2. *Measuring Ring Widths* Each core is sanded down with a belt sander using medium-gnt paper and then finished by hand with flourgrade-gnt paper The nngs 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 nng-widths measured individually from the innermost nng 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 nngs, no two sequences of nng 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 nng 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 Expenments earned 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 nng widths, LIN-C04, 05, 08, and 45, have been cross-matched with each other The nng 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 nng widths of C08 matches the sequence of nng widths of C45 best when it is at a position starting 20 nngs after the first nng of C45, and similarly for the others The actual *t*-values between the four at these offsets of best correlations are in the matnx Thus at the offset of +20 nngs, 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 nng-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 nng 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 f-value' method The actual method of cross-matching a group of sequences of ring-widths used in the Laboratory involves grouping and averaging the ring-width sequences and is called the 'Litton-Zainodin Grouping Procedure' It is a modification of the straight forward method and was successfully developed and tested in the Laboratory and has been published (Litton and Zainodin 1991, Laxton et *al* 1988)

4. ***Estimating the Felling Date*** As mentioned above, if the bark is present on a sample, then the date of its last ring is the date of the felling of its tree Actually it could be the year after if it had been felled in the first three months before any new growth had started, but this is not too important a consideration in most cases The actual bark may not be present on a timber in a building, though the dendrochronologist who is sampling can often see from its surface that only the bark is missing In these cases the date of the last ring is still the date of felling

Quite often some, though not all, of the original outer rings are missing on a timber The outer rings on an oak, called sapwood rings, are usually lighter than the inner rings, the heartwood, and so are relatively easy to identify For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure 2, both indicated by arrows More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear The builder, therefore, may remove some of the sapwood for precisely these reasons Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling

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

Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before (Oak boards quite often come from the Baltic and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56))

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure 2 was taken still had complete sapwood but that none of the soft sapwood rings were lost in coring By measuring into the timber the depth of sapwood lost, say 2 cm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

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

5. ***Estimating the Date of Construction*** There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998 and Miles 1997, 50-55) Hence provided all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after (Laxton *et al* 2001, figure 8 and pages 34-5 where 'associated groups of fellings' are discussed in detail) However, if there is any evidence of storing before use or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this

6. ***Master Chronological Sequences*** Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known In Fig 6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow This process is illustrated in Fig 6 We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981 It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram As can be seen, it is well

replicated in that for each year in this penod 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 laboratones 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 covenng many short penods

7. ***Ring-width Indices*** Tree-nng dating can be done by cross-matching the ring widths themselves, as descnbed 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 nng-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 nng-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 matunng A similar phenomena can be observed in the lower sequence of (a) starting in 1835 In both the widths are also changing rapidly from year to year The peaks are the wide nngs and the troughs are the narrow nngs 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

f-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

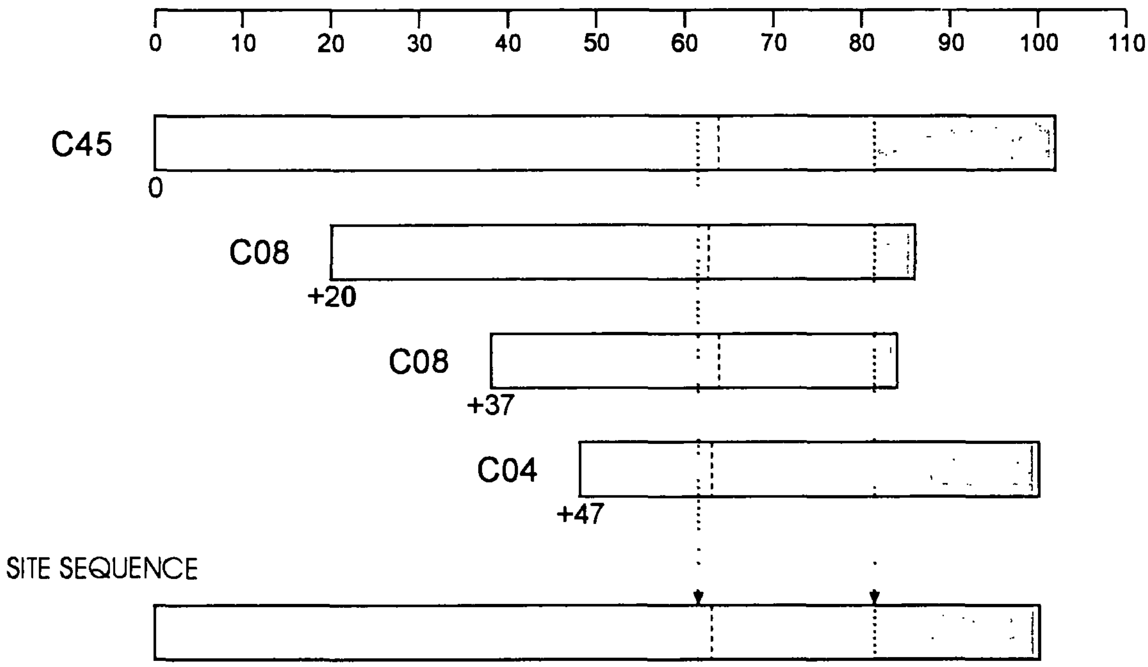


Figure 5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

The *b*ar 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 (*offs*ets) to each other at which they have maximum correlation as measured by the f-values

The f-value/offset matrix contains the maximum f-values below the diagonal and the offsets above it Thus, the maximum f-value between C08 and **C45** occurs at the offset of +20 rings and the f-value is then **5 6**

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

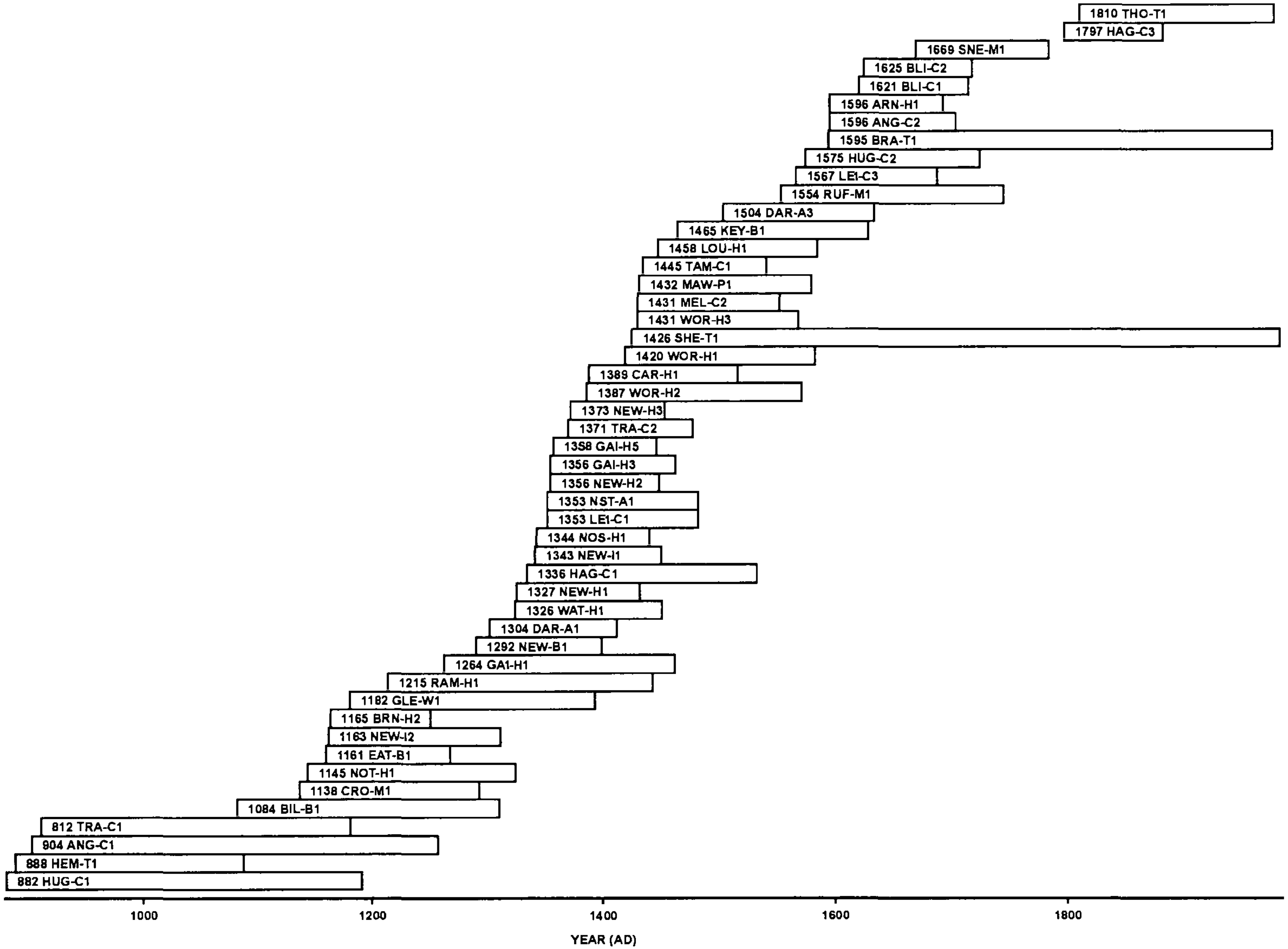
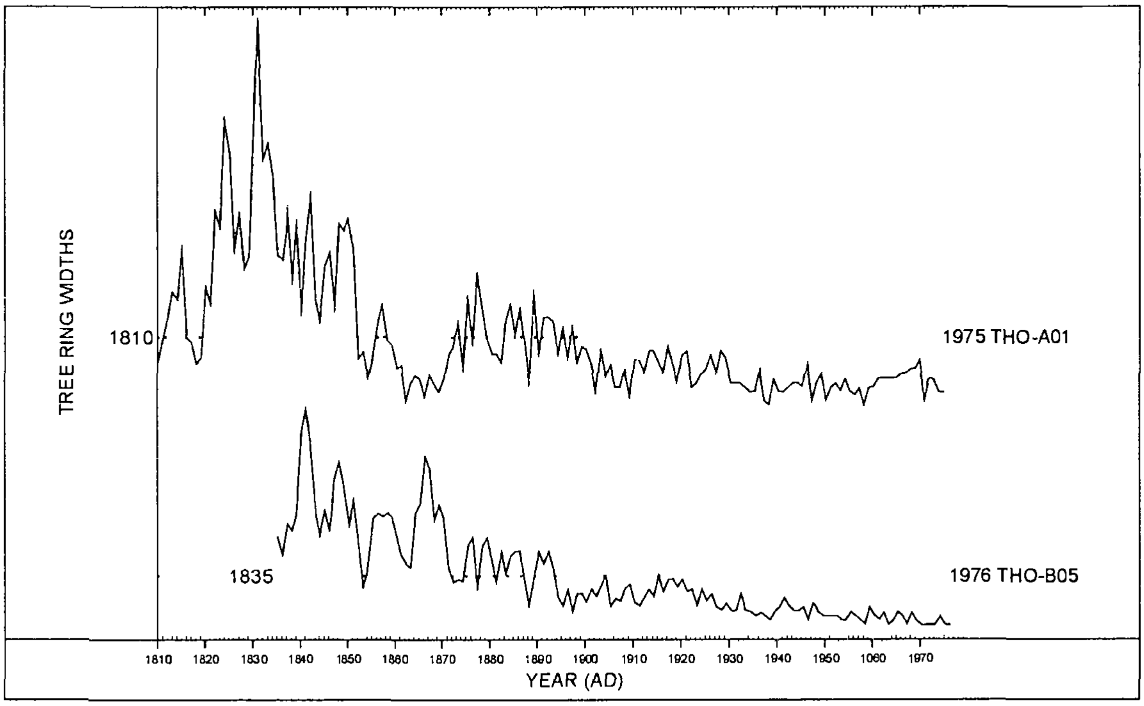


Figure 6· Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

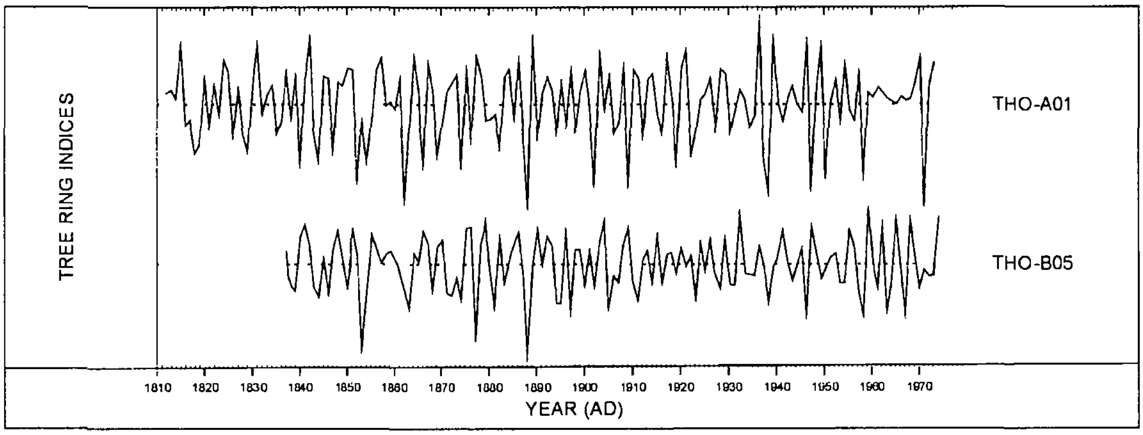


Figure 7 (a): The raw rıng-wıdths of two samples, THO-A01 and THO-B05, whose fellıng dates are known Here the nng wıdths are plotted vertıcally, one for each year, so that peaks represent wıde nngs and troughs narrow ones Notıce the growth-trends ın each, on average the earlıer rıngs of the young tree are wıder than the later ones of the older tree ın both sequences

Figure 7 (b). The *Baıllıe-Pılcher* ındıces of the above wıdths The growth-trends have been removed completely

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