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55 AND 57 WESTGATE ROAD, NEWCASTLE UPON TYNE
TREE-RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold, Robert Howard and Cathy Tyers

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Research Department Report Series 95/2007

55 and 57 Westgate Road, Newcastle upon Tyne
Tree-Ring Analysis of Timbers

Alison Arnold[1], Robert Howard[1] and Cathy Tyers[2]

Summary

Core samples were obtained from 33 pine timbers from what appeared to be two phases of roof construction of this very fine building at 55 and 57 Westgate Road, Newcastle upon Tyne. The analysis of these samples produced six site chronologies, NWCFSQ01–SQ06, comprising between two and ten samples. These site chronologies range in length from 80 to 190 rings.

Despite being compared to an extensive collection of relevant reference material, none of the six site chronologies, or any of the remaining ungrouped pine samples, could be dated.

Keywords

Dendrochronology
Standing Building

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Introduction

The building which now forms 55 and 57 Westgate Road in Newcastle upon Tyne (NZ 246 639, Figs 1 and 2) is listed as grade-II*. It is of three storeys, plus attics, and has seven bays fronting the road. Although there may be fragmentary medieval fabric in the cellars, the bulk of the building is stylistically of late-seventeenth century date, substantially remodelled in the mid-eighteenth century. To the rear, out of view of the general public, are several rooms, the walls and ceilings of which are decorated with very fine plastered swags and figurines; the stairs, topped with its domed ceiling, is particularly impressive. In long-term use as a noted local supplier of artist's materials, and the offices of Newcastle Arts Centre, the building has suffered from a general lack of day-to-day maintenance and has undergone some, albeit relatively minor, alteration commensurate with retail functions. Since the close of business there has also been the theft of some fixtures and fittings, such as the stair balustrade. As a result of gradual neglect the building has been placed on English Heritage's Building at Risk register.

There are no timbers visible to the lower floors which would help determine the date of the building by dendrochronology, and it is only in the roof that any timber is accessible. It would appear that these roof timbers, all of pine, represent two phases of construction. The earlier roof appears to have been formed of at least six principal-rafter king-post trusses, there being short raking struts from near the ends of the tiebeams to the principal rafters. The heads and feet of the king posts are straight, not 'joggled'. A section of ridge piece survives on the earlier roof trusses at the east gable, and there are sockets at corresponding levels in the chimney stacks rising from the spine wall and in the west gable. The date of this earlier roof is unknown, but on the basis of its form of construction, it is believed to date to the later-seventeenth century.

At some point, much of the timber of this earlier roof was cut out and removed and a second roof was constructed, this later work 'fossilising' the remaining timbers of the earlier roof. Why the earlier roof was not removed entirely is not understood. This second, or later, roof again comprises six principal-rafter king-post trusses, these being set immediately against the remnants of the trusses from the earlier roof. There are again struts, or, more correctly, raking braces, to these more recent trusses, which rise to the principal rafters from 'shoulders' ('sloping joggles') near the base of the king posts and, instead of being straight as in the earlier roof, the heads of the king posts have 'splayed heads' where they receive the principal rafters. The date of this later roof is also unknown, but it is believed, again based on the form of its construction, to date to the mid-eighteenth century. A view of a typical set of timbers, showing primary and secondary timbers, is given in Figure 3.

Sampling

Sampling and analysis by tree-ring dating of the timbers within 55 and 57 Westgate Road were commissioned by English Heritage at the request of the North East Regional Historic Building Team. The purpose of analysis was to attempt to produce dating evidence from the timbers and hence inform forthcoming grant-aided repairs. In addition this assemblage of pine timbers provided a good opportunity to further the English Heritage research programme on the dendrochronological analysis of conifers. This ongoing research project has, when the opportunity has arisen, been investigating the viability and value of analysing conifer timbers from historic contexts (Groves 2000). The primary aim is to extend the scope of British dendrochronology to allow the production of dating evidence for conifer structures, the timbers of which, according to documentary evidence, forest history and recent dendrochronological studies (eg Groves 2002, Groves and Locatelli 2005, Howard *et al* 2006), are likely to have been imported. Successful analysis has the benefit of not only providing dating evidence for the building under investigation but also information relating to the source of the timber and hence the trade in timber.

Thus, from the timbers available a total of 33 core samples was obtained. Each sample was given the code NWC-F (for Newcastle, site 'F), and numbered 1–33. Twelve samples, NWC-F01–12, were obtained from the smaller number of earlier timbers available (designated as 'red' timbers in the accompanying plans), whilst 21 samples, NWC-F21–41, were obtained from the larger number of second phase roof timbers (designated as 'grey' timbers in the accompanying plans). Due to the potential difficulties associated with the analysis of imported conifers (eg Groves 2000; Groves 2004), a more extensive sampling strategy is usually applied, and in this instance all potentially suitable timbers associated with both roofs were sampled.

The positions of these samples were marked at the time of coring on plans made by Simpson and Brown, Architects, and provided by English Heritage (Fig 4). Details of the samples are given in Table 1. The trusses have been numbered from east to west and other elements identified on a north or south basis as appropriate.

The Laboratory would like to take this opportunity to thank Mr Michael Tilley, now owner of 55 and 57 Westgate Road, for his dedication to the restoration and renovation of this building, and for his enthusiasm for this programme of tree-ring analysis. We would also like to thank John Nolan of Northern Counties Archaeological Services for the use of his notes on the description and phasing of the building. Various dendrochronologists from Scandinavia and countries around the Baltic Sea have kindly either carried out cross-dating procedures or made reference data available. Reference data has also been obtained from the International Tree-Ring Data Bank based in Boulder, Colorado, funded by the National Geophysical Data Center (part of the World Data Center).

Analysis

Each of the 33 samples obtained was prepared by sanding and polishing. It was seen at this point that three samples, NWC-F06, F27 and F31, had too few rings for reliable analysis and they were rejected. The growth-ring widths of the remaining 30 samples were measured, however, and compared with each other by the Litton/Zainodin grouping procedure (see appendix). At a minimum value of t=4.5, six groups of cross-matching samples could be formed, the relative positions of these being shown in the bar diagrams of Figures 5–10. The cross-matching samples of each group were combined at their indicated off-set positions to form site chronologies NWCFSQ01–SQ06.

Since the timbers were likely to date to the mid-seventeenth to mid-eighteenth century, it was anticipated that they were probably imported from Scandinavia or ports on the Baltic or White seas. Each site sequence, and each of the six remaining ungrouped samples, was therefore compared to an extensive range of European pine reference chronologies, including those available from Scottish sites, which consist of both native and imported timbers. There was however, no satisfactory cross-matching. Consequently the site sequences and ungrouped samples were also compared with reference chronologies from Canada and the north-eastern area of the United States of America, but again no consistent conclusive results were obtained for any of the ring sequences. The data were sent to various colleagues in possible source areas but, despite these exhaustive checks, no reliable results were obtained for any of the ring sequences, and thus the dendrochronological analysis has been unable to provide precise calendar dates for any of the timbers. This analysis is summarised below.

Site chronology	No. of samples	No. of rings	Date span
NWCFSQ01	10	190	undated
NWCFSQ02	4	122	undated
NWCFSQ03	2	98	undated
NWCFSQ04	2	93	undated
NWCFSQ05	4	82	undated
NWCFSQ06	2	80	undated

Interpretation and conclusion

Analysis by tree-ring dating of material from Westgate Road has produced six site chronologies comprising between two and ten samples, these site chronologies being between 80 and 190 rings long. It is noticeable that of the various site chronologies created, the one with the most samples is made up entirely of material from the earlier roof. This, combined with the generally high *t*-values obtained between the individuals included in this group, would suggest that the timbers used in this roof are from the same locality or woodland. In addition, the variation in the relative dates of the heartwood-sapwood boundaries is consistent with these timbers being the product of a single felling period. The material from the later roof produces somewhat less satisfactory cross-matching, which could be the result of the use of timber from multiple diverse sources, but is also likely to have been adversely affected by the relative shortness of the ring sequences from this later roof. The timbers in the later roof have noticeably wider average ring widths and shorter ring sequences than those used in the early roof (Fig 11) implying that these timbers were derived from shorter-lived, faster-grown trees. The dendrochronological analysis of the later timbers therefore cannot either confirm or refute whether the timbers used represent a single phase of felling.

The failure to produce any reliable dendrochronological dates for any of the pine timbers from either of the roofs is clearly disappointing, particularly in the light of recent successes with various conifer assemblages (eg Groves and Locatelli 2005; Howard *et al* 2006; Arnold *et al* forthcoming). The dendrochronological dating of conifer timber in this country is, however, in its infancy and the lack of success seen here should not be regarded as discouraging. A significant percentage of timbers from successfully analysed sites have far more than 100 rings, and at 107 Jermyn Street it was noticeable that none of the samples analysed which had less than 100 rings were successfully dated (Groves and Locatelli 2005). Whilst this does not explain the failure to date the well-replicated 190-year site sequence, NWCFSQ01, from the early roof timbers, the remaining site chronologies produced are all relatively short and none is particularly well-replicated, thus reducing the chances of successful dating. However, as the conifer research project progresses and relevant reference data becomes more extensive, both from sites in England and potential source areas, it may prove possible to provide dates for at least some of the material from these two roofs.

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Table 1: Details of samples from 55 and 57 Westgate Road, Newcastle upon Tyne

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	'Red' (earlier) phase timbers					
NWC-F01	King post, truss 1	135	30	------	------	------
NWC-F02	South principal rafter, truss 2	74	no h/s	------	------	------
NWC-F03	King post, truss 2	117	no h/s	------	------	------
NWC-F04	King post, truss 3	126	38	------	------	------
NWC-F05	South principal rafter, truss 3	110	46	------	------	------
NWC-F06	South strut, truss 3	nm	---	------	------	------
NWC-F07	King post, truss 4	88	no h/s	------	------	------
NWC-F08	King post, truss 5	110	21	------	------	------
NWC-F09	South principal rafter, truss 4	125	61	------	------	------
NWC-F10	South strut, truss 4	100	no h/s	------	------	------
NWC-F11	King post, truss 6	160	50	------	------	------
NWC-F12	South principal rafter, truss 6	143	28	------	------	------
	'Grey' (later) phase timbers					
NWC-F21	North principal rafter, truss 1	62	no h/s	------	------	------
NWC-F22	Tiebeam, truss 1	188	no h/s	------	------	------
NWC-F23	North strut, truss 1	88	26	------	------	------
NWC-F24	South principal rafter, truss 1	71	47C	------	------	------
NWC-F25	Tiebeam, truss 2	97	20	------	------	------
NWC-F26	King post, truss 2	90	no h/s	------	------	------
NWC-F27	North strut, truss 2	nm	---	------	------	------
NWC-F28	Tiebeam, truss 3	73	no h/s	------	------	------
NWC-F29	North principal rafter, truss 3	69	35	------	------	------
NWC-F30	King post, truss 3	101	h/s	------	------	------

Table 1: Continued

Sample number	Sample location	Total rings	*Sapwood rings	First measured ring date	Last heartwood ring date	Last measured ring date
	'Grey' phase timbers continued					
NWC-F31	North strut, truss 3	nm	---	------	------	------
NWC-F32	North upper purlin, truss 3–4	138	64C	------	------	------
NWC-F33	South lower purlin, truss 3–4	82	18	------	------	------
NWC-F34	North principal rafter, truss 4	70	28	------	------	------
NWC-F35	North strut, truss 4	68	31C	------	------	------
NWC-F36	South principal rafter, truss 4	61	35	------	------	------
NWC-F37	King post, truss 5	80	10	------	------	------
NWC-F38	North principal rafter, truss 6	73	33	------	------	------
NWC-F39	North strut, truss 6	75	24	------	------	------
NWC-F40	King post, truss 6	98	h/s	------	------	------
NWC-F41	Tiebeam, truss 6	73	no h/s	------	------	------

*h/s = the heartwood/sapwood boundary
C = complete sapwood is retained on the sample

Figure 1: Map to show general location of 55 and 57 Westgate Road, Newcastle upon Tyne.

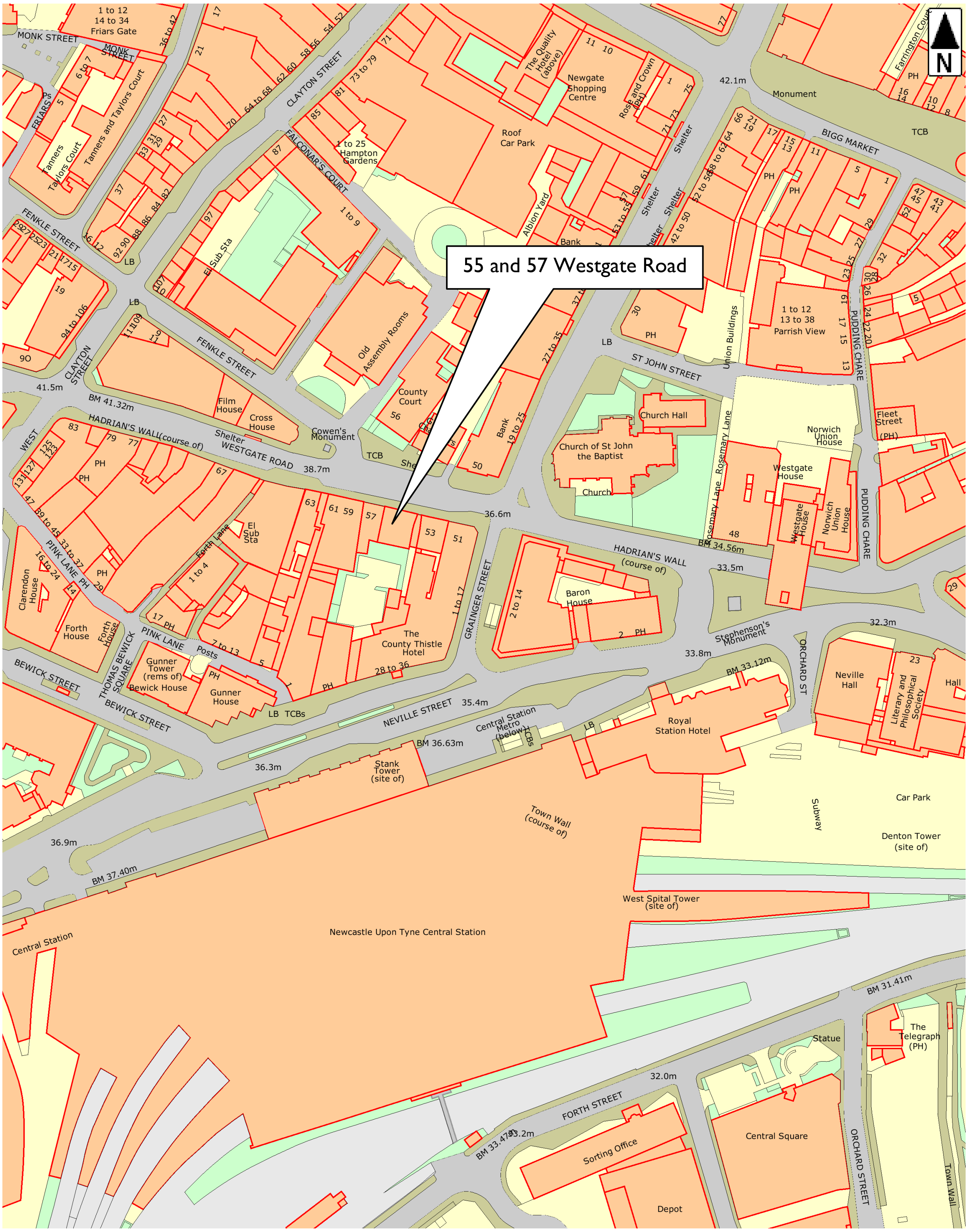


Figure 2: Map to show specific location of 55 and 57 Westgate Road, Newcastle upon Tyne.

Figure 3: View of the roof showing the earlier 'red' phase timbers behind the later 'grey' phase timbers

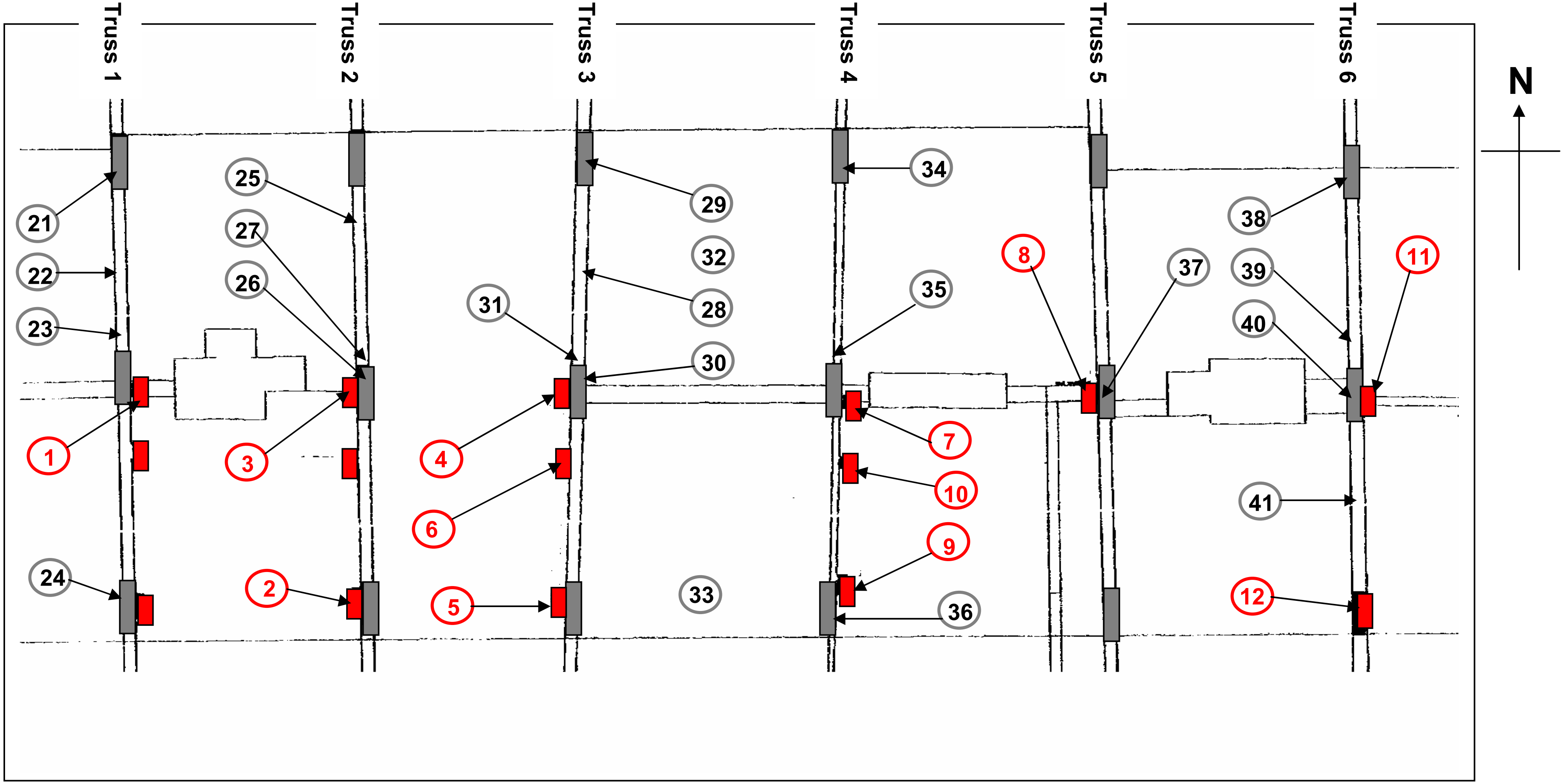


Figure 4: Plan to show location of samples from the earlier seventeenth-century timbers (red) and the later eighteenth-century timbers (grey)

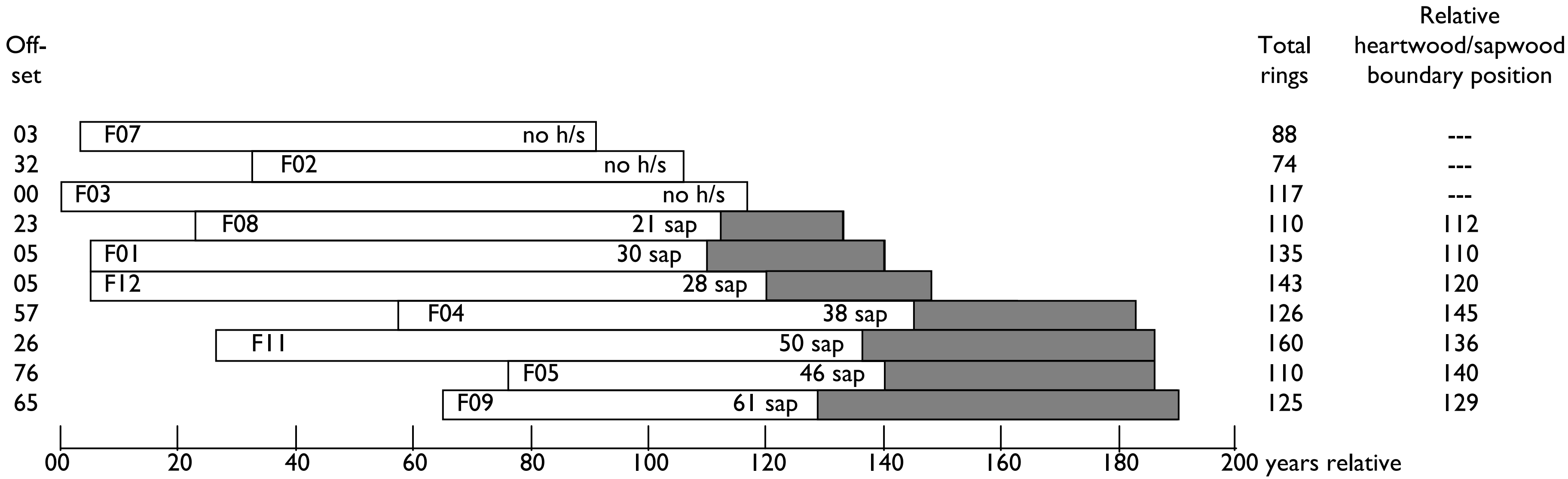


Figure 5: Bar diagram of the samples in site chronology NWCFSQ01

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

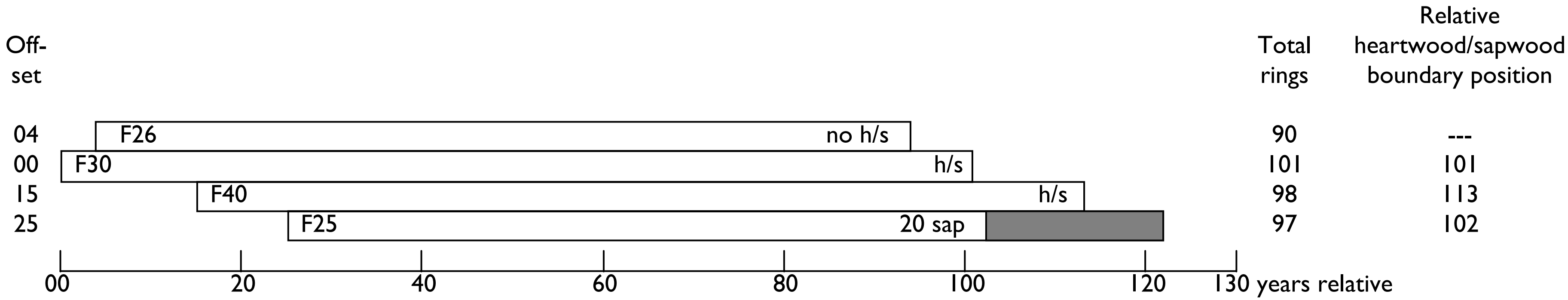


Figure 6: Bar diagram of the samples in site chronology NWCFSQ02

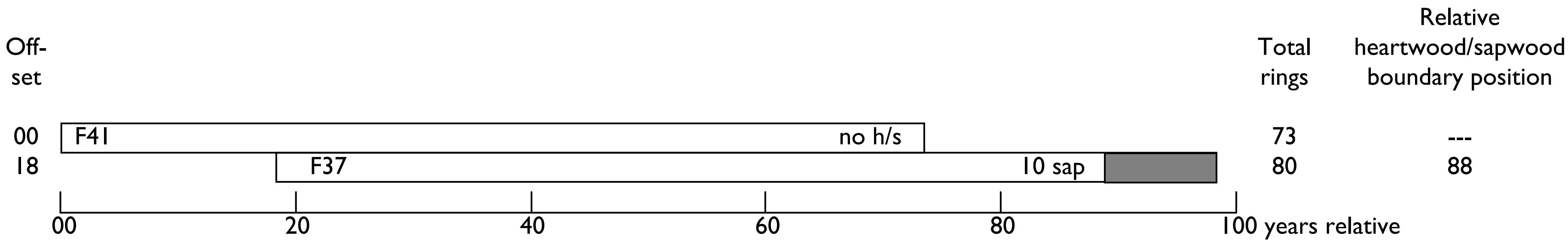


Figure 7: Bar diagram of the samples in site chronology NWCFSQ03

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

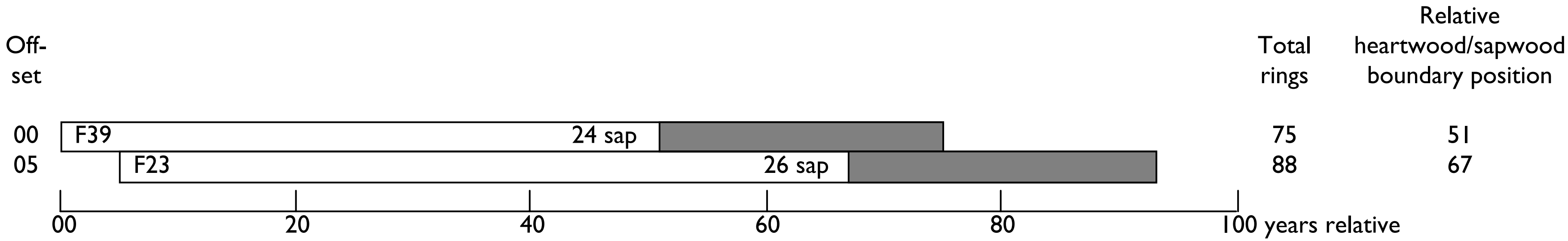


Figure 8: Bar diagram of the samples in site chronology NWCFSQ04

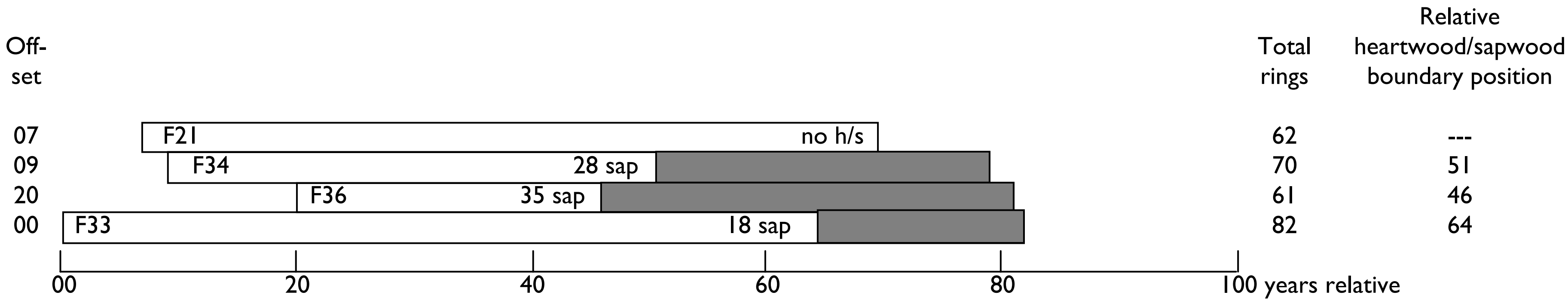


Figure 9: Bar diagram of the samples in site chronology NWCFSQ05

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

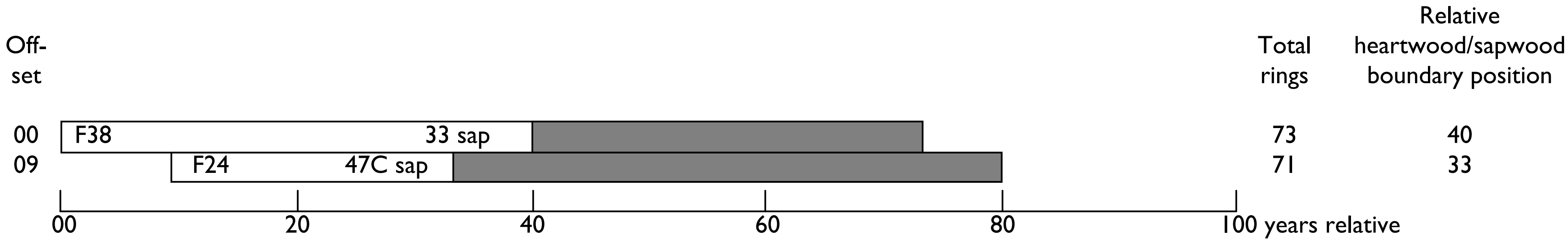


Figure 10: Bar diagram of the samples in site chronology NWCFSQ06

White area = heartwood rings, shaded area = sapwood rings
C = complete sapwood is retained on the sample

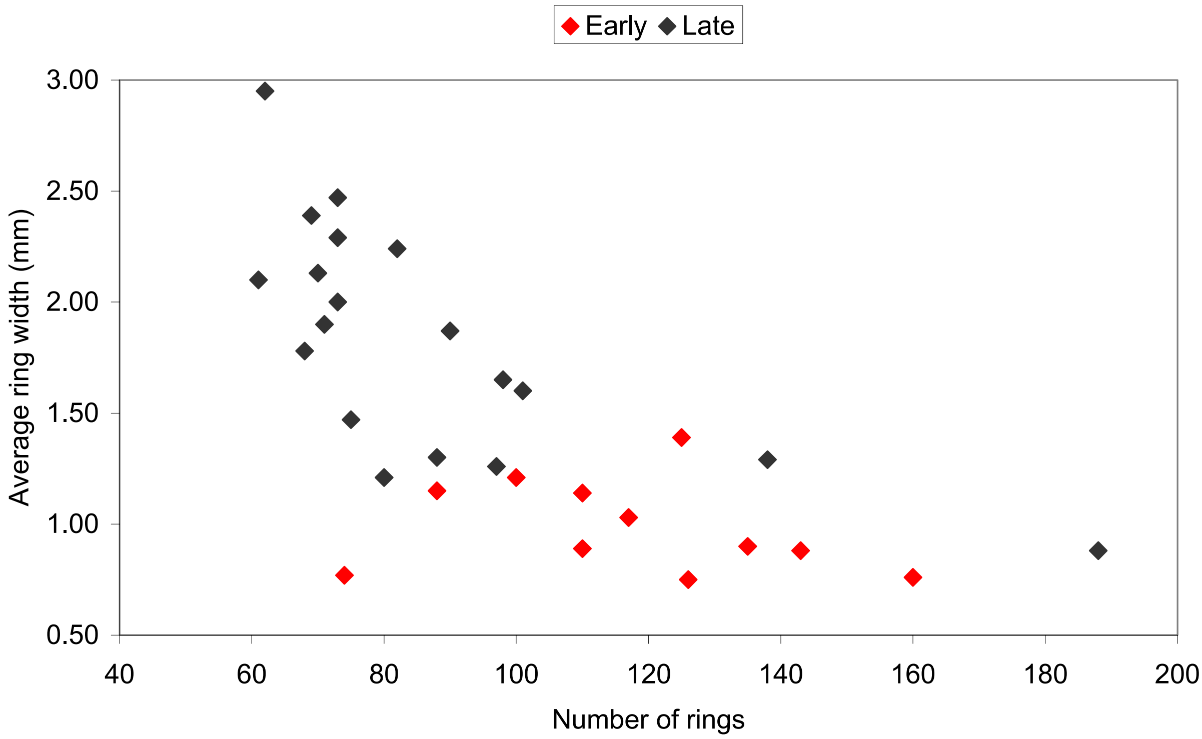


Figure 11: Diagram comparing the ring sequence length and average ring widths of the earlier roof timbers and the later roof timbers. Ring sequence lengths are, in the absence of pith and bark, an underestimate of tree age. Pine trees have a noticeable growth trend of decreasing ring width with increasing age, so the average ring widths tend to be an overestimate of growth rate, as it is the narrower outermost rings that have been trimmed from these timbers

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 8–10 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 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 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 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 2 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 2cm, 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 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 Figure 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 Figure 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

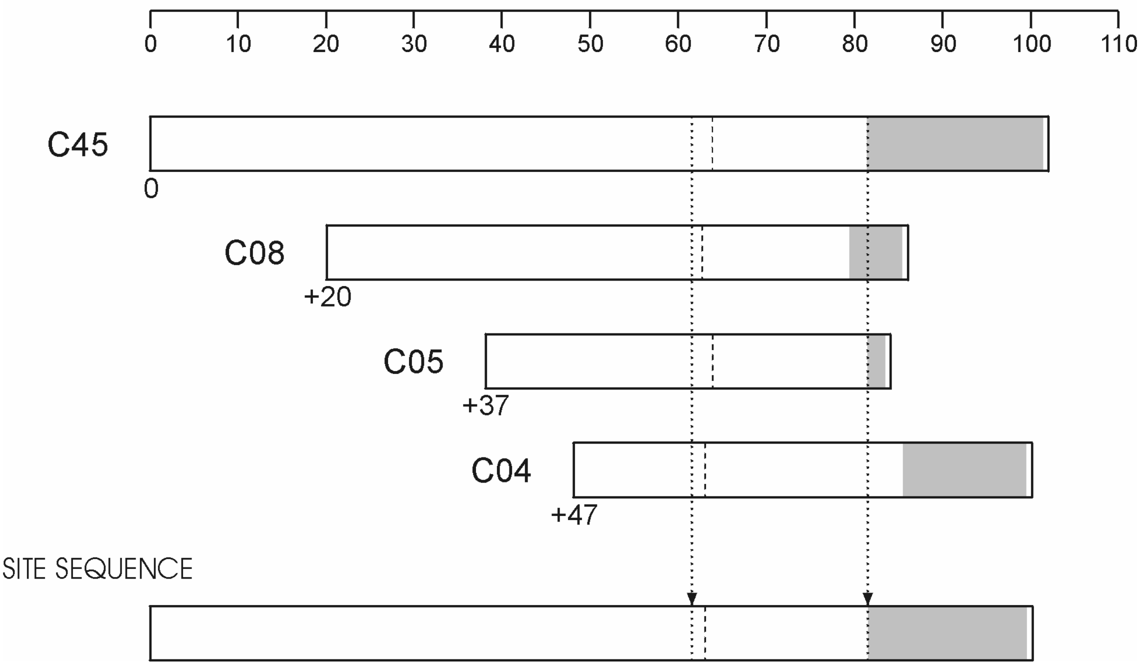


Figure 5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them.

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

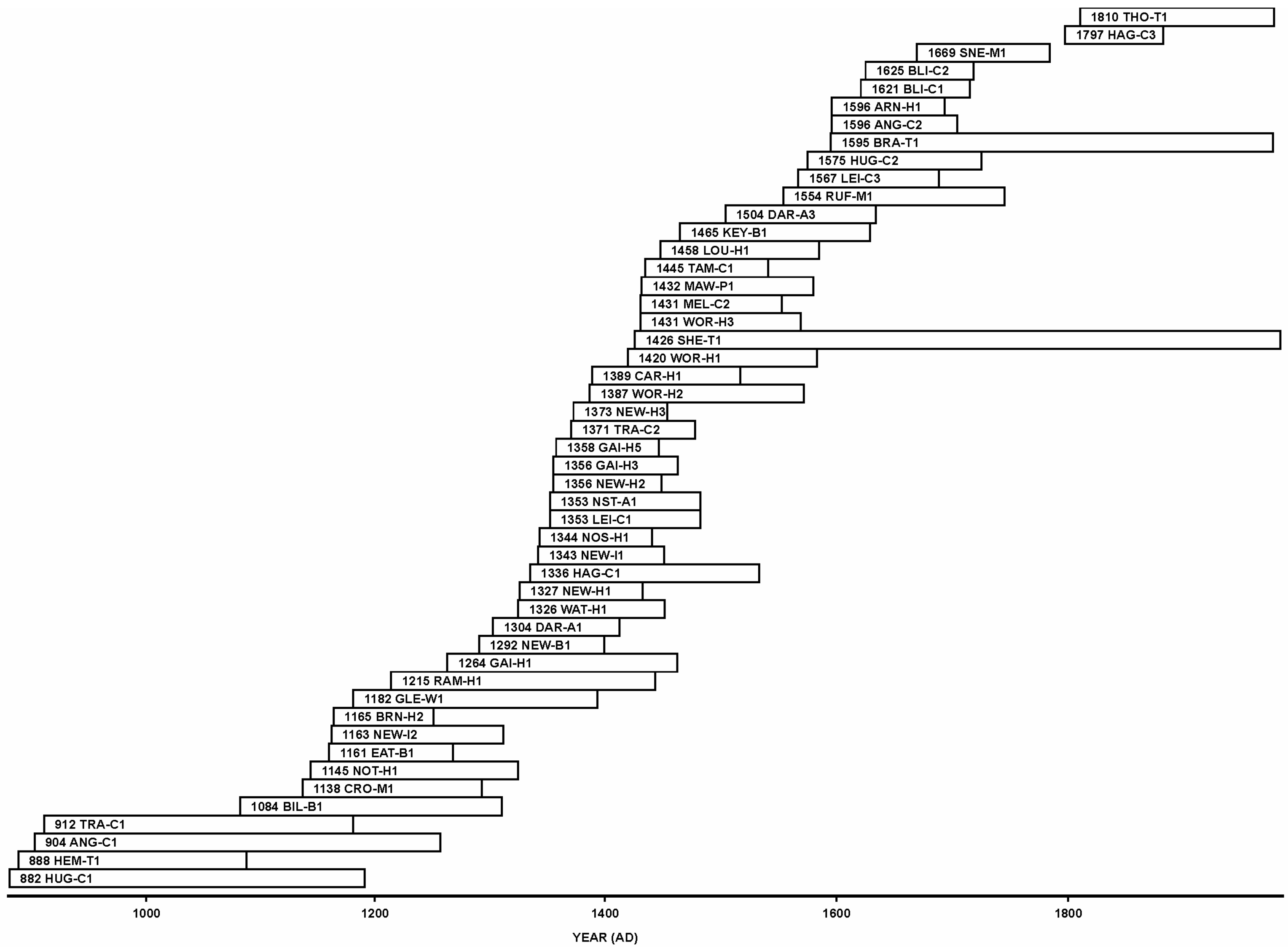
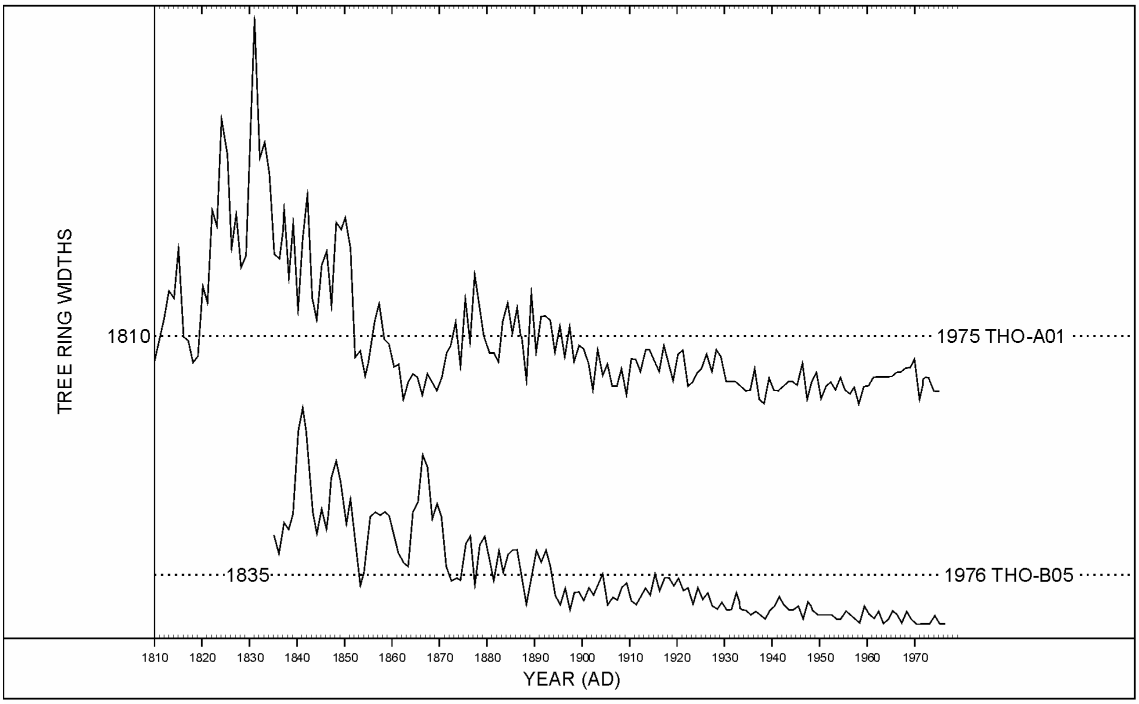


Figure 6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

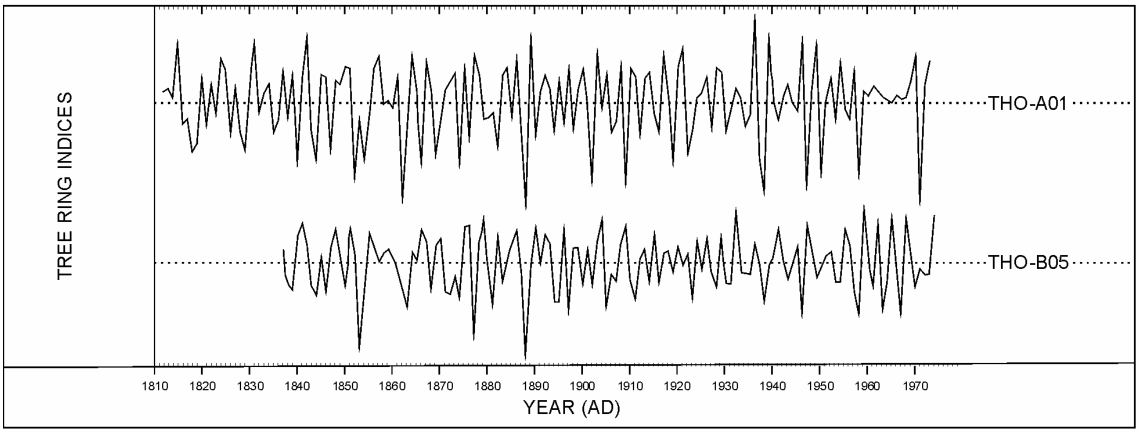


Figure 7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young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