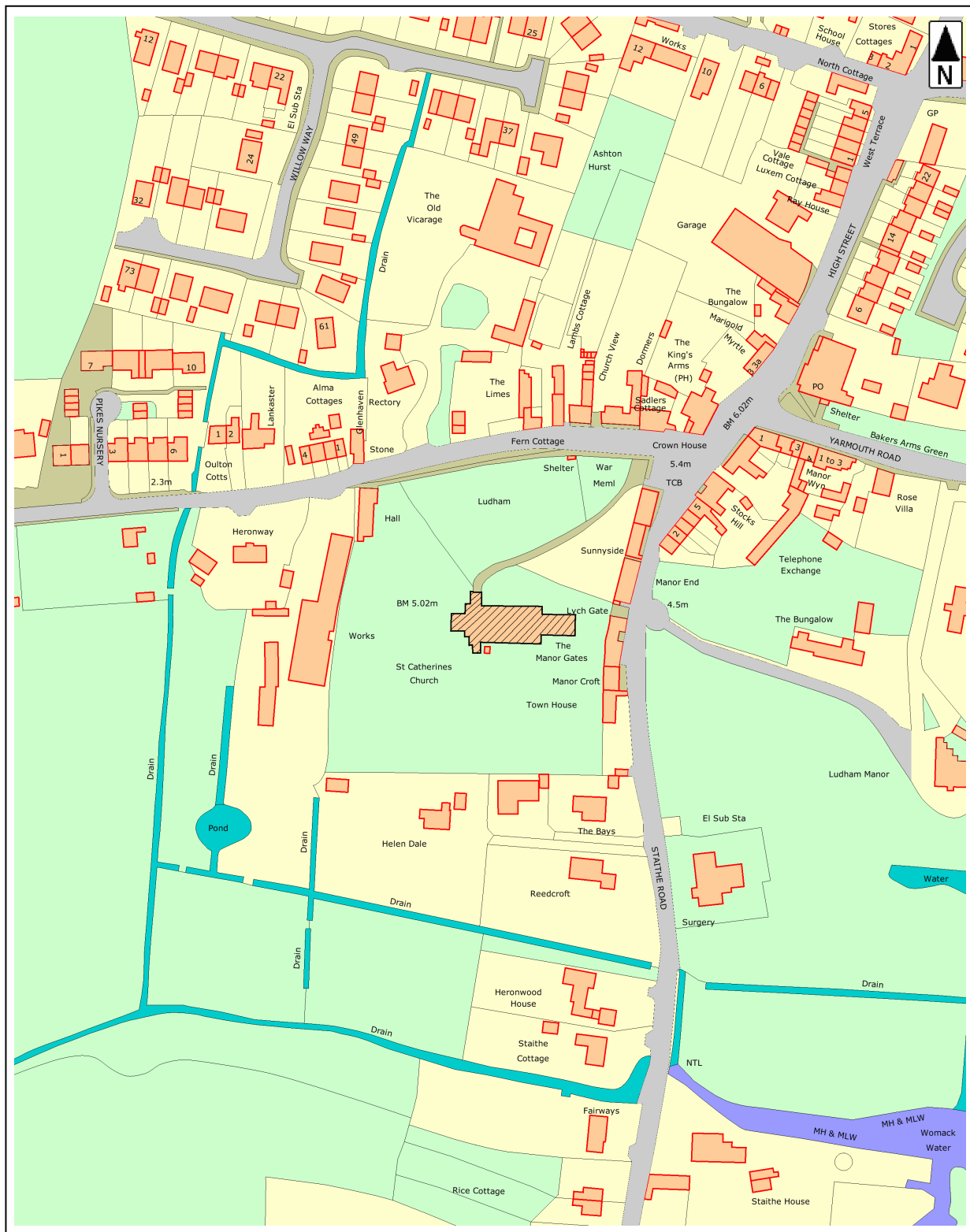


Figure 2: Map to show the location of St Catherine's Church

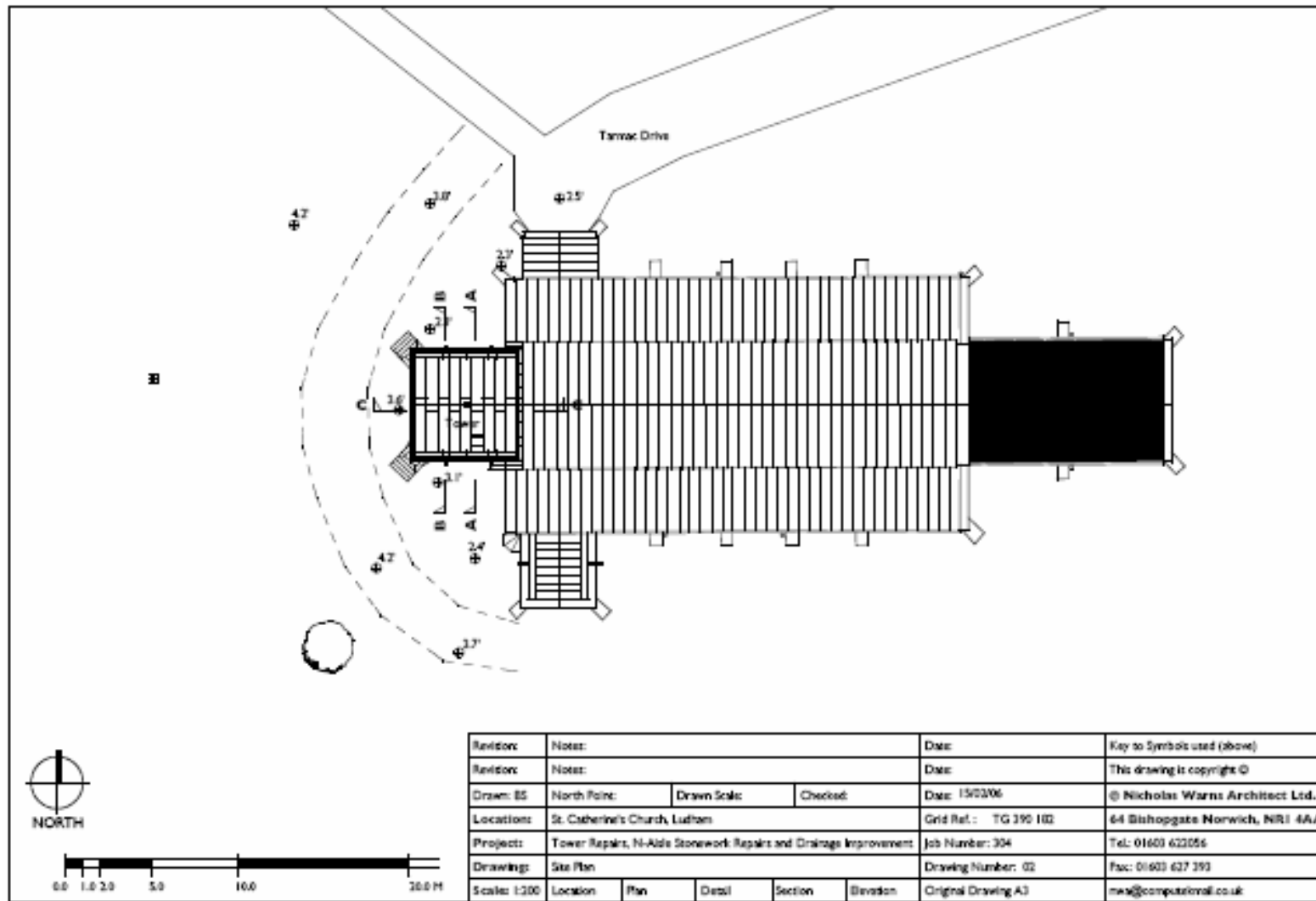


Figure 3: Site plan (Nicholas Warns Architect Ltd)



Figure 4: West tower roof, looking north-east

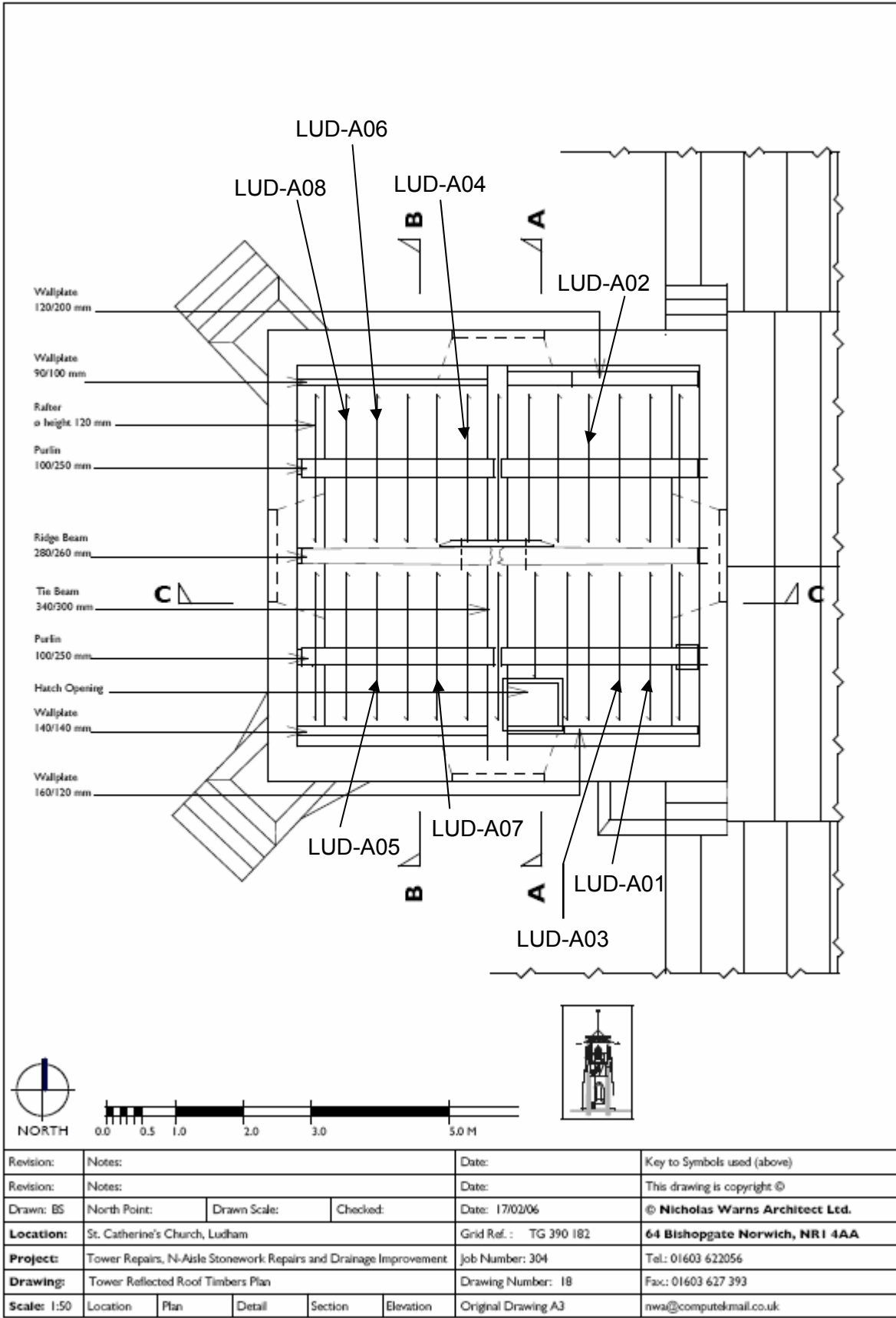


Figure 5: West tower roof; plan (Nicholas Warns Architect Ltd)

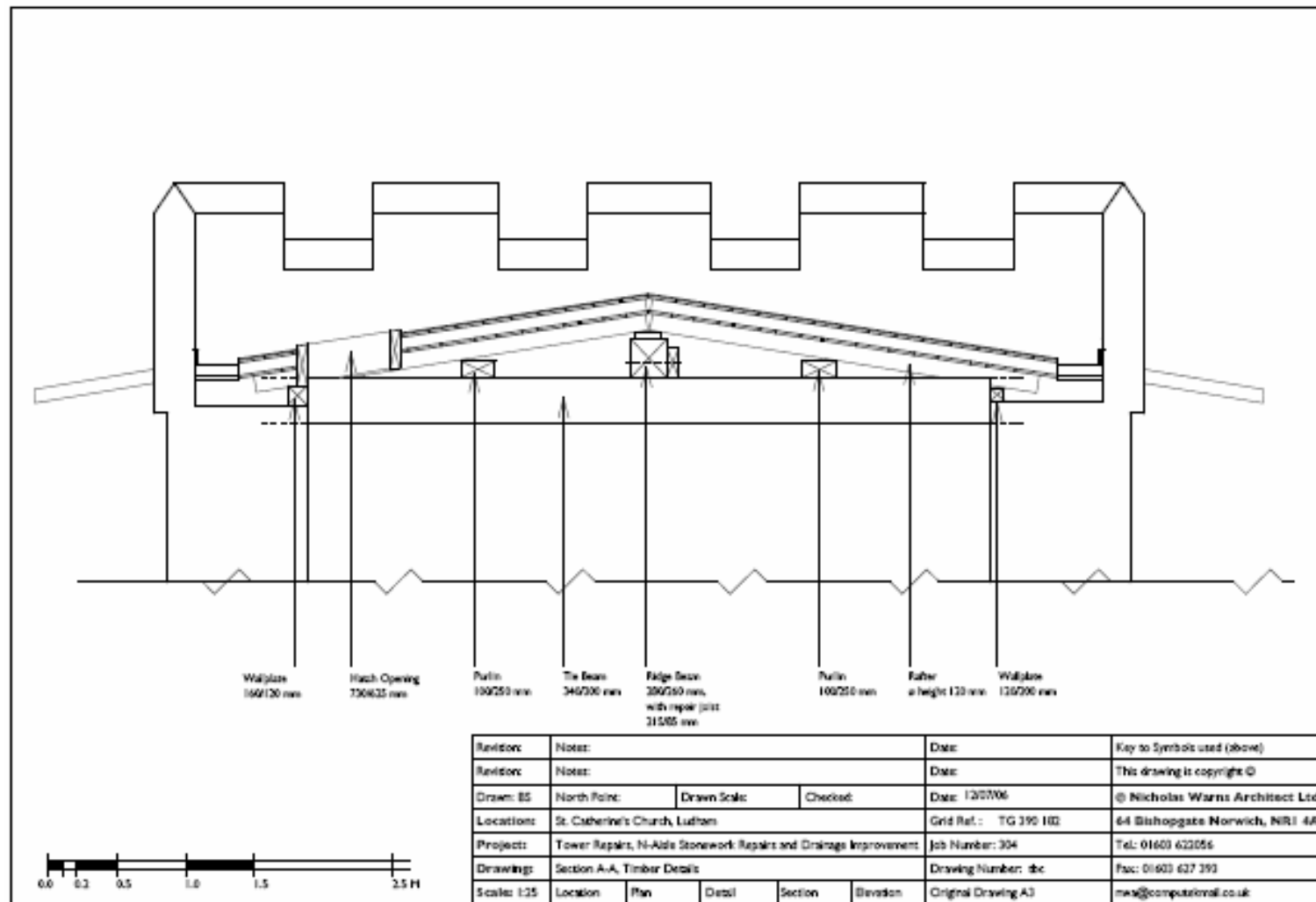


Figure 6: Section A–A (Nicholas Warns Architect Ltd)

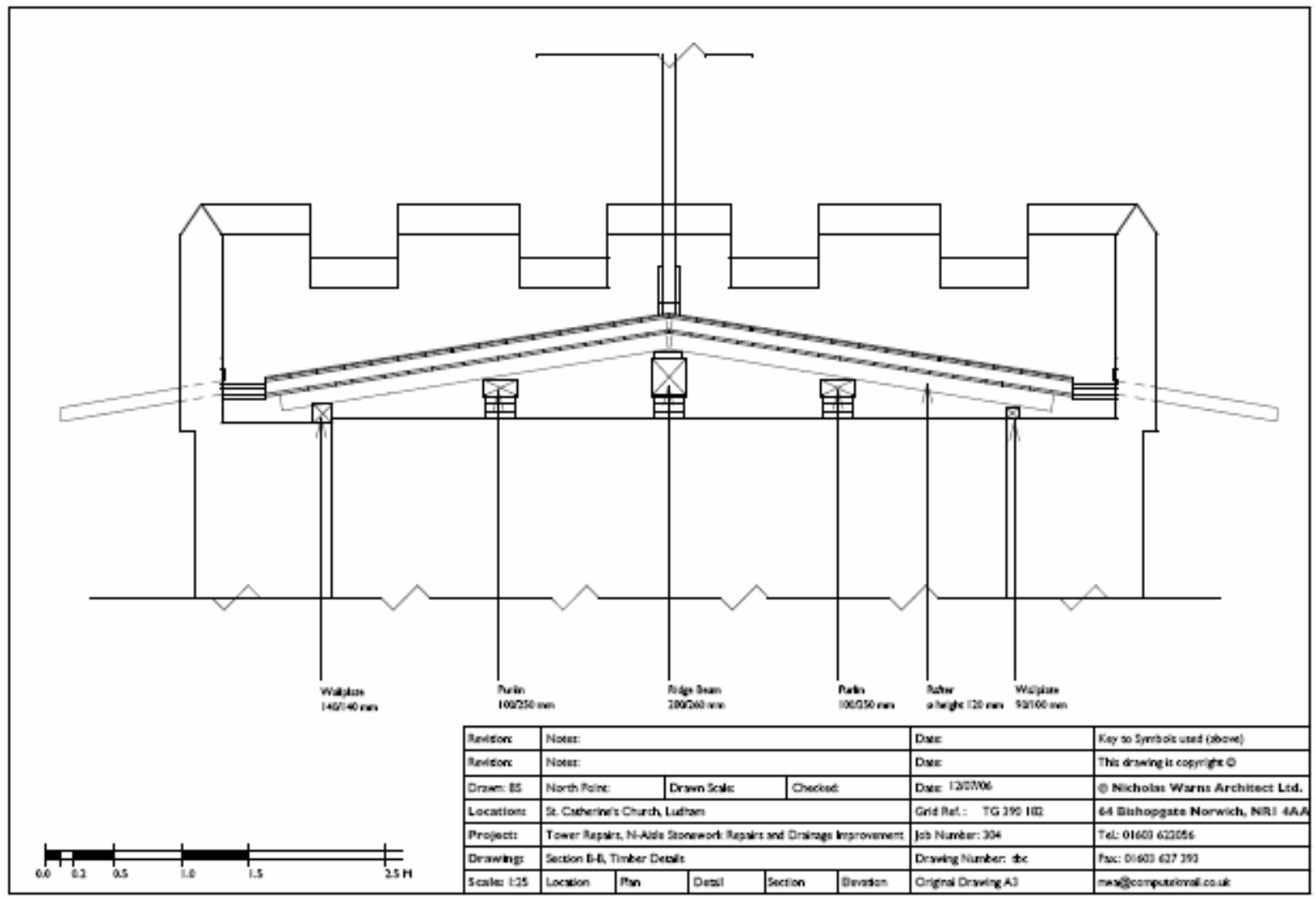


Figure 7: Section B-B (Nicholas Warns Architect Ltd)

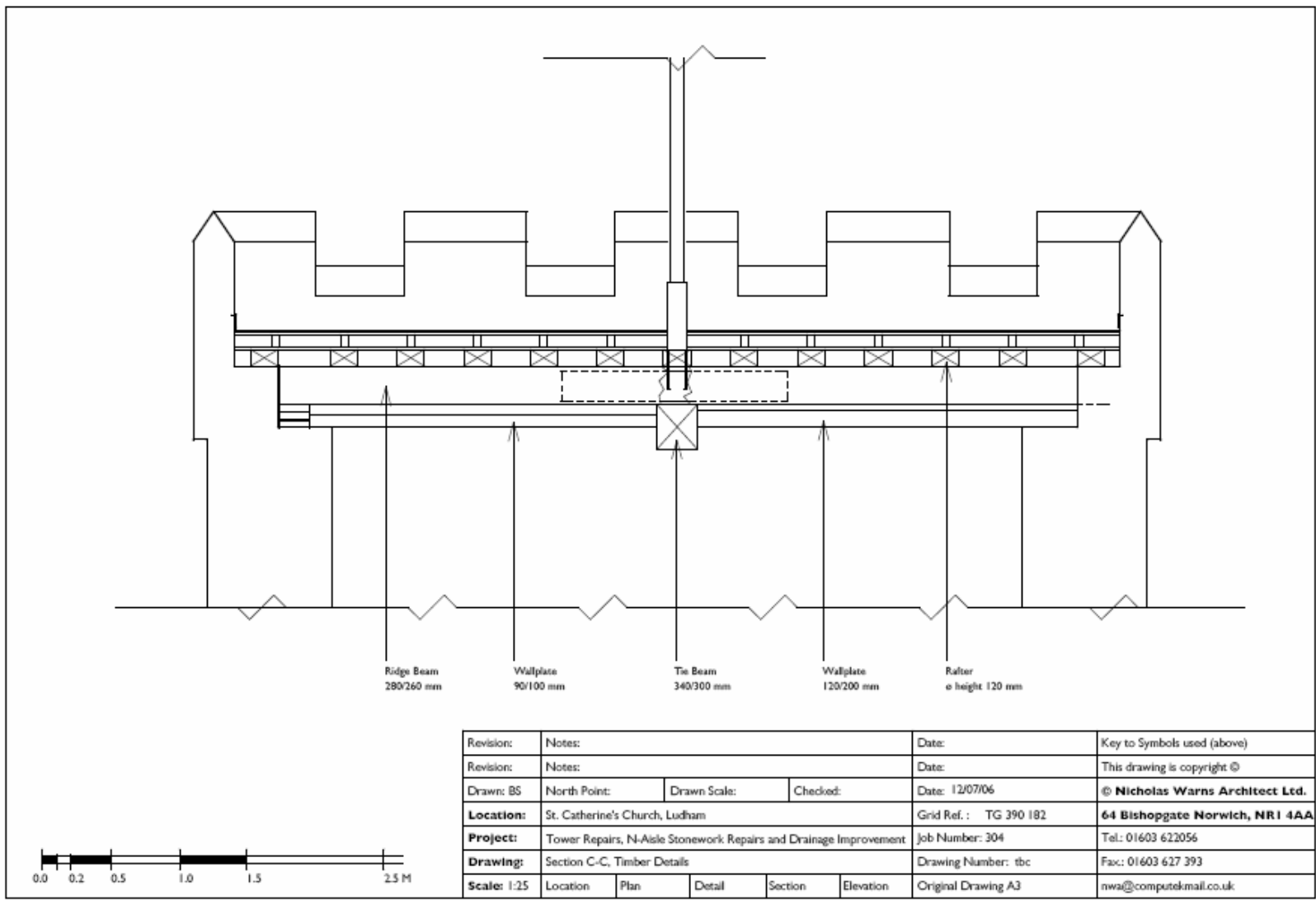


Figure 8: Section C-C (Nicholas Warns Architect Ltd)

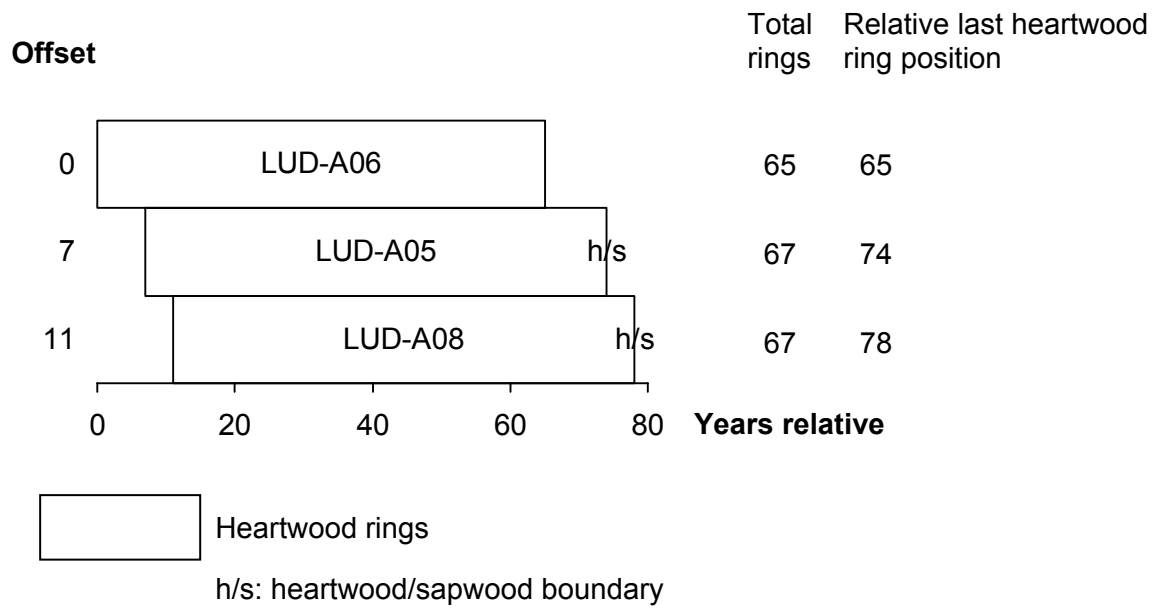


Figure 9: Bar diagram of samples in undated site sequence LUDASQ01



Figure 10: Bar diagram of samples in undated site sequence LUDASQ02

Data of measured samples – measurements in 0.01mm units

LUD-A02A 52

187 445 405 425 525 569 442 371 403 432 575 227 409 413 392 447 497 366 327 393
761 692 399 221 379 183 334 413 214 110 60 89 103 76 119 176 69 74 248 164
82 97 107 107 54 113 94 121 89 97 124 142

LUD-A02B 41

283 413 435 470 466 547 388 411 454 500 573 440 255 435 168 272 327 186 85 54
96 146 112 185 166 63 75 107 109 80 91 123 52 50 60 66 74 107 112 118
133

LUD-A03A 40

530 494 488 609 529 438 226 198 258 270 457 539 458 520 499 502 390 299 321 431
222 423 383 258 379 231 124 217 251 319 191 205 190 184 132 121 226 164 234 171

LUD-A03B 40

527 526 492 600 522 450 225 254 234 284 446 538 465 516 472 520 391 306 322 407
237 412 416 255 406 238 137 209 263 307 202 213 189 182 127 114 223 174 240 176

LUD-A04A 44

291 366 393 368 148 154 249 280 404 371 363 286 304 259 198 279 154 121 246 263
177 177 153 209 287 193 168 215 275 252 170 277 220 175 196 164 183 80 119 190
141 64 77 60

LUD-A04B 44

291 350 394 369 155 149 244 279 390 344 351 286 316 258 194 251 148 122 265 269
178 157 141 194 273 209 174 203 283 281 184 324 269 176 189 156 178 85 102 169
133 77 75 68

LUD-A05A 67

303 374 466 111 269 198 159 150 191 193 227 272 237 225 321 231 242 78 76 104
170 185 163 186 248 281 220 280 286 253 196 232 260 389 351 329 278 255 190 149
165 216 150 126 87 73 78 61 85 154 203 177 214 177 118 139 150 103 131 108
78 78 72 77 95 135 110

LUD-A05B 67

306 371 475 164 275 199 152 157 195 191 237 252 248 222 318 231 278 91 73 105
175 183 163 176 228 274 194 257 263 254 206 229 254 438 360 290 282 245 189 142
174 194 170 99 91 79 69 55 95 133 212 182 216 178 119 133 136 111 141 116
89 74 77 79 107 147 117

LUD-A06A 54

383 376 494 465 346 499 628 233 196 163 142 185 229 321 255 375 386 344 313 328
325 171 73 100 199 198 200 295 291 301 276 285 369 264 161 187 185 331 226 164
173 165 189 124 174 173 95 76 63 59 45 41 52 127

LUD-A06B 65

168 304 361 210 324 397 447 343 513 576 229 194 145 145 193 231 310 263 353 377
316 328 331 404 120 81 109 187 140 178 237 322 320 278 297 387 279 149 216 204
386 265 205 203 157 204 130 174 203 111 78 74 58 76 52 61 143 140 231 319
195 109 127 143 110

LUD-A07A 57

114 194 250 270 270 312 339 305 251 191 334 333 370 339 344 287 400 246 225 135
227 268 362 308 185 279 249 270 366 339 339 342 147 322 160 254 285 179 80 48
99 148 105 144 168 59 69 127 128 55 95 91 47 49 47 49 69

LUD-A07B 57

131 187 236 262 277 316 325 302 278 195 321 337 362 348 351 289 353 233 227 153
217 270 362 301 198 268 234 269 365 342 335 340 152 325 170 269 273 184 74 56
102 140 95 153 159 70 69 117 120 56 83 117 35 48 46 57 70

LUD-A08A 67

239 202 206 269 332 296 321 383 256 220 305 250 301 74 64 141 173 286 243 321
337 370 342 318 347 282 303 312 326 491 76 159 147 153 208 218 317 381 213 82
81 79 109 127 185 252 261 278 361 336 196 173 232 88 64 81 103 99 139 115
148 166 185 50 46 45 45

LUD-A08B 67

199 209 198 265 331 299 316 389 263 215 313 266 290 80 69 133 181 285 250 303
343 386 344 326 353 271 320 305 343 484 80 150 166 161 201 203 316 371 231 76
87 82 114 118 167 278 256 289 373 337 194 164 247 89 67 77 102 88 131 120
158 158 195 57 45 43 48

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 complement 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

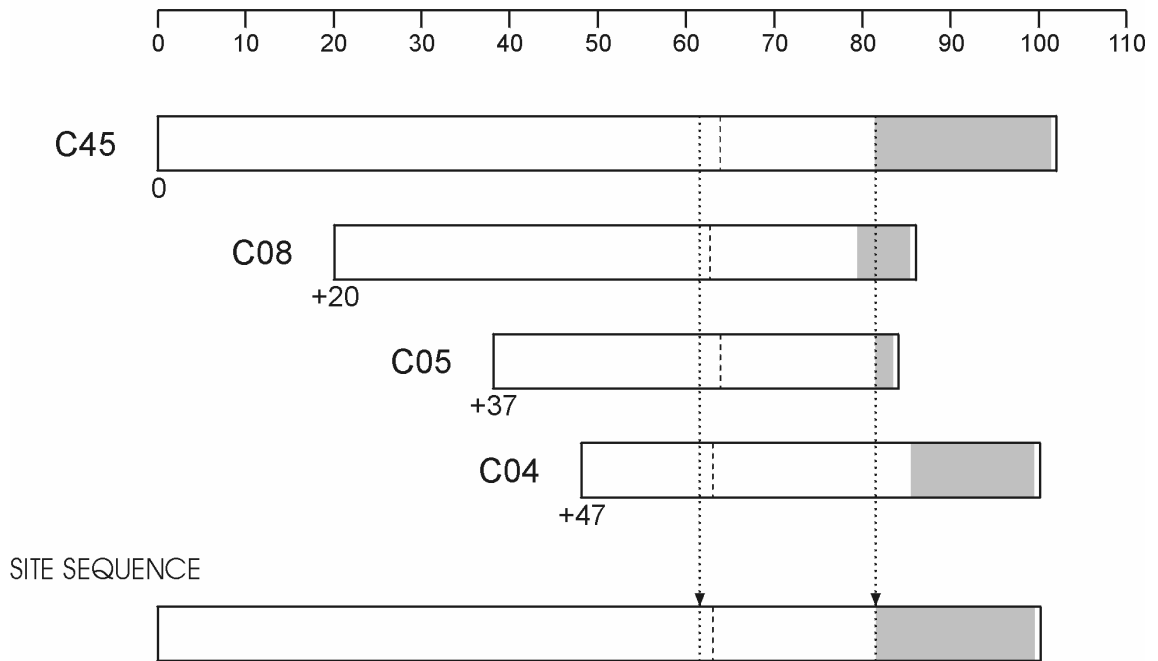


Figure 5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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.

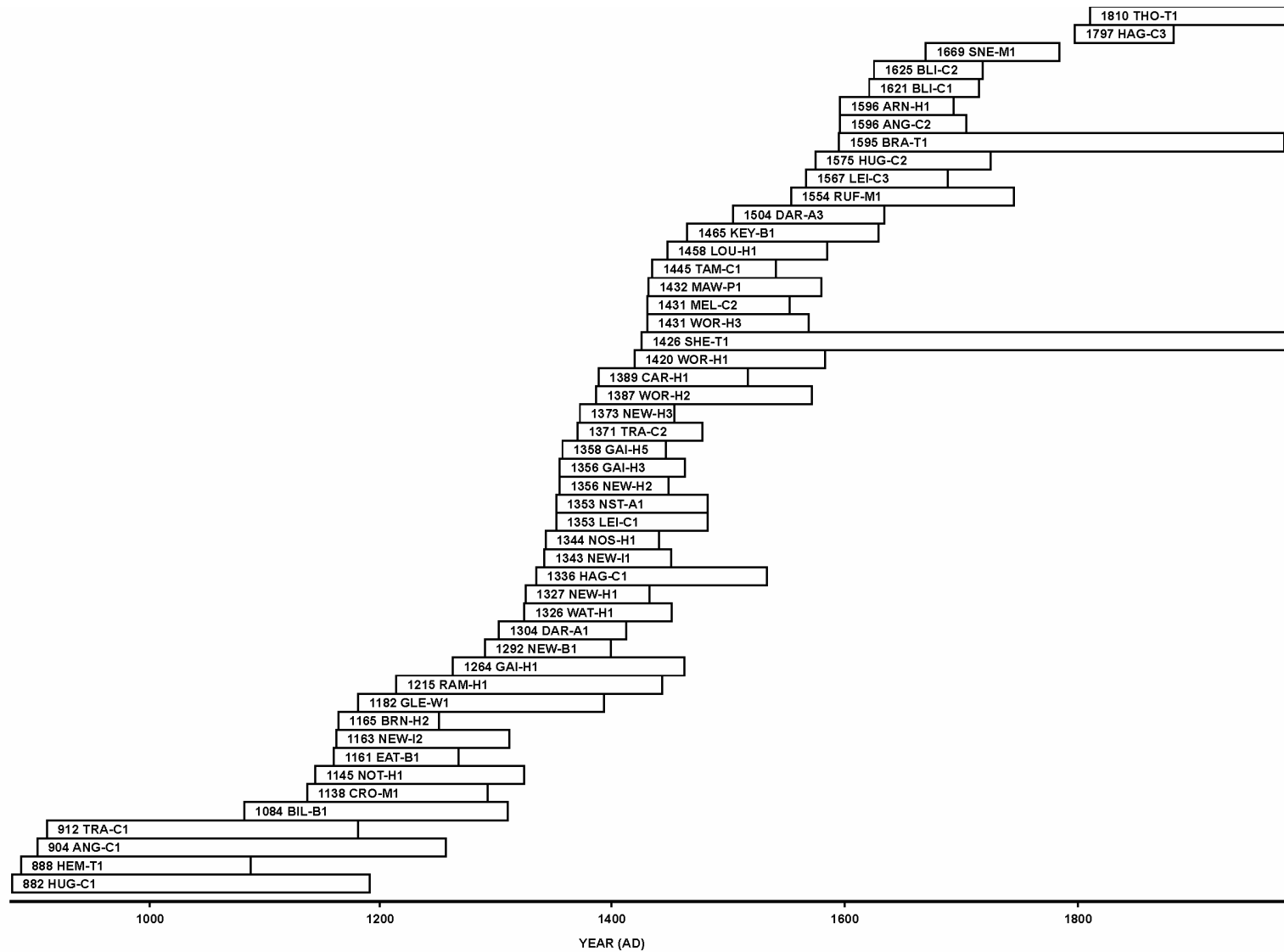
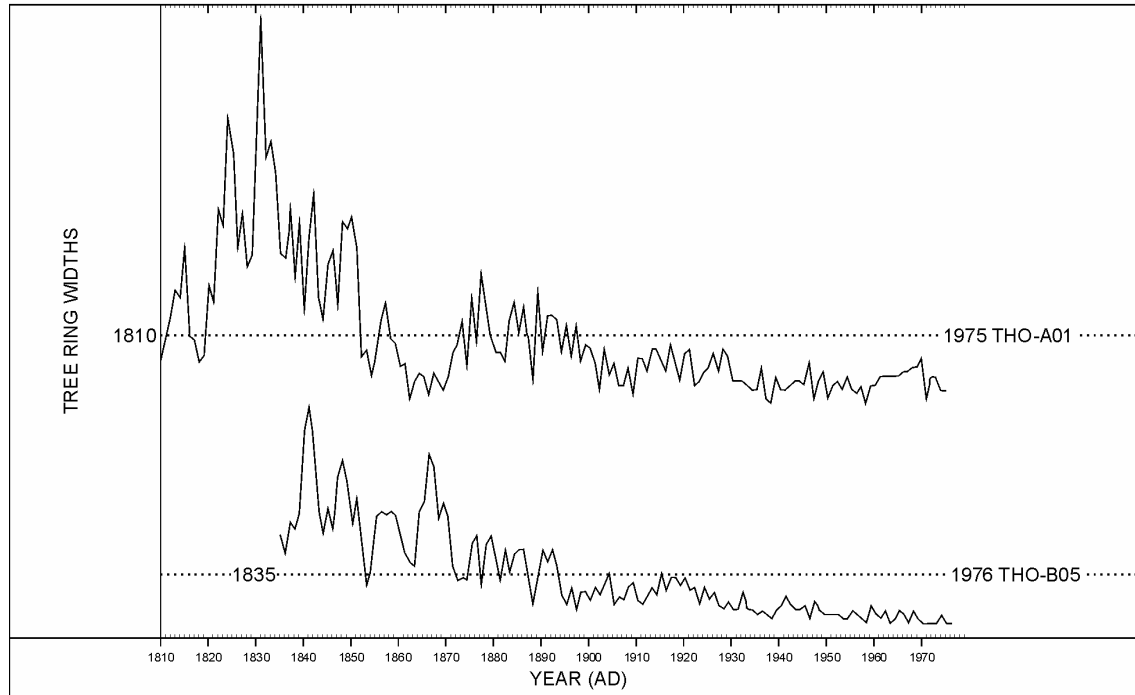


Figure 6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

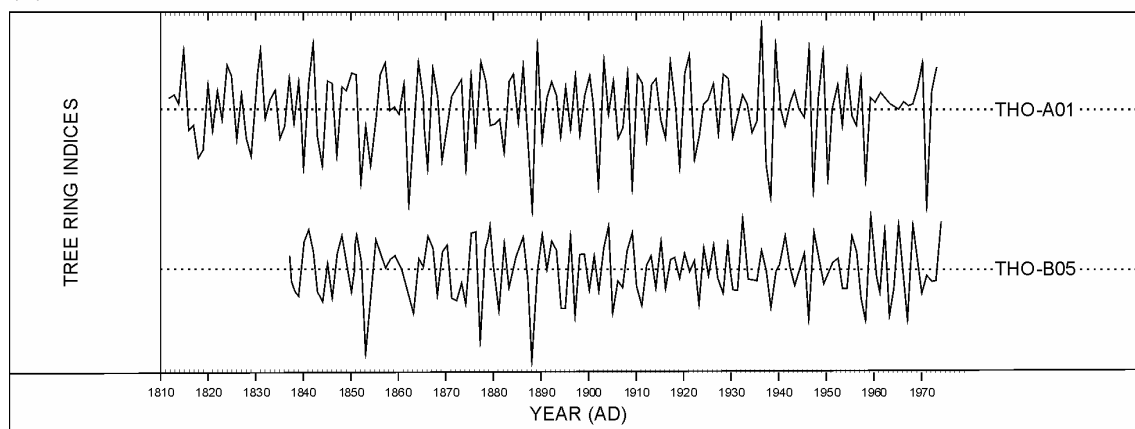


Figure 7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young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

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