Historic England

Scientific Dating

# Newcomen Terrace Foreshore
# Redcar
# North Yorkshire

## Tree-ring Assessment and Analysis of Timbers

Alison Arnold, Robert Howard, and Cathy Tyers

Discovery, Innovation and Science in the Historic Environment

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Front Cover: Tree stumps at Newcomen Terrace, Redcar. Photograph Don O’Meara.

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# REDCAR
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## Tree-ring Assessment and Analysis of Timbers

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SUMMARY
Sampling for dendrochronological analysis was attempted on a number of tree-stumps exposed during low tides on the foreshore in front of Newcomen Terrace, Redcar, but, given the decayed nature of the material, samples suitable for dendrochronology could not be obtained. Samples in the form of cross-sectional slices were, however, obtained from five other timbers found here, these believed to be fallen trees or possibly worked timbers. Analysis of these five samples produced a single site chronology comprising two ring-width series and being 64 rings long. Neither this site sequence nor any of the three remaining ungrouped, but short, single ring-width series could be dated.

CONTRIBUTORS
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ACKNOWLEDGEMENTS
We would firstly like to thank Don O'Meara for bringing the timbers sampled here to the attention of Historic England's Scientific Dating team, and for requesting tree-ring sampling and analysis, and Stephen Sherlock for stepping in to help. We would also like to thank the team at Redcar & Cleveland Borough Council: Ian Pickles, Guy Allen, Adrian Miller, and David Marsay, who helped with permissions and the logistics of accessing the assemblages, and Tim Brown (Conservation Advisor, Redcar & Cleveland Borough Council) and Chris Twigg for keeping watch and reporting regularly on the sightings prior to our site visit. Thanks too to Alison Kentuck, Receiver of Wrecks for the Maritime and Coastguard Agency (MCA), for her help and advice. Finally, we would like to thank Shahina Farid (HE Scientific Dating Team) for commissioning this programme of tree-ring dating, and for her valuable contributions to this report.

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# INTRODUCTION

Due to the action of the tides and a spate of storms off the north-east coast of England during the autumn of 2018, a series of features was exposed along the foreshore at Redcar in North Yorkshire. Although somewhat dispersed and spread out, the material lay on the beach forward of Newcomen Terrace, generally between Turner Street to the north-west and the Redcar Beacon to the south-east, being centred approximately on NZ 60243 25471, about 100m to the NW-N-NE of 54.620243N, -1.068066W (Figs 1 and 2a–b).

These features were reported as comprising a series of parallel timber posts in the inter-tidal zone, which were interpreted as a possible post-medieval 'rutway' (a structure associated with the hauling of boats up and down the foreshore for launching and landing), two expanses of tree stumps, and fallen, or possibly worked, timbers. The submerged forest is discussed in Sherlock (2019). The fragmentary carcass of a wooden ship was also reported, this being moved up and down the beach by the tides and winds. The tree-ring analysis of the wreck has since been reported separately (Arnold *et al* 2020).

# SAMPLING

Dendrochronological analysis was requested by Don O'Meara, Regional Science Advisor for Historic England. This was commissioned in the hope that the results produced would provide independent dating evidence to inform the significance and enhance understanding of the exposed timber assemblage.

Due to the action of the sea, almost all the stumps (ie the surviving sections just above the spread of the root systems), which were exposed just above the sand and shingle, had been hollowed out leaving virtually nothing suitable for sampling for dendrochronology (Figs 3a–b). The stumps were also very soft and may have been of a species other than oak. A small number of test slices were taken of these but most broke up under the action of cutting and none gave any worthwhile cross-sectional pieces.

Other timbers on the foreshore appeared to be either fallen trees, with again an apparent mixture of oak and other species, or possibly worked timbers, these latter all appearing to be of oak (Figs 4a–b). Slices were taken from as many as could be cleaned and lifted clear of the sand, shingle, and mud for safe chainsawing, but again many of these were very soft and many, again, disintegrating as they were cut. However, five reasonably good cross-sectional slices were obtained using a chainsaw, all of them from oak (*Quercus* spp) timbers.

Although a structure described as a potential 'rut-way' had been reported, there was no sign of these timbers at the time of sampling. Given the nature of the shore here, it is likely that this feature had been covered by the movement of the sandbars by the time of our visit.

Each of the five cross-sectional slices obtained from fallen oak trees or potentially worked oak timbers was given the code RED-T (for Redcar 'Timbers'), and numbered 01–05 (Table 1). No fragments from the small number of disintegrated test slices were retained for wood identification purposes.

## ANALYSIS AND RESULTS

Each of the five cross-sectional slices obtained was first frozen to consolidate its structure before having its hardened surfaces prepared with a scalpel blade to clearly reveal the annual growth rings. Although three of the samples had fewer than the 50 rings here deemed optimum for reliable analysis, the annual growth ring widths of all five samples were measured, the data of these measurements being given at the end of this report.

The data of the five samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix). This comparative process resulted in the production of a single group comprising two samples, these cross-matching with each other at a *t*-value of 5.4. The two cross-matching samples were combined at their indicated offset positions to form REDTSQ01, a site chronology with an overall length of 64 rings (Fig 5). Site chronology REDTSQ01 was then compared to an extensive corpus of reference data for oak from the British Isles and elsewhere in northern Europe, but there was no satisfactory cross-matching and these two samples must, therefore, remain undated.

Site chronology REDTSQ01 was then compared to the three remaining ungrouped samples, but there was no further satisfactory cross-matching. These three ungrouped samples were then compared individually to the full corpus of reference data for oak from the British Isles and elsewhere in northern Europe, but again there was no satisfactory cross-matching and they too must remain undated.

## INTERPRETATION AND CONCLUSIONS

Analysis by dendrochronology of samples from five foreshore oak timbers has produced a single site chronology comprising two samples, although, despite being compared to a large reference database spanning the prehistoric through to modern period, the samples are undated. However, although undated, given the similar relative position of the heartwood/sapwood boundary on both samples, what may be said is that it is likely that the two timbers are coeval, and, given the level of cross-matching between them, it is possible that they are from trees that may have been growing in the same general area of woodland.

It is possible that the lack of dating amongst these timbers is due to them being from places, or growing during time periods, for which there is currently insufficient reference data available to provide a cross-match. Furthermore, bearing in mind the contextual nature of their find-site (ie a dispersed assemblage of timbers washed up on a foreshore and exposed at the whim of shifting sand bars), it is possible that most of the timbers are of different dates. This has the effect of making some of them ‘singletons’ and while single samples with higher numbers of annual rings can, on occasion, be dated, it is much more difficult than with cross-matching groups of samples which provide replicated data. Given this situation it is perhaps not unexpected that these timbers containing so few growth rings are undated. This undated material will be reviewed periodically as further reference chronologies become available and these timbers may, in due course, also be dated.

The, at present, very limited understanding of the relatively rare survival in the form of a submerged forest can only be addressed by comprehensive investigations. Should this opportunity arise then it is recommended that a programme of dendrochronology, along with extensive sampling for species identification, forms an integral part of this investigation.

# REFERENCES

Arnold, A J, Howard, R E, and Tyers C, 2020 *Newcomen Terrace (The Redcar Beacon), Redcar, North Yorkshire, Tree-ring Assessment and Analysis of Wreck Timbers*, Historic England Res Rep Ser, 262/2020

Sherlock, S J, 2019 A Submerged Forest on the Foreshore at Redcar, NZ60302570, *Yorkshire Archaeol J*, 91(1), 162–6

# TABLES

*Table 1: Details of tree-ring samples from the timber scatter to Newcomen Terrace Foreshore, Redcar, North Yorkshire*

| Sample number | Sample location | Total rings | Sapwood rings* | First measured ring | Last heartwood ring | Last measured ring |
|---|---|---|---|---|---|---|
| | | | | | | |
| RED-T01 | Timber 1 | 47 | no h/s | ------ | ------ | ------ |
| RED-T02 | Timber 2 | 62 | h/s | $1^{SQ01}$ | $62^{SQ01}$ | $62^{SQ01}$ |
| RED-T03 | Timber 3 | 58 | h/s | $7^{SQ01}$ | $64^{SQ01}$ | $64^{SQ01}$ |
| RED-T04 | Timber 4 | 39 | no h/s | ------ | ------ | ------ |
| RED-T05 | Timber 5 | 37 | no h/s | ------ | ------ | ------ |

h/s = the heartwood/sapwood boundary is the last ring on the sample
$XX^{SQ01}$ = relative position within site sequence REDTSQ01

# FIGURES

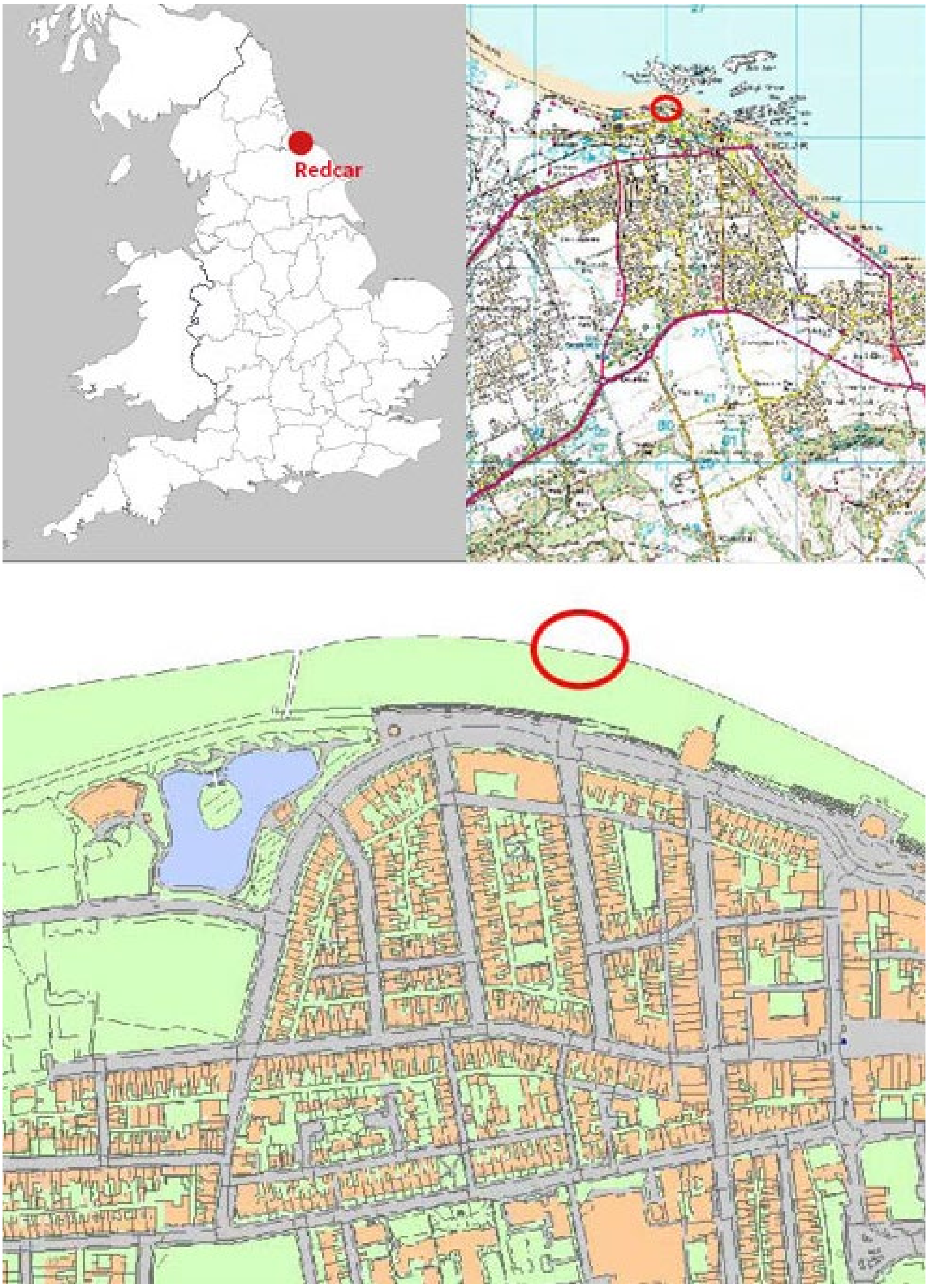
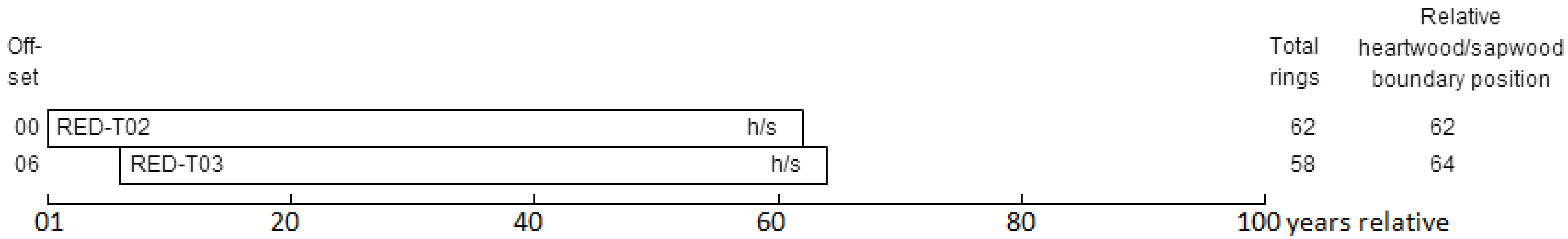



*Figure 1: Maps to show the location of the submerged timbers at Newcomen Terrace in Redcar, circled. Scale: top right 1:52,913; bottom 1:3,307. © Crown Copyright and database right 2022. All rights reserved. Ordnance Survey Licence number 100024900*

*Figure 2a/b: General views of the foreshore area looking north-west (top) and south-west (bottom) Regent Cinema to mid-view with Redcar Beacon beyond (photographs by Robert Howard)*

*Figure 3a/b: General views of foreshore tree-stumps (photographs by Robert Howard)*

*Figure 4a/b: General views of possible fallen trees (top) and possible worked timbers (bottom; photographs by Robert Howard)*




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

*Figure 5: Bar diagram of the samples in site chronology REDTSQ01*

## DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

RED-F01A 47
311 439 582 457 346 287 423 363 185 202 295 317 303 364 270 228 185 202 164 125
112 123 140 110 135 112 103 92 118 121 118 168 276 290 269 156 192 209 143 160
143 220 175 179 157 156 178
RED-F01B 47
317 409 557 482 328 308 411 364 196 207 273 300 293 317 226 178 193 170 178 127
110 107 157 90 151 120 115 129 129 148 123 157 232 281 272 138 184 220 140 118
176 239 168 173 154 151 190
RED-F02A 62
259 260 354 254 225 250 250 249 246 298 242 324 254 207 193 121 134 107 132 185
146 149 147 141 196 171 157 153 110 118 128 89 108 152 115 120 153 148 126 121
120 170 153 121 112 127 138 134 138 129 192 150 146 171 148 180 139 163 132 109
131 129
RED-F02B 62
267 290 328 274 219 236 233 248 256 294 257 334 269 245 185 118 142 110 140 185
147 138 157 140 195 161 183 172 127 125 136 102 100 145 112 120 157 135 117 128
121 170 146 130 115 120 146 128 143 123 198 157 140 173 153 168 140 165 121 118
130 124
RED-F03A 58
195 202 210 293 238 280 240 150 212 158 150 179 144 203 167 150 146 146 181 182
164 166 168 163 171 149 125 154 133 148 144 132 113 103 103 135 170 128 100 117
155 131 150 120 195 179 194 192 200 168 171 179 145 131 140 151 114 157
RED-F03B 58
204 234 173 309 268 285 241 166 198 174 148 155 146 197 182 152 145 139 186 164
172 165 165 159 190 142 121 161 128 146 134 119 117 94 115 139 153 117 101 118
149 150 139 135 189 168 192 200 208 162 165 184 141 135 145 146 104 160
RED-F04A 39
275 388 329 366 90 39 62 74 126 112 134 124 148 178 157 286 282 338 395 329
464 353 369 301 264 331 253 248 250 261 237 173 175 103 96 109 182 194 198
RED-F04B 39
262 455 315 370 71 58 65 72 119 109 136 127 137 181 161 294 262 339 409 313
448 368 338 307 261 324 265 235 246 248 262 184 167 123 93 100 184 207 208
RED-F05A 37
345 482 391 313 332 384 353 430 360 370 368 456 366 456 367 401 389 398 326 348
310 289 378 265 268 193 318 300 314 300 262 263 312 192 176 212 234
RED-F05B 37
340 502 383 300 343 382 356 440 382 353 347 465 343 459 357 401 425 376 348 368
336 296 382 275 253 226 309 309 307 295 257 286 295 209 182 201 227

# APPENDIX: TREE-RING DATING

## The Principles of Tree-Ring Dating

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

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

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

### *1. Inspecting the Building and Sampling the Timbers.*

Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

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

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

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

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

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


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

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


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

## 2. *Measuring Ring Widths.*

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

## 3. *Cross-Matching and Dating the Samples.*

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

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

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for

C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

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

### *4. Estimating the Felling Date.*

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

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

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 40 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 40 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. Oak boards quite often come from the Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

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

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

### *5. Estimating the Date of Construction.*

There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998; Miles 1997, 50–5). Hence, provided that all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after

(Laxton *et al* 2001, fig 8; 34–5, where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storage before use, or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

### *6. Master Chronological Sequences.*

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

### *7. Ring-Width Indices.*

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

*t*-value/offset Matrix

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

Bar Diagram

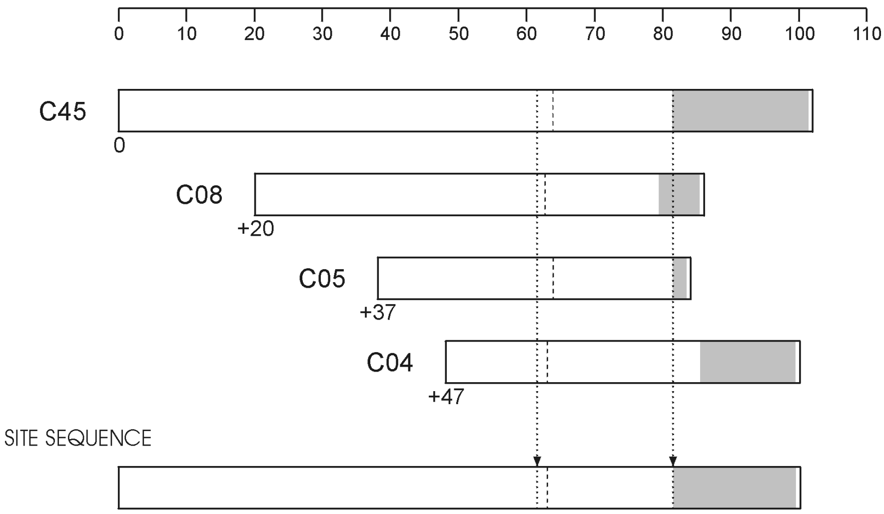



*Figure A5:  Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them*

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

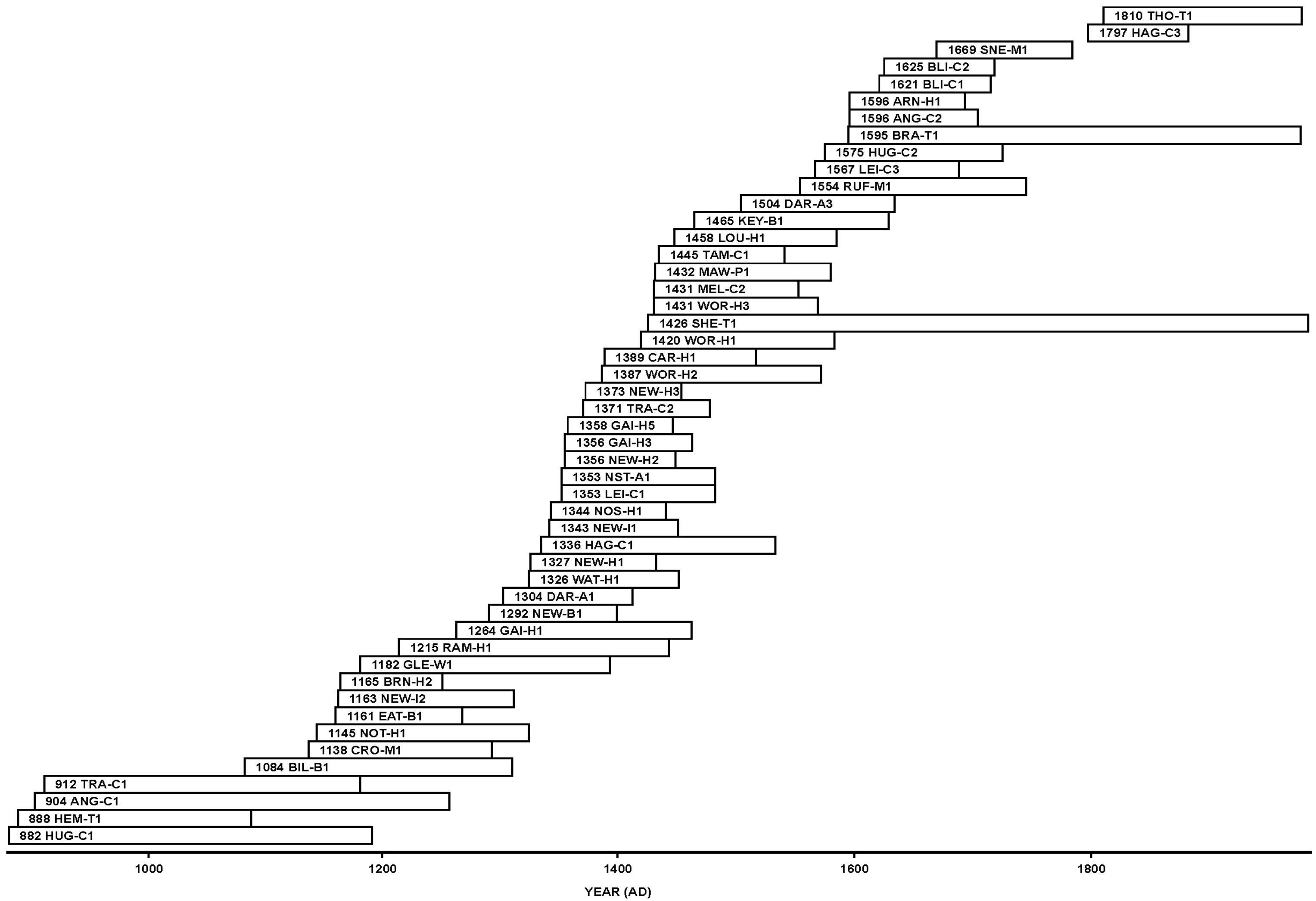
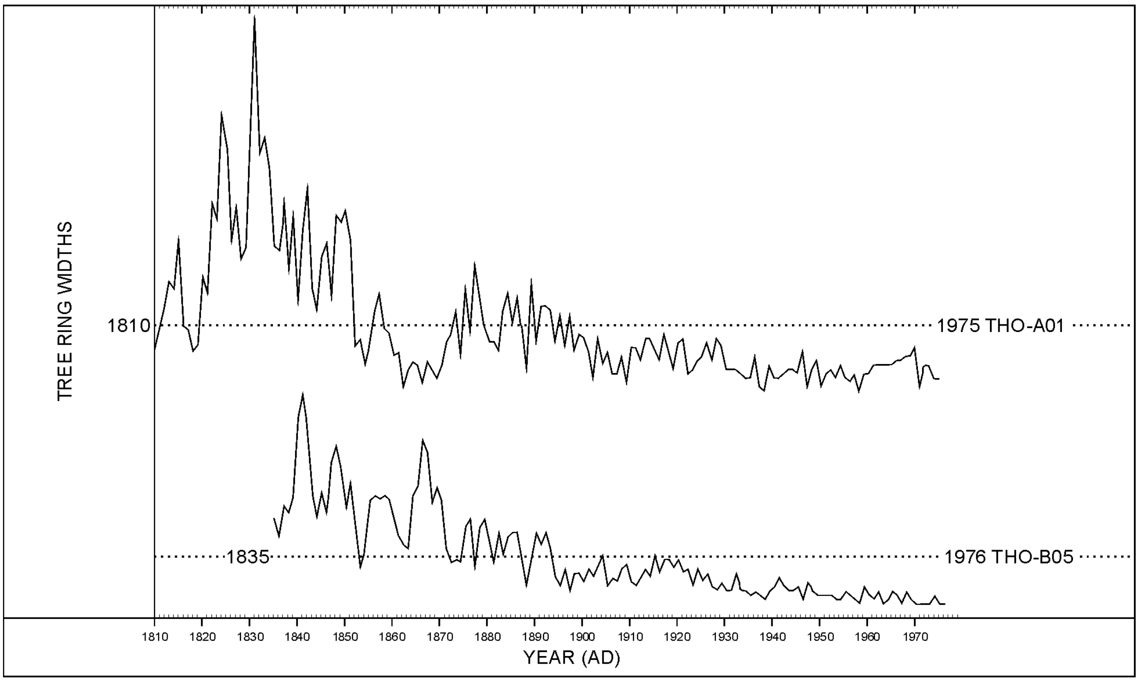



*Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87*

(a)




(b)

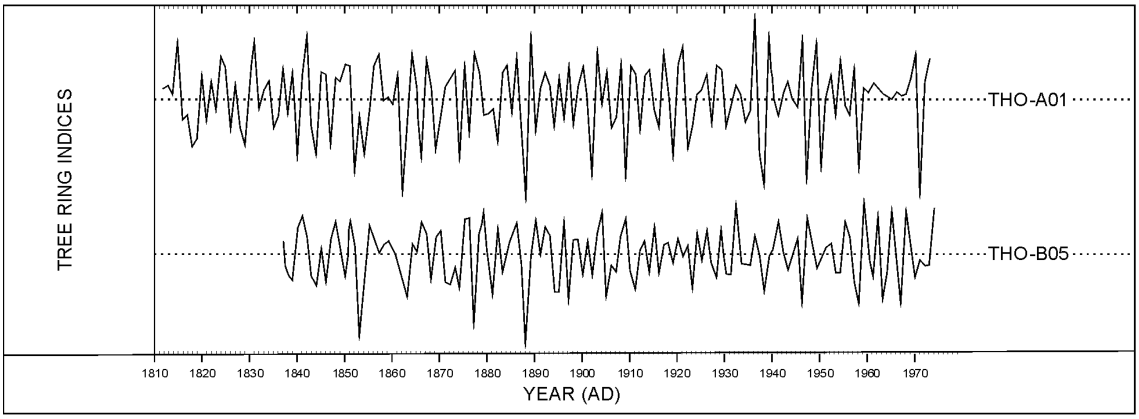



*Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known*

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

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

The growth trends have been removed completely

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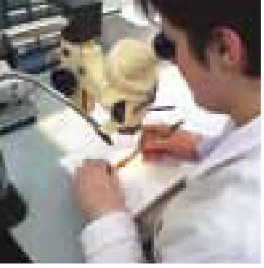
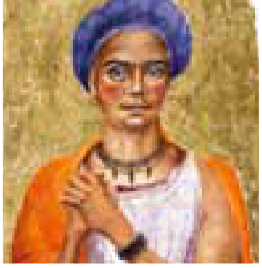


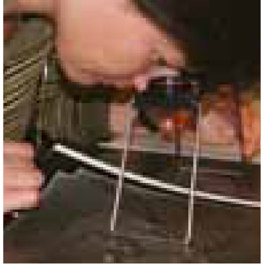


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