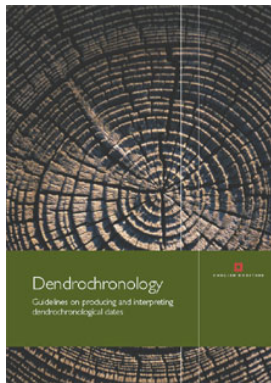




Historic England

Dendrochronology: Guidelines on producing and interpreting dendrochronological dates



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Dendrochronology

Guidelines on producing and interpreting
dendrochronological dates



ENGLISH HERITAGE

Preface

Twenty-five years ago the provision of absolute tree-ring dates on a routine basis was not available to British archaeologists and historians. Since then we have seen the production of a continuous tree-ring chronology in Ireland going back before 5000 BC, and an almost complete chronology for England. The world's oldest trackway, the Sweet Track, has been dated, and hundreds of precise dates have been provided for other historic and prehistoric sites and structures of all periods. The tree-ring samples and their data have in turn been used for radiocarbon calibration, climatological and other environmental studies, and even to suggest dates for eruptions of prehistoric volcanoes and changes in Chinese dynasties.

More recently the way the archaeological resource is managed has also changed dramatically. The publication of Planning Policy Guidance Notes 16 and 15 (PPG 16, Department of Environment 1990; PPG 15, Department of Environment and Department of National Heritage 1994) and *Management of archaeological projects* (English Heritage 1991) have had a profound effect on the management of archaeological and historical projects with much more emphasis put on conservation (Semple Kerr 1990). But in order to manage our historic buildings and archaeological remains efficiently, it is first necessary to understand them. Since the date of a structure is of primary importance to understanding, dendrochronology is being used more and more where there are wooden remains and timber-framed buildings. These guidelines have therefore been prepared as an aid to those involved with projects that might benefit from the use of dendrochronology.

Although dendrochronology is a simple dating method in concept, it cannot be used to its full potential without intelligent sampling and interpretation of the results. This guide aims to provide the user with a step-by-step introduction to dendrochronology. Although it can be used outside the British Isles, it is primarily aimed at the British user. It is not intended to replace the advice given by the dendrochronologist assigned to a particular project, but should be used as a complementary aid.

It is hoped that the guidelines will enable the user to be more critical of tree-ring results. While it is concerned primarily with the dating of structural timbers and artefacts, it includes information about the non-chronological data, which should be recorded as part of the sampling and analysis process, and summarises some of the current socioeconomic and environmental aspects of tree-ring research. It does not aim to cover the sampling and analysis of wood assemblages for woodland management studies (see instead English Heritage 1996).

The guidelines have been produced in the Sheffield Dendrochronology Laboratory and therefore reflect the methodology and standards in operation there. This does not necessarily imply that methods employed in other laboratories are inferior (see Appendix 1 for a list of contact addresses); and, clearly, it is not intended that these guidelines should in any way prohibit further development of methodology or recommended procedures. This is the first attempt to produce a guideline document for dendrochronology and therefore it is unlikely to be perfect. Any comments on this draft should be sent to the Ancient Monuments Laboratory (see address in Appendix 1) so that they can be considered for inclusion in future editions.

How to use the guidelines

The document is divided into two main sections together with a bibliography, contact addresses, and glossary.

Part 1 is a theoretical methodology section included for general interest and to provide a background to the practical advice given in Part 2. As well as describing the principles and history of dendrochronology, it gives a brief introduction to the methodology and indicates when dendrochronology should be used and what information it might provide. **Part 2** gives a step-by-step guide to the processes involved from planning a project through to the dissemination of results, with practical advice for the user at each stage.

It is not necessary to read the document from cover to cover, although it may be useful to anyone wanting a quick introduction to dendrochronology. **The user** (project managers, building historians, local government archaeologists, Inspectors of Ancient Monuments and Historic Buildings, Historic Buildings architects and conservation officers, owners of historic buildings and art-historical objects etc) should read Part 2, particularly the sections dealing with planning and sampling. For convenience, there are different sections for standing buildings, waterlogged wood, art-historical objects, and living trees. Section 2.7.1 on reporting standards may be helpful for determining whether a contracted dendrochronologist is following good practice. If further background is needed, Part 1 should be consulted. Experienced **dendrochronologists** should find little that is new in these pages, but newcomers to the field may find Part 2 useful in establishing a code of good practice when dealing with clients.

Conservators, environmental specialists, and wood technologists will also be familiar with much in these guidelines, but they may find Part 2 useful if they have to give advice to archaeologists or building historians. Finally, those in need of a quick reminder of the do's and don'ts of dendrochronology should refer to Appendix 2 for First Aid for Dendrochronology.

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Part I

An introduction to dendrochronology

1.1

What is dendrochronology?

Dendrochronology or **tree-ring dating** makes use of the annual pattern of growth shown by most tree species in temperate regions. Each year trees such as oak put on a layer of new wood under the bark. The thickness of that layer – the tree-ring – will depend on various factors. The genetic make-up of the tree and the type of soil in which it is rooted both play a role, as do other environmental factors, but generally it is climatic factors that determine whether the ring will be wide or narrow. Conditions favourable to growth will result in a wide ring; unfavourable ones will produce a narrow ring. Therefore, examination of the annual growth rings of a tree will reveal not only its age, but also the fluctuating climatic conditions during its lifetime. Within restricted geographical units, trees of the same species growing at the same time will show similar trends in tree-ring growth. This can be seen by measuring the widths of the rings from different trees, plotting them against time in years, and superimposing the plots, known as **tree-ring curves**. Trees in the same woodland will show a high degree of agreement in year-to-year variation over long periods of time. The latter is most pronounced in samples from the same tree and this very strong similarity can sometimes be used as a means of determining when two timbers have been cut from a single tree. The process of synchronising two ring patterns is known as **crossmatching** or **crossdating**. It should produce only one true position of match. Figure 1a shows the position of match between two ring sequences; if one of the sequences is offset by one year to either side of that illustrated, there would be no agreement between the two curves, and hence no tree-ring match (Fig 1b).

Although crossmatching shows up best between trees from the same site, similarity in ring pattern can also be seen between trees from different woodlands, particularly if a site master curve (made up from a group of trees from each woodland) is used. In this way, crossmatching can often be obtained over considerable distances, such as London to Belfast, Sheffield to Exeter, and even Worcester to southern Germany.



In order to make use of the chronological information contained in the tree-rings, long **tree-ring chronologies** have to be constructed by overlapping ring patterns from successively older samples (Fig 2). The aim is to produce a long year-by-year record of mean tree growth far back in time. In practice, the chronology will be constructed so that each year is represented by data from several samples of the same tree species. This process of **replication** is crucial for ensuring the validity of any reference chronology.

The tree-ring pattern from a timber of unknown date can then be compared to the ring pattern of the reference chronology to locate the portion with which it is most similar; a process not unlike that of fingerprinting. When an acceptable **match** has been found, the date of each ring on the test sample can be read off the reference graph with calendrical precision.

Dendrochronology is therefore an accurate and precise dating method and, since the production of tree-ring dates relies solely on the similarity between ring patterns, the results are completely independent of other dating evidence, history, or theory. The dates, provided they are produced by an experienced dendrochronologist and are from a secure context, should take precedence over those produced by any other means.

Dendrochronology has two major drawbacks: first, not all samples date; second, it only dates the rings in the wood sample. This is not necessarily the same as the date the timber was felled nor the date it was used. If bark is present, the date of the last measured ring will be the year in which the tree last grew, and the method will be precise to the year. If bark is not present, the date of felling will be less precise (see section 1.3.10).

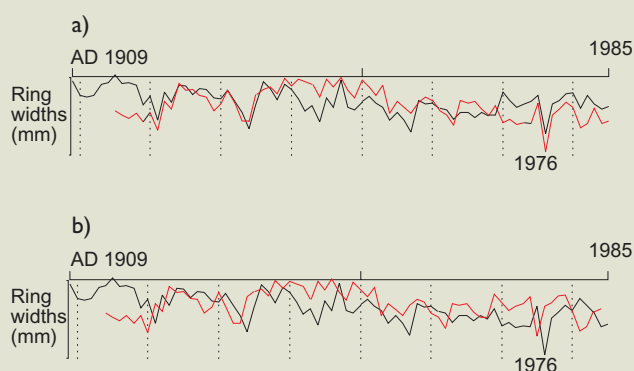


FIG 1 Ring patterns from two living oak trees at Quendon, Essex; both were sampled in 1985. The vertical scale is logarithmic: a) shows the curves in their matching position; the narrow ring at drought year 1976 is marked; b) shows the result of shifting one of the curves by just one year – there is no longer a match (J Dobie)

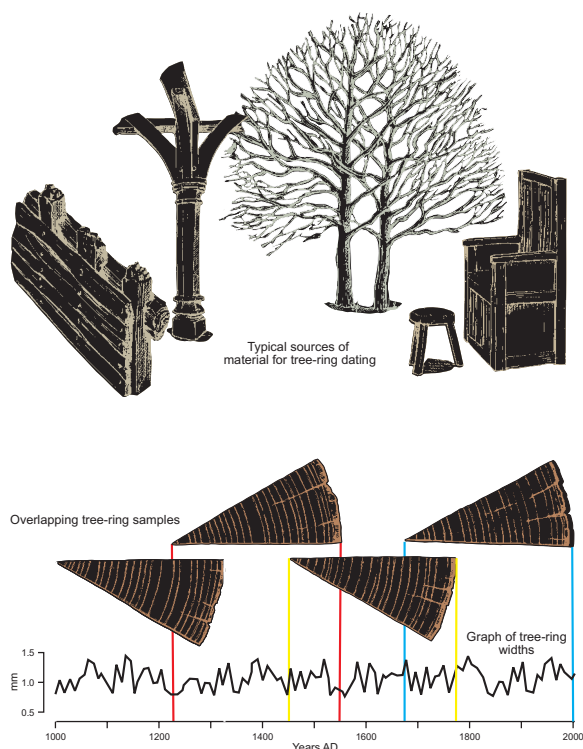


FIG 2 Chronology building (J Dobie)

1.2 Historical background

The science of dendrochronology was pioneered by A E Douglass, an American astronomer, early in the twentieth century. He used tree-rings as proxy climatic records to extend his climate data back in time further than written records. His major breakthrough came when he extended his tree-ring data from living trees by crossmatching them with a ring sequence from archaeological timbers, thus placing many previously undated prehistoric structures precisely in time. He and his successors at the Tree-Ring Laboratory in Tucson, Arizona, went on to construct long chronologies, including the 8200-year sequence from the long-lived bristlecone pines, which was used as the first radiocarbon calibration standard. Much of the crossmatching was done, not by measuring the absolute ring widths, but by comparing signature plots, which mapped the incidence of particularly narrow rings. An account of this early American work can be found in Baillie (1982) and in Schweingruber (1988). The method was taken up in Germany in the late 1930s, and was gradually introduced to other countries; Baillie (1982; 1995) describes its development in the British Isles. While American dendrochronology used data from conifers, European work depended mainly on oak (*Quercus* spp.), the major structural timber in many areas. The temperate nature of the climate, compared to that of the American Southwest, meant that signature plots were not the best aid to crossmatching. Instead each ring had to be measured and the ring widths represented as graphs for comparison purposes; only then did the tree-ring matches become apparent. In the 1960s and 70s, computer programs were developed to speed up the crossmatching process, to provide a statistical measure for the quality of the tree-ring match, and to handle the increasingly large amounts of tree-ring data that were being produced. The microcomputer is now indispensable to the modern tree-ring laboratory. However, most dendrochronologists still consider it necessary to check results by visual comparison of the tree-ring graphs.

1.2.1 Chronology coverage

There are now many long oak chronologies throughout Europe. The Northern Ireland chronology, for example, goes back to 5452 BC (Brown *et al* 1986; Pilcher *et al* 1995), while a German sequence from the Rhine area extends back to 8480 BC (M Spurk and M Friedrich

personal communication May 1997). Other species have also been used for dating purposes, but the potential of non-oak species for dating is only now beginning to be developed in Britain. In England, over the years, many regional sequences of oak have been constructed. These were initially dated by bridging them with chronologies from Germany and Ireland. For the historic period there is now a continuous sequence that runs from the present back to AD 404, and another from Roman contexts covering 434 BC – AD 315. The latter is still reliant on cross-links with Ireland and Germany for its dating since no English tree-ring sequence has been found that spans the fourth century AD. Both the ‘Roman’ chronology and the AD 404 to present-day sequence are represented by master sequences from many sites. **As a result, the chances of dating timbers from historic contexts in most parts of the British Isles are high. This is especially true if a replicated site master can be produced for the context, where each year of the chronology is represented by data from several samples.** There is some regional variation, however, and for the time being, dating tends to be less successful in areas such as south-west England and East Anglia. Research is underway in both areas to produce strong chronologies, which will help to alleviate this situation (Groves forthcoming (a); Tyers 1993). The English prehistoric period is covered by a sequence running from 323 BC back to beyond 5000 BC, but it includes data from only a few areas (Baillie 1995; Brown and Baillie 1992). The chances of dating timbers from prehistoric sites is therefore less good than for the historic period. But recent breakthroughs have included the successful dating of the Neolithic Sweet Track in the Somerset Levels, Bronze Age platforms at Flag Fen, Cambridgeshire,

and Caldicot, Gwent, and an Iron Age building at Goldcliff, also in Gwent.

Some of the more commonly used chronologies are listed in Table 1. All these chronologies contain data from more than one site, and therefore may not be independent. ‘England’ and ‘East Midlands’, for example, both contain data from Sherwood Forest, and therefore are not independent from the sequence from the early fifteenth century to the present. This interdependence of the chronologies has not always been understood, particularly by new workers who are unfamiliar with the development of tree-ring chronologies in the British Isles. Composite chronologies are useful as a guide to dating but should be backed up by correlation with *independent* chronologies, that is, those constructed from data from single sites.

1.3 Methodology

1.3.1 Preparation and initial examination

Samples should first be divided into oak and non-oak, since this will influence how their cross-sections are prepared. Oak is easily recognisable by its distinct bands of large spring vessels and wide medullary rays running radially from pith to bark (Figs 3 – 7). Any non-oak species can be identified by taking thin sections from the transverse, radial, and tangential planes, and identifying diagnostic features using a key, such as *The anatomy of European woods* (Schweingruber 1990) and *Computer-aided wood identification* (Wheeler et al 1986).

TABLE 1 Some of the commonly used composite oak chronologies. These all contain data from more than one site and are not always mutually exclusive. For example, components of REF6 and REF8 are also included in ENGLAND

CHRONOLOGY	DATE SPAN
BELFAST LONG CHRONOLOGY (Brown <i>et al</i> 1986)	5289 BC – AD 1981
EAST MIDLANDS (Laxton and Litton 1988)	AD 882 – 1981
ENGLAND (Baillie and Pilcher personal communication)	AD 404 – 1981
OXFORD (Haddon-Reece and Miles unpubl)	AD 1061 – 1987
REF6 (Fletcher 1977)	AD 780 – 1193
REF7 (Fletcher unpubl)	AD 993 – 1267
REF8 (Fletcher 1977)	AD 416 – 737
SCOTLAND (Baillie 1977)	AD 946 – 1975
SOUTHERN ENGLAND (Bridge 1988)	AD 1083 – 1589

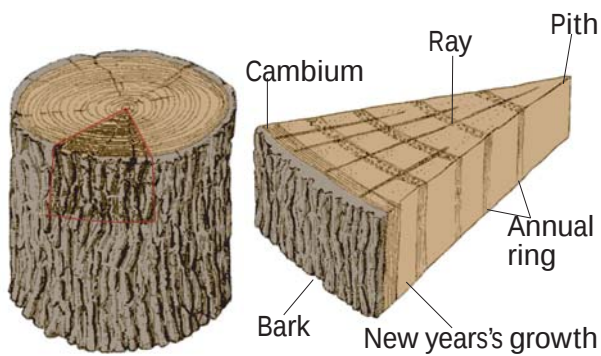


FIG 3 Cross-section of oak in relation to the parent trunk
(J Dobie)

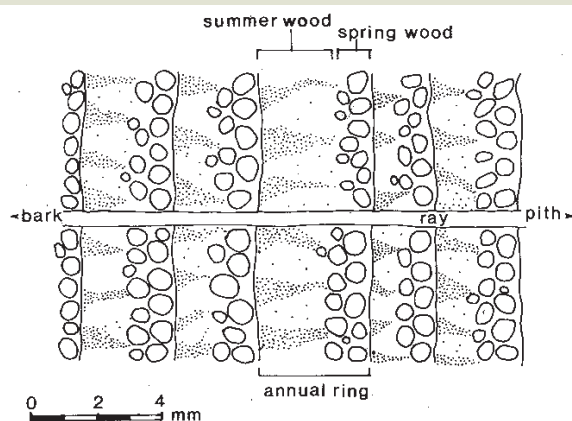


FIG 4 Sketch of oak structure as seen down the microscope
(J Dobie)

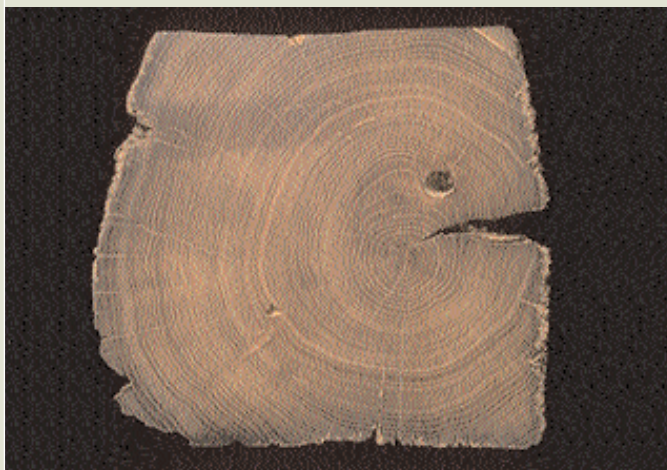


FIG 5 Slice of oak timber after its cross-section has been sanded © English Heritage Photographic Library

There are no hard and fast rules for the preparation of wood samples. The objective is to clean the cross-section so that the boundary of each ring is clearly visible; the means of obtaining this are often a matter of personal preference. Dry oak samples – slices and cores – are often prepared by paring or sanding the cross-sections (Figs 5 and 6).

Some laboratories use a power planer before sanding the sections. The size of grit used for sanding decreases from coarse to fine. Samples with narrow bands of rings will require a finer grit than those with average to wide rings. After sanding or paring, the boundaries of the rings can be highlighted by rubbing chalk into the surface of the cross-section. A thumb nail rubbed over the surface can also enhance the transition from one ring to the next! Wet samples are frozen for at least 48 hours and their cross-sections cleaned with a Surform plane and/or a sharp blade; they are then left to thaw (Fig 7). Oak timbers that have been conserved by freeze-drying or impregnation by PEG (polyethylene glycol wax) are generally pared with a knife. Rubbing the surface with a soft brush or wire wool sometimes makes the ring boundaries clearer. Charcoal samples can be snapped to give a clean break across the transverse section or cleaned with a soft brush.

The above techniques can also be used on samples of ash, beech, and elm. Conifers are either left to dry very thoroughly before sanding, or they are frozen and surfaced as above. The latter only works if the wood is completely waterlogged, so some samples will benefit from soaking in water for at least 24 hours before being frozen.

Once an acceptable finish has been obtained, a record is made of the cross-sectional dimensions, the orientation of the annual rings, the presence of sapwood, and the presence of any growth anomalies. A note is also made of timbers that might have come from the same tree. The orientation of the rings is illustrated by a rough sketch; if more detail is required, the sketch can be drawn to scale (1:1). The orientation of the rings and hence the timber conversion type can also be identified by a code letter. This makes a convenient shorthand system during timber assessment and for the purposes of computation. One such system is described in Crone and Barber (1981); another is illustrated in Figure 8.

1.3.2 Measurement

Ring widths are measured, generally to an accuracy of 0.01 mm, on a travelling stage (Fig 9). The stage illustrated here was custom-built, but others are available commercially. The stage is connected to a microcomputer, which uses a suite of specially written dendrochronology programs (Tyers 1997). Other laboratories either use commercially available software or have developed their own.

The wood sample is viewed through a low-power binocular microscope with the crosswire aligned with the start of the first ring. The stage is moved along until the crosswire reaches the start of the next ring, after which a button is depressed and the distance moved is entered into the computer (usually done using the left mouse button). To make it easier to recheck the measurements, every tenth ring is marked with a dot using a needle (wet samples) or felt tip (dry samples); every 50th ring has two dots, and 100th three dots. This can be done before or during the measurement process.

It is usually only necessary to measure oak samples once but it is imperative that a note is made during measurement of any 'problem rings'. This might be where rings are very narrow or where wide spring wood could represent two rings rather than one. In some cases, the boundaries of the ring are so problematical that it is better not to measure them but to make a note of approximately how many unmeasured rings have been omitted. If the problem rings are in the middle of a sample, it is sometimes possible to measure the sections to either side of the problem and date the two sequences separately. Any anatomically abnormal rings should also be noted during measurement since this may be indicative of environmental effects such as frost (eg Fletcher 1975; LaMarche and Hirschboek 1984).

1.3.3 Crossmatching

Most tree-ring laboratories use a combination of three methods to ensure reliability: visual matching, statistical tests, and replication. All these methods are independent of external dating evidence such as architectural styles or pottery types.

1.3.4 Visual matching

The measured ring sequences are plotted as graphs, either by hand or using a plotter linked to a computer.

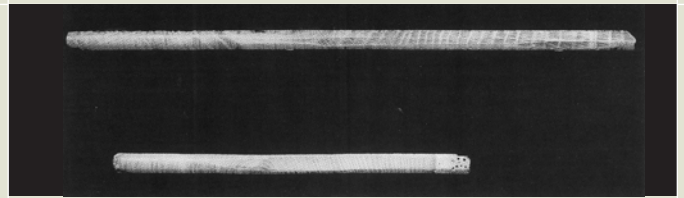


FIG 6 Cores after their cross-sections have been prepared; sapwood is present on the right of the bottom core.

It is lighter in colour and contains worm holes

© English Heritage Photographic Library



FIG 7 Slice of waterlogged oak after it has been prepared; the lighter-colour sapwood can be seen on the left

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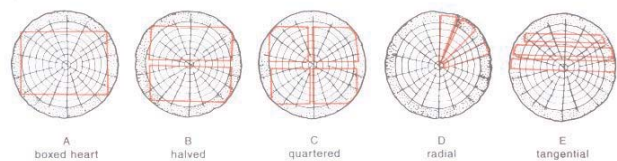


FIG 8 Typical cross-section found in wooden structures; shading = sapwood. These conversion types can be coded for ease of recording and computation. The main types are illustrated here but intermediate sections are often found (J Dobie)



FIG 9 Measuring equipment in use © English Heritage Photographic Library

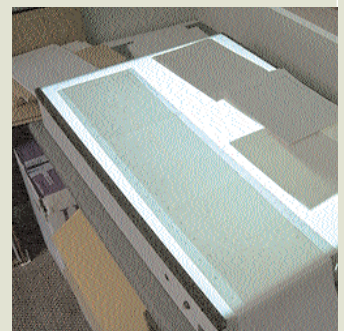


FIG 10 Comparing graphs on the light table © English Heritage Photographic Library

Each graph can then be compared to each other on a light box to check for similarities between the ring patterns that might indicate contemporaneity (Fig 10). A note is made on the graph of the position of any problem or anomalous rings; this allows any 'problem years' noted during measurement to be checked. If an error is detected, the graphs can be checked by reference to the wood samples and the error corrected (see also Schweingruber 1988, 73).

Ring sequences within a site or structure are first crossmatched before being combined into a site master. Since timbers from the same structure or building are often from the same woodland, this process could be done entirely on the light box. In practice, computer programs are often used as a guide to possible matches and the results checked by eye. Although computers are used to aid the crossmatching process, in most laboratories it is the experience of the dendrochronologist in assessing the quality of the visual matching that dictates whether or not a match is accepted. The human eye has a capacity for pattern recognition that goes far beyond that of any computer program so far written. As well as looking at the year-to-year agreements between two ring patterns, the eye can also appraise the similarity in longer-term trends. Essentially, it appears that the area between the two graphs gets smaller as the match gets better. While visual matching is a subjective method, it has been tried and tested throughout Europe and America for many years, and it has been shown repeatedly that experienced dendrochronologists produce the same results. It has also been verified by the use of entirely statistical methods (Okasha 1987; Hillam and Tyers 1995).

1.3.5 *t* values and computer crossdating

It is important, however, that statistical methods are used in crossmatching: first, to save time and, second, to quantify the certainty of the visual match. In the British Isles, crossmatching routines are usually based on the Belfast CROS program (Baillie and Pilcher 1973). This calculates the product moment correlation coefficient *r* for each position of overlap between two sets of data. Unlike earlier programs (Eckstein and Bauch 1969), this process is parametric since it takes into account the magnitude of the ring widths as well as the change in direction from one year to the next (that is, whether one ring is wider than the next or *vice versa*). The value of *r* does not take into account the length of overlap between two curves, so the value of Student's *t* is calculated from *r* to introduce a measure of significance in relation to the length of overlap. In other words, the *t* value provides a measure of the probability of the observed value of *r* having arisen by chance. The proviso of the original program is that 'even when the computer indicates a high degree of confidence in the crossdating, this must still be checked visually' (Baillie and Pilcher 1973, 11). The latter authors used 3.5 as an arbitrary value above which a match might be expected. This value of *t* gives a 0.1% significance level for ring patterns with 100+ rings. That is, a value of 3.5 should happen by chance about once in every 1000 mis-matches (Baillie 1982, 84). This does not mean that every value of 3.5 or above has to be correct, which is why many dendrochronologists use visual matching to check the results. In practice, matching graphs often produce values well over 3.5. Table 2 shows the *t* values obtained for a group of living trees in the same woodland (Hillam and Groves 1993).

TABLE 2 *t* value matrix for known matches between living oak trees from a deciduous valley woodland at Brockadale Nature Reserve, Wentbridge, West Yorkshire. Relatively young trees were selected so that the results would be comparable to those obtained from historic contexts, values less than 3.0 are not printed

SAMPLE Start date (AD) End date (AD)	1 1926 1984	2 1931 1980	3 1929 1984	4 1884 1984	5 1933 1984	6 1932 1984	7 1927 1984	8 1924 1984	9 1937 1984
1	*	6.3	5.6	3.1	4.2	4.2	4.0	4.9	3.9
2		*	7.7	6.7	5.5	3.2	3.7	6.0	—
3			*	7.3	5.1	4.1	4.3	6.7	—
4				*	5.4	4.3	3.8	6.9	4.2
5					*	4.9	4.8	3.9	—
6						*	5.8	—	—
7							*	3.1	—
8								*	5.0
9									*

Note that while some pairs of trees crossmatch with t values well over 3.5, a few pairs have values less than 3.0. If samples from such a pair had been obtained from a historical context, they would have failed to crossmatch even though they were contemporary. This is one of the reasons why it is better to have more than one sample per context.

Several modifications of the original program have been written since 1973 (eg Litton and Zainodin 1987; Munro 1984; Okasha 1987; Wigley *et al* 1987), and so the same version is not necessarily used in each laboratory. This is not critical, provided that it is stated which program is used. At Sheffield, for example, the Munro version is often used initially because it is quicker, but t values from the 1973 version are always quoted in the archive report. Other variants of the t value may not produce identical results but they should produce the same pattern of results. When two contemporary ring sequences are compared, t values are obtained for every position of overlap; there should be one positive t value that stands out as higher than the rest, regardless of which version is used.

Published crossmatching procedures in the British Isles that rely entirely on computer programs include the Litton-Zainodin grouping technique (Laxton and Litton 1988; Litton and Zainodin 1987, 1991) and the SORT-STRING method (Crone 1988). An informal test on a large group of data from panel paintings suggests that crossmatching using a computer program, without reference to graphs, gives the same dates as the traditional method that relies on an interaction between visual and computer matching (Hillam and Tyers 1995). However, the latter method provides more non-chronological information, such as same tree information and insights into provenance, than does the former. It is also a much better way of checking for measurement errors.

1.3.6 Replication

The third form of check available to the dendrochronologist – replication – is used in all laboratories. When ring sequence C is tested against two matching graphs, A and B, then if C matches A, it should also match B. Similarly, if D matches A, it should also match B and C and so on. If C appears to match A but not B, one of the results may be spurious, and all the tentative matches in the group should be rechecked. This does not mean that every pair of ring sequences from a matching group will produce t values over 3.5 (Table 2), but as a general rule it is a very good way of indicating

where there may be problems with the crossmatching. Replication operates at several levels (Baillie 1995, 27). First, and most importantly, the matching ring sequences that make up a site master curve should replicate each other. The master curves themselves should also replicate each other so that as each new tree-ring chronology is produced, it provides additional replication for those produced previously. But replication at the master curve/chronology level does not necessarily guarantee that all the sequences within a chronology are correctly matched. Tree-ring data are surprisingly robust and a chronology that includes, for example, three out of ten sequences incorrectly placed, may still date, based on the seven correctly placed ring sequences. However, the dates for the three incorrect ones will be wrong, and the archaeologist or historian would receive incorrect dates for three timbers. It is therefore imperative that the matching of the individual samples within any chronology is correct.

As an example of the interactions of the above methods, crossmatching can be summarised as follows. A group of 6 – 8 samples are measured and tree-ring curves produced. The graphs are checked for errors of measurement. The data are then tested for similarity using a computer program based on the Belfast CROS program. Potential matches are checked visually. Tree-ring sequences that give acceptable matches and replicate each other are averaged to produce a master curve against which any unmatched ring sequences can be tested. Tentative matches with the master are checked by looking at the matches with the components of the master and, if acceptable, the newly matched sequences are incorporated into the master. When the final master curve has been obtained, it and any unmatched sequences are compared by computer against dated chronologies. If t values over 3.5 are obtained with several independent chronologies over the same period (that is, there is replication) and the visual matching is acceptable, the absolute dating can be accepted.

In practice, t values are usually over 4.0 with at least some over 5.0. For example, the chronology from the barn at King's Pyon near Leominster, Hereford and Worcester, dates to 1346 – 1480 (Groves and Hillam 1993). At this position, it matches 94 independent chronologies with t values greater than 3.5: 50 are between 3.5 and 5.0, 26 between 5.1 and 6.0, and 17 over 6.1. Of course, only a few of these results can be quoted in the archive report and the *Vernacular architecture* date lists (for reporting and publication of dates, see below, sections 2.7 and 2.8). The exact procedure may differ from laboratory to laboratory, but the results should be the same whatever method used.

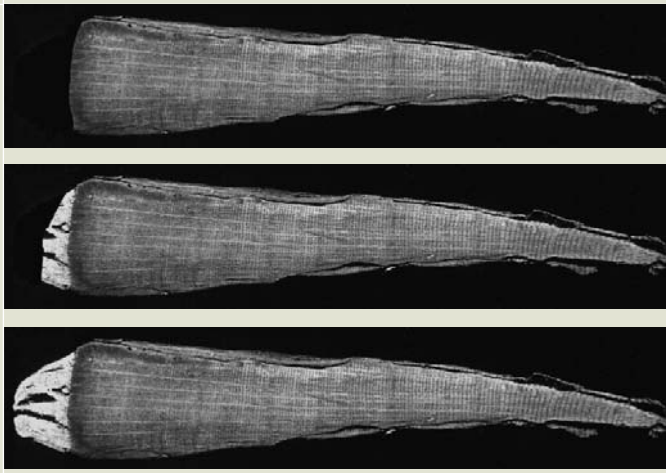


FIG 11 Examples of the three levels of precision provided by dendrochronology: a) heartwood rings only – felling is an unknown amount of time after the date of the outer ring on the left; b) incomplete sapwood – a felling date range is obtained using a sapwood estimate; c) complete sapwood – the date of the outer ring on the left give the year of felling

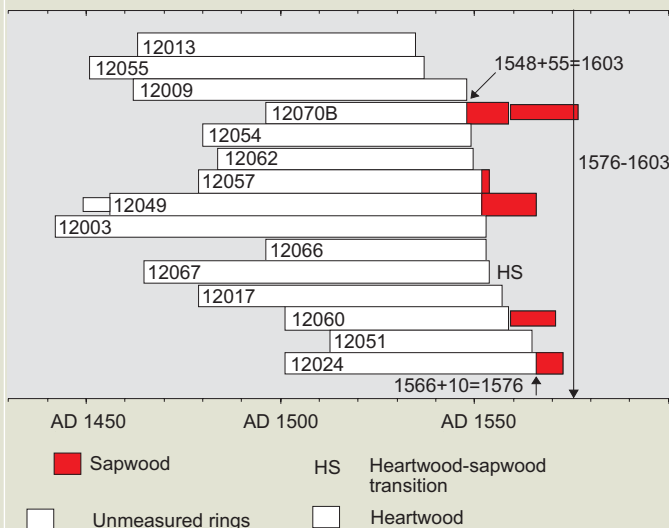


FIG 12 How to estimate felling date ranges for a group of timbers assumed to be contemporary. The Sheffield sapwood estimate of 10-55 rings is used but can be replaced by other published estimates. Adding 55 years to the oldest date of the heartwood-sapwood transition and ten years to the youngest gives an estimated felling date range of AD 1576-1603 (J Dobie)

1.3.7 Samples from the same tree

Research on samples from living trees indicates that ring sequences from different trees generally produce a Student's *t* value lower than 10 (Table 2), although samples from the same tree do not always produce values greater than 10. For a non-modern assemblage, *t* values greater than 10 provide an indication of some, but not necessarily all, of the timbers that are likely to have originated in the same tree. Examination of the samples and the tree-ring graphs can be useful in verifying doubtful cases. If samples are thought to derive from the same tree, their tree-ring widths are first averaged to produce a single sequence before they are included in the site master. This avoids introducing bias into the site curve.

1.3.8 Construction of master chronologies

Master curves summarise the information present in the individual matching ring sequences by enhancing the climatic signal and depressing the background noise from the local environment of the trees. A match is therefore more likely between two master curves than between sequences from two single samples from different sites. Masters can be constructed in several ways (Baillie 1982, 86). The simplest method is to sum the ring widths at each year and divide by the number of samples. The ring width data can also be 'smoothed' or 'detrended' before averaging them by fitting, for example, a five-year running mean or an exponential curve to produce a series of tree-ring indices. This has the advantage of preventing the over-representation of the wide-ringed samples at the expense of those with narrow rings. The decision whether or not to detrend, and the choice of filter, varies from laboratory to laboratory. Indices are generally used when extracting climatic information from tree-rings (see section 1.5.4) but their use does not necessarily improve the number of samples dated.

1.3.9 Presentation of results

When the crossmatching process is complete, calendar dates can be assigned to the individual ring patterns. The results are then illustrated by means of a bar diagram. This shows the relative positions of the matching ring sequences (eg Figs 12, 13, and 15). Sapwood and unmeasured rings are marked so that different felling phases can be identified. This is useful for interpreting the results, particularly when there is reuse or more than one phase of construction.

1.3.10 Interpretation

Once the ring pattern has been dated, the tree-ring date of that pattern has to be related first to the felling of the tree and then to the use of the timber. If the sample has bark or bark edge, the date of the last measured ring is the date in which the tree was felled. It is sometimes possible to be even more precise. A complete outer ring indicates that the tree was felled during its dormant period in winter or early spring (see Baillie 1982, fig 2.1). If the ring is incomplete, felling took place during the growing season in late spring or summer. If the spring vessels are only just forming, then the tree was felled in April/May at about the same time as the tree was coming into leaf. The exact time that this happens will vary from tree to tree and from year to year depending on the genetic make-up of the tree and the climate, respectively. Sometimes the season of felling is indeterminable. It is not usually possible, for example, to differentiate between an incomplete ring and a complete narrow ring. When in doubt, the season of felling should not be given.

In the absence of bark edge, sapwood becomes important (Fig 11). Sapwood is the outer part of a tree which transports the sap. In oak, it is recognisable microscopically by open pores in the springwood; these become filled with growths called tyloses when the sapwood becomes the heartwood. There is also usually a colour difference between heartwood and sapwood. In waterlogged wood, the heartwood is black or dark brown and the sapwood very light brown or light grey, depending on the chemical nature of the surrounding deposit. The sapwood in building timbers is usually slightly lighter in colour than the heartwood. It can be easily recognised by the presence of worm holes, since insects will attack the sapwood but normally avoid the harder heartwood. True sapwood should not be confused with the band of rings sometimes visible just inside the sapwood. This appears to be of similar width to sapwood and often shows a colour change, but the vessels are filled with tyloses (Hillam 1987). It is particularly noticeable in sub-fossil timbers. When the latter are exposed, they first lose their bark and true sapwood and then begin to decay along this 'false sapwood' boundary.

Although there is some variation in the number of sapwood rings between trees, and even within a single tree, the number of sapwood rings in oak is generally relatively constant, and therefore the likely number of missing sapwood rings can be estimated. Various **sapwood estimates** have been published (eg Hillam *et al*

1987; Hughes *et al* 1981; Laxton and Litton 1988).

A sapwood estimate of 10 – 55 rings has been used at Sheffield for over ten years. This figure was the result of a study carried out in 1984/5 on data from all timbers with full sapwood. It represents the range of the 95% confidence limits for the number of sapwood rings in British oak trees over 30 years old (Hillam *et al* 1987). New analyses on the much larger data set available in 1997 indicates that a range of 10 – 46 would be more realistic for England and Wales (Tyers personal communication). This means that 19 out of every 20 trees examined should have between 10 and 46 sapwood rings, inclusive, and that the actual value could be anywhere between 10 and 46. Other laboratories use similar figures, some producing differing estimates based on regional variations (see the date lists published in *Vernacular architecture*).

Age of the tree and its geographical location do have an influence upon the total number of sapwood rings. Across Europe there is an east – west variation in the number of sapwood rings. Timbers that have originated further east have fewer sapwood rings (Baillie 1995, 23). This has important implications where timbers have been imported from outside the British Isles, such as from the eastern Baltic region. Polish timbers so far examined, for example, have had a minimum of nine sapwood rings and maximum of 36 (Wazny 1990).

Where incomplete sapwood is present, the felling date range is estimated by adding the minimum and maximum number of likely missing rings to the date of the heartwood – sapwood transition. The felling date range can sometimes be refined when a group of timbers are assumed to be contemporary since their individual ranges can be combined (Fig 12). Where sapwood is absent, the felling date is expressed as a *terminus post quem*, ie the date before which the timber is unlikely to have been felled. This is obtained by adding ten years, the minimum number of missing sapwood rings, to the date of the last measured heartwood ring. The actual felling date could be much later depending on how many heartwood rings have been removed. Some examples of studies where sapwood is poorly represented can be found in the *ESF handbook on dendrochronological dating* (Eckstein *et al* 1984).

Sapwood is present in non-oak species such as ash or elm, but is usually physically indistinguishable from the heartwood. In the absence of bark edge, the date of the last measured ring is the earliest possible date that the timber could have been felled.

1.3.11 Relationship between felling and use

Once the felling date of a timber has been estimated, factors that might have affected it when it was used must also be taken into account. If the timber is a repair or has been reused, for example, its date of felling will be different to the date of the structure. Although the tree-ring dates for the measured rings are precise and independent, the interpretation of these dates can often be improved by other evidence. It is therefore important that tree-ring analysis is accompanied by relevant timber records: timber recording sheets for waterlogged wood (English Heritage 1996) and plans and records for building timbers (IFA 1996). Expert examination of structural timbers before and during sampling will often indicate whether they have been seasoned and/or reused. This information should always be made available to the dendrochronologist.

Seasoning is the drying and hardening of timber by storing it for several years so as to render it fit for use. However, the seasoning of timber for general building purposes is a fairly recent introduction. Previously, trees were usually felled and used as required (Charles and Charles 1995, 46; Rackham 1990, 69; Schweingruber 1988, 147). There are some exceptions. Timber boards for panelling and furniture, for example, would have to be seasoned to prevent warping. One estimate is that on average panelling is stored for 3 – 10 years before use (Bauch *et al* 1978), but recent work suggests that panelling can be used within a year of felling. Other examples of seasoning are generally to be found in high-status structures rather than in vernacular buildings. The roof timbers in the Blackfriars Priory at Gloucester, for example, were a gift from Henry III, and these had apparently been seasoned (Rackham *et al* 1978), although there are opinions to the contrary (Miles personal communication). New results from timbers damaged by the fire at Windsor Castle support the latter view since they show that in the fifteenth and sixteenth centuries at least, timber was felled and used almost immediately (see below).

Stockpiling. There will be a time interval between felling and use whenever a third party is involved between the supplier and user. It may also occur where large quantities of timbers are collected for major building projects. The construction of cathedrals are an obvious example of this, and stockpiling has been detected at Lincoln (Simpson and Litton 1996) and Salisbury (Simpson 1996). At Ware Priory, many of the timbers

were felled, and presumably used in or soon after 1416, but at least four others were felled earlier in 1391, 1394, 1395, and 1410, respectively (Howard *et al* forthcoming (a)). The complex building at 26 Westgate Street, Gloucester, also contains timbers with felling dates spread over several years (Howard *et al* forthcoming (b)). Similarly, panels for paintings may have been stored in an artist's studio for several years.

Repairs. These can be identified by a change in building style and/or timber joints. In standing buildings, a dendrochronologist taking cores can also sometimes detect a difference between primary timbers and later repairs by a change in the wood itself. In the tree-ring record, repairs can be detected by the appearance of distinct phases of felling in the bar diagram. These felling phases will be easier to identify if the timbers have sapwood or, better still, bark edge (eg Fig 13).

Reuse. Timber has always been a precious commodity and it was reused whenever possible. Timbers from the late first century AD quay along the Thames waterfront in London, for example, were used in the early second century AD quay that followed it and so on. Similarly Salzman (1979) quotes examples of complete buildings being demolished and the timbers used elsewhere. Again, the presence of sapwood on samples is critical here. Without sapwood, the identification of reused timbers, from the tree-ring results alone, is only possible if there is a relatively long time span between primary and secondary use. To maximise the value of the tree-ring dates, it is imperative that there is close liaison between the dendrochronologist and others closely involved with the site, such as excavator, building historian, and wood technologist.

1.4 When can dendrochronology be used?

In theory dendrochronology can be used on any timber or artefact – on charcoal as well as wood – from an archaeological site, standing building, or waterlogged deposit such as a peat bog. In practice, however, there are limitations.

The **type of wood** is important. The rings of oak, for example, are strictly annual. A ring might be locally absent, particularly near a knot, but so far there have

been no recorded instances of absent rings. This contrasts with trees such as alder or pine, whose rings are not always annual. They sometimes 'miss' putting on new growth over all or part of the circumference, or they may show 'false' rings, where one year's growth may look like two. The problem of missing or false rings can sometimes be overcome by measuring more than one radius per sample but this is only possible where a complete slice of trunk is available. Oak still remains the most commonly used species in British dendrochronology, but the method is being extended to include some non-oak species (Groves and Hillam 1988). Ideally, a long chronology should be produced for each species under consideration, but this is not usually possible. Instead, samples of Neolithic ash, medieval beech, Post-medieval elm, and prehistoric pine have been dated successfully by producing a site master curve and testing it against dated oak chronologies. Species such as alder, birch, and willow are not likely to be datable because of indistinct growth rings.

The **number of annual rings** can also be a limiting factor. The success of dendrochronology depends on a ring pattern being unique in time so that a particular ring pattern should not be repeated at any other period of time than the one over which the parent tree was growing. This is generally true for ring sequences over 100 years long but is less so as the number of rings decrease. Samples with fewer than 50 rings are therefore usually rejected, although where there are many samples per structure, particularly if bark edge is present, those with 30 – 50 rings might be datable (see the example from Fiskerton in section 1.5.1). **Ring patterns with fewer than about 30 rings are definitely not unique and should not be used for dating purposes** (Mills 1988).

The optimum number of rings required is also dependent on the **number of samples**. A single sample with 150 rings, for example, might be datable whereas one with 50 rings probably will not be. Six samples with 50 – 80 rings from the same structure on the other hand would have a much better chance of being dated than a single sample. In practice, it is rarely worthwhile examining single samples from a site unless they have more than 100 rings.

The size of timber is less important dendrochronologically since there is no simple relationship between size and the number of rings. A large timber from a tree grown in open conditions might contain only a few wide rings. By contrast a small

piece of wood from a tree growing in dense woodland on an exposed slope, might contain over 100 narrow rings. This is illustrated in Figure 6. The top core contains 34 rings in 215mm while the bottom one has 60 rings in 130mm.

The number of rings will also be dependent on how the timber was converted. A boxed heart, for example, is likely to have fewer rings than a quartered trunk, and a tangentially split plank less than a radially split one.

The usefulness of a sample will also depend on its **quality**. Timbers with no bark or sapwood can provide only limited information. Broken samples are often unusable since the ring sequence will not be continuous. If it is a clean break, it is sometimes possible to measure across the break. Alternatively, it might be usable if one or more of the broken pieces has enough rings to be dated on its own. This tends to rule out many of the pieces of charcoal found in this country because they often shatter into small pieces. The sample should also be free from knots since these distort the ring widths and sometimes obscure the ring pattern altogether. Finally, some samples will contain ring patterns that are unsuitable because the rings are too narrow for accurate measurement. If the ring boundaries cannot be distinguished with absolute certainty, it is better to reject the sample. Attempting to measure the rings would result in an undated ring sequence or, if the problem was at either end of the sequence, it would probably match but it would introduce errors into the master curve. It is, however, sometimes possible to measure the rings with clear ring boundaries and then count the number of unmeasurable rings. This is particularly useful where the sapwood is too worm-eaten to measure the rings accurately. Provided the above criteria are met (suitable wood type, sufficient number of rings, readable ring pattern), the following might be suitable for tree-ring dating:

A Standing buildings

- structural timbers
- panelling
- floorboards

B Waterlogged wood

- structural timbers
- other artefacts eg boats, barrels
- sub-fossil trees from peat bogs or submerged forests

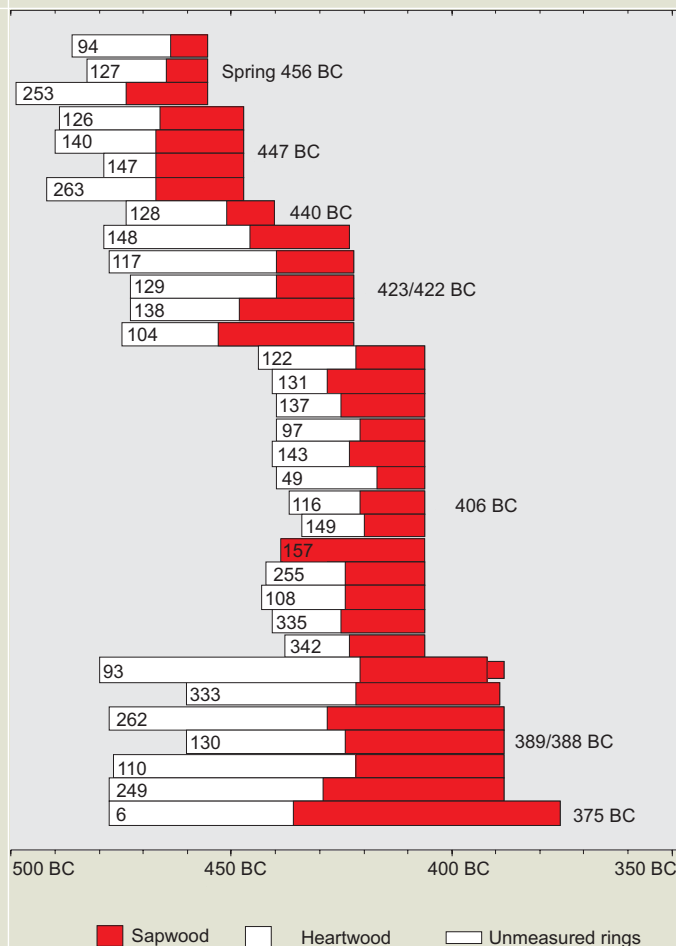


FIG 13 Bar diagram for timbers from the Iron Age causeway at Fiskerton, Lincolnshire. All the samples illustrated had bark edge and unless stated otherwise, all were felled in winter/early spring. Felling dates are given in italics. Note that sample 157 is all sapwood (J Dobie)

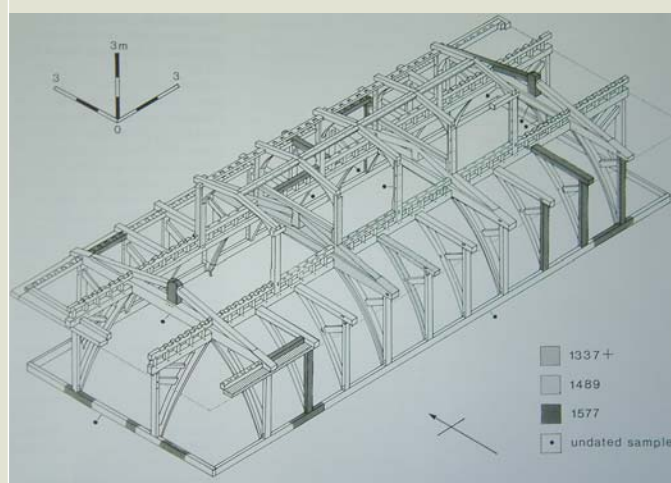


FIG 14 Isometric projection of the current kitchen roof as it might have looked before the nineteenth century alterations; timbers from each phase are shown in different shades (drawing provided by John Pidgeon; redrawn by J Dobie)

C Art-historical items

- panel paintings
- books with panel covers
- furniture
- musical instruments
- sculptures
- other items

D Living trees

I.5 What information will dendrochronology provide?

I.5.1 Dating

Although dendrochronology is a dating technique, **the submission of a sample does not guarantee the production of a date.** Even though the chances of dating can be increased by the submission of several samples per structure, some timbers are intrinsically undatable, however many rings they might have. The parent trees might have grown under abnormal conditions or been subjected to management regimes. We do not know, for example, what effect pollarding may have on a ring sequence. Similarly, the timber might have been imported from an unknown geographical region outside the range of available reference chronologies.

If a date is produced, the method is generally more precise than any other dating method but it must be stressed that **dendrochronology can only date the rings in the timber.** Its precision with respect to the date of felling will depend on the completeness of the timber (see above, section 1.3.10). Where bark edge is present, dendrochronology can rewrite history or, in the prehistoric period, provide a detailed chronology of events that would otherwise have been indistinguishable. Some examples are given below.

I Annetwell Street, Carlisle. Dating in the historic period can be illustrated by the results from the complex urban site of Annetwell Street in Carlisle. Excavations at Carlisle have revealed the remains of many Roman military and civic structures. Dendrochronology has been important in providing a detailed independent chronological framework for the development of this town on the north-west frontier of the Roman Empire in the first

century AD. Before the study, dating evidence relied on coins, pottery, and the writings of Tacitus, in particular his work on the life of his father-in-law Agricola. These had been interpreted to indicate that the first fort was constructed in AD 79 (Caruana 1990; McCarthy *et al* 1989).

Over 500 oak samples were examined from the Annetwell Street excavations by Cathy Groves (forthcoming (b)). There were numerous samples with more than 200 rings and these provided a basic chronology for the site. Many of the other samples were small, no more than 50 – 100mm across, but they were narrow ringed and often had bark edge thus providing precise dates. The analysis indicated that the timbers were local; they seem to have been used soon after felling although reuse of timber was sometimes detected. The first wooden fort was constructed from timbers felled in the winter/early spring of AD 72/73. Modifications were made to the fort throughout the period AD 72 – 82, and there was a major rebuild of the interior in AD 83 – 5. There was no detectable felling of timber during AD 86 – 92, a period which coincides with a major reorganisation of forces within the Roman Empire. More timbers were felled in AD 93/94 with a few felled during AD 95 – 7.

The surrounding rampart shows a similar development to that of the fort. It was constructed in AD 72/73, repaired in AD 84/85, and finally rebuilt in AD 93/94. After this, stone replaced timber as a building material and dendrochronology ceases to be useful. The results outlined above are likely to change the historical interpretation of the development of the Roman north-west frontier in Britain during the first century AD. They also confirm that the writings of Tacitus are not always reliable. His date of AD 79 for the founding of Carlisle coincides with the time when his father-in-law Agricola was governor of Britain whereas it is now clear from dendrochronology that Carlisle was in fact founded under Petillius Cerialis some six or seven years earlier. It has long been suspected that Tacitus was economical with the truth so as to improve the image of Agricola (Birley 1973; Caruana 1990). Now that this theory has been confirmed by dendrochronology, the use of the term 'Agricolan' in British history and archaeology will have to be revised.

2 Fiskerton, Lincolnshire. The Iron Age site at Fiskerton lies 8km east of Lincoln on the north bank of the River Witham. Examination of the site and its surroundings

revealed a number of timber posts and various metal artefacts including a La Tène I sword in an iron scabbard. The wooden structure consisted of a double row of clustered posts which ran perpendicular to the river. Excavation of a 20m stretch of this causeway produced about 170 oak and alder samples for analysis. Traditional excavation techniques indicated that the posts represented at most two phases of construction, but the tree-ring results showed that the causeway had a long history of construction and repair (Hillam 1992). The exact date of construction cannot be determined because many of the posts – those that had fewer than about 30 rings or were alder – could not be dated. The first felling event in the tree-ring record is the summer of 456 BC (Fig 13). Timbers were then felled periodically, often every 16 – 18 years, and used in pairs to repair or consolidate the causeway at regular intervals along its length. For example, 14 posts were felled in 406 BC. Later, the causeway was reinforced at the north end of the excavation using worked oak timbers. These do not give precise felling dates because of absence of sapwood, but they indicate that timbers were still being felled after 339 BC.

This example shows that use can sometimes be made of samples with shorter ring sequences. Twelve timbers had more than 80 rings; these were used to produce the initial site master. The remaining sequences were crossmatched using visual matching to form internal groups, which were then matched against the working master curve to produce detailed relative dating. Absolute dating was achieved later. No reference was made to the excavation plan until after the relative dating had been carried out.

3 The Great Kitchen, Windsor Castle, Berkshire.

Analysis of timbers from the roof of the Great Kitchen was part of the tree-ring project initiated after the fire of November 1992 (Hillam forthcoming (a); Hillam and Groves 1996). The appearance of the Kitchen had been drastically altered in the seventeenth and nineteenth centuries but the English Heritage recording project after the fire indicated that the masonry shell and much of the roof was medieval (Fig 14). A total of 54 samples were analysed from 52 timbers; some were cores from timbers *in situ*, others were slices taken from timbers that had fallen during the fire or been replaced during renovation.

The ring sequences were crossmatched into two main groups (Fig 15). The first group 'Windsor early' is made up of 14 matching ring sequences, while the second

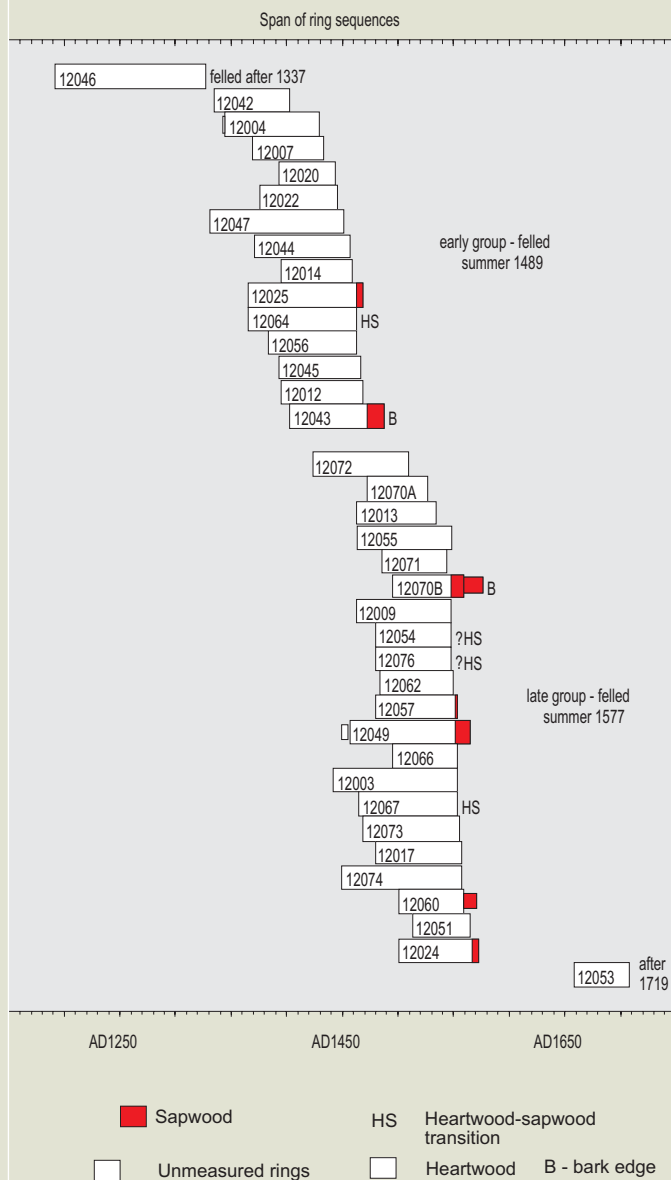


FIG 15 Bar diagram showing the ring sequences from the roof of the Great Kitchen at Windsor Castle (J Dobie)

'Windsor late' contains 21 ring sequences. Master curves were made of the 'early' and 'late' groups and these were tested against dated reference chronologies. 'Windsor early' matched with numerous chronologies over the period 1331 – 1488 and 'Windsor late' showed good correlation over 1423 – 1573. Two additional timbers were also dated, one for the period 1192 – 1327 and the other for 1658 – 1709. The latter sequence is only 52 years long, which in tree-ring terms is regarded as very short. The crossmatching, however, both visual and statistical, is so good that it cannot be ignored; for example it gives a t value of 9.1 with the Essex late chronology (Tyers 1993).

The interpretation of the results is particularly interesting because there are two detailed accounts of the architectural history of Windsor Castle with which to compare the tree-ring dates. These are *Architectural history of Windsor Castle* (Hope 1913) and *The history of the King's work* (general ed Colvin), which will be referred to as Hope and HKW, respectively.

Fourteenth-century construction. The earliest timber dated by dendrochronology is a lower wallplate from truss I. Its last measured ring is heartwood and dates to 1327; it was therefore probably felled after 1337. This is likely to correspond with the major rebuilding undertaken in the Upper Ward for Edward III in the mid-fourteenth century. There is documentary evidence for work on the Kitchen dating to 1362 – 3. The timber could easily relate to this phase but, with the data so far collected, dendrochronology cannot prove this.

Fifteenth-century rebuild. Most of the 'early' group of timbers contained only heartwood rings. However, sample 12043 with a ring sequence dating to 1403 – 89, retained all its sapwood rings. The last ring was incomplete, indicating that the timber was felled in the summer of 1489. The other timbers have end dates ranging from 1429 to 1469. This is consistent with a group of timbers from which only sapwood has been lost, and in fact 12025 and 12064 both show traces of sapwood. It is therefore probable that all the dated timbers in this group are contemporary and have a felling date in summer 1489.

Hope makes no reference to any work on the kitchen at this time, but the HKW (vol III, 306) notes that in 1489, under Henry VII, repairs to the castle were commissioned 'in haste'. Various sums of money were paid to craftsmen between July 1489 and April 1490 to carry out these

repairs. The craftsmen include a carpenter, mason, and plumber, and the purchase of lead is mentioned. *HKW* concludes that the main task of the repairs was 'the renewal of a defective roof somewhere in the castle'. The above results appear to identify the roof in question as that of the Great Kitchen.

Sixteenth-century repairs. The 'late' group of timbers also consist mostly of heartwood rings, although there are traces of sapwood remaining on a few. The closeness in date of the end years or the heartwood – sapwood transitions suggests that all the timbers are contemporary. The sample which provides a precise felling date for the repair timbers is 12070. This has 11 measured sapwood rings, the outer one of which dates to 1559. The remainder of the sapwood is badly worm-eaten making it impossible to measure the rings with any accuracy. Seventeen complete rings and an outer incomplete ring were counted between the last measured ring and the bark edge. Assuming the ring boundaries in the worm-eaten section were identified correctly, the timber was felled in the summer of 1577.

Hope (p274) quotes a list of 'the moste necessarie places to be firste considered upon for to be repaired wthin the Castle of Windesore this yeare 1577'. Included in the list is 'the greate Keechin roof', which was to be 'searched and if neede be newe made'. Later, Hope (p275) documents charges made in November 1577, including one for 'the Kytchen Roof'. It would seem therefore that the 'late' timbers in the kitchen roof were felled and used almost immediately in late 1577.

Eighteenth-century repair. The most recent timber dated by dendrochronology is 12053, a cheek piece from the south side of truss IV. Its last measured heartwood ring dates to 1709, indicating that it was probably felled after 1719. Documentary evidence is sparse for this period. There is no reference to the eighteenth-century Kitchen in either Hope or *HKW*. Hope (p347) suggests that practically nothing was done to the Castle beyond ordinary repairs. It is therefore not possible at present to relate this timber to any known building work at the Castle, a task made more difficult by lack of precise felling date.

As well as providing precise dates for the timbers, and identifying a phase of reconstruction so far undocumented, the results confirm two facts about oak. First, it is very durable. Even though they had been through intense heat for many hours, the oak timbers

escaped relatively unscathed. Second, comparison of the tree-ring results with the documentary evidence confirms that green timber was used for building purposes until relatively recently. The rebuild of 1489/1490 and the repairs of 1577 both used unseasoned timber. Although this is generally accepted in the literature (eg Charles and Charles 1995; Rackham 1990), it is rare to see it proved so decisively. Furthermore, the shortness of time between felling and use indicates that in this case there was no stockpiling of timbers. In both 1489 and 1577, building work was commissioned and the timber was felled to order.

1.5.2 Authentication

Dendrochronology can be used to detect fake or misattributed works of art. Schweingruber (1988, 169) describes the tree-ring analysis of two violins, supposedly made by Stradivarius. The tree-ring results indicated that the wood could not have been used before about 1910. Since Stradivarius lived at the turn of the seventeenth century, the two violins must have been fakes.

The same logic can be applied to paintings but the results can be more problematical than the above example. There is generally an unknown time lapse between date of last measured ring, date of felling, transport of the timber, and use. In addition, the timber on which a painting was executed may be reused. Alternatively, the transfer of a panel painting from its original support to a more recent one is not unknown (Easthaugh personal communication 1995). For all these reasons, dendrochronology should not be over-zealously relied upon in these circumstances, although it can provide information about the timber with which to augment that derived by the art-historian from other sources (documents, painting style, pigment analysis, X-rays, and so on).

1.5.3 Radiocarbon calibration and 'wiggle-matching'

The existence of continuous tree-ring chronologies extending back in time over several millennia has made it possible to calibrate the radiocarbon time scale (eg Pearson *et al* 1986). Since the production of ¹⁴C in the atmosphere is not constant, contrary to the initial assumptions underlying ¹⁴C dating, radiocarbon determinations must be calibrated relative to the radiocarbon content of wood samples of known age. There are several calibration curves that can be used to calibrate radiocarbon results. These are described in

special calibration editions of the journal *Radiocarbon* (1986: vol 28, part 2A; 1993: vol 35, part 1). **Calibrated radiocarbon results can be used to date timbers where tree-ring dating has proved unsuccessful.** Wood samples, containing several annual rings, are taken at known intervals (usually of 10 or 20 years) from the timber to be dated and submitted for high-precision radiocarbon dating. The radiocarbon results are then used to replicate a portion of the calibration curve, which is fixed in calendrical time, by 'wiggle-matching' against the known age calibration data (Bronk Ramsey 1995). This method can result in the production of very precise dates (see, for example, Pearson 1986, and Hillam *et al* 1990). These should be quoted as 'cal BC' or 'cal AD', since they rely on radiocarbon determinations, and to distinguish them from absolute dates derived from historical sources and dendrochronology, which are expressed as 'BC' or 'AD'.

1.5.4 Other information

The analysis of a timber assemblage can also provide non-chronological information and this potential should not be ignored. Some of these were mentioned in the dating examples given above. A group of samples from a standing building might provide information about the size and age of the trees and how they were converted into timbers. Does the timber represent a whole trunk or was it shaped from a quartered trunk, for example? Which timbers were derived from the same tree? Similar data can be extracted from a waterlogged assemblage. Such results, combined with data from other specialists as well as from other sites and structures, can provide significant information on woodland management and timber utilisation for different periods of history and prehistory. The examination of samples from living trees can contribute to the interpretation of landscape history, forest ecology, and other ecological studies, as well as being a vital source of reference for dendro-chronologists. Some of these applications are reviewed by Banks (1992) and by Fritts and Swetnam (1989).

Tree-ring data from all sources also contain information about:

- Climatic fluctuations in the past. **Dendroclimatology** involves complex statistics and is not carried out during routine dating processes. At present the only period for which it is feasible is the modern one, for which there is a network of chronologies from living trees of known origin. The best detailed introduction

to the subject can be found in *Tree-rings and climate* (Fritts 1976); for a more general introduction, see Baillie (1995, 140).

- Other environmental data. Although the ring patterns of trees cannot be crossmatched globally, in certain years, decreased growth can be detected across continents. These years have been termed 'marker' years. Some of them have been interpreted as the effect of climatic deterioration possibly due to dust veils and increased sulphur produced after volcanic eruptions. The narrow ring of 1628 BC, for example, which has been found in trees from England, Ireland, Germany, and the USA, may be an indirect effect of the eruption of Thera in the Aegean. This research is described in detail in Baillie (1995).
- Socioeconomic conditions. The distribution of start and end dates of tree-ring chronologies is not random but instead shows certain periods where there were hiatuses in building activity. One of these occurs in the fourteenth century and has been attributed to the effects of the Black Death (Baillie 1995, 124); others are also described by Baillie (1995, 122–30).
- **Dendroprovenancing.** Now that there is a network of chronologies across northern Europe, with defined regional differences, it is possible to start looking for the origins of timber. When attempting to date timbers from a structure in Britain, it is usual to begin by testing the master sequence against chronologies from the same region. If it fails to match, the search is widened to include all chronologies from the British Isles, and finally, if there is still no result, chronologies from elsewhere in Europe are included. If a match is found with a chronology from Poland, and there is poor correlation with British chronologies over the same period, then it seems reasonable to assume that the timbers in question have come from the Baltic region (Hillam and Tyers 1995). Similarly, if timbers from a Viking ship excavated in Denmark match with a chronology from Dublin but not those from Scandinavia, the inference is that the boat was built with Irish timber (Bonde and Crumlin-Pedersen 1990).
- Other applications of dendrochronology – for example fire history or the movement of glaciers – can be found in Banks (1992), Fritts and Swetnam (1989), and Schweingruber (1988).

Part 2

Practicalities: interactions between user and practitioner

2.1 Planning

Users with archaeological projects should follow the procedures set out in the second edition of *Management of archaeological projects* (English Heritage 1991), subsequently referred to as MAP2. These formal management procedures are designed for the efficient execution of archaeological projects, within set time and cost constraints, from fieldwork to publication and creation of a site archive. The model put forward in MAP2 is designed for a large project but can be adapted for smaller ones. It sub-divides a project into Phases 1

to 5, each of which is monitored and reviewed as the project progresses: 1 project planning, 2 fieldwork, 3 assessment of potential for analysis, 4 analysis and report preparation, and 5 dissemination (Table 3). Users with waterlogged deposits should also consult the revised guidelines on waterlogged wood (English Heritage 1996).

At the time of writing no such guidelines exist for standing buildings, but similar procedures should be followed. Since dendrochronology will result in an archive report based on the dating of the timbers, it should be accompanied by a programme of building recording to enable a fuller understanding of the building. The recording will normally be funded separately. It is important that the recording and plans are of the highest quality since the interpretation of the tree-ring dates may be dependent on them. A booklet on standards and guidance for the recording of standing buildings has recently been produced (IFA 1996).

TABLE 3 MAP2 and dendrochronology: a check list for project leaders and dendrochronologists

PHASE	ACTION
1 Planning	a) inform dendrochronologist that site with wet wood might exist b) get preliminary advice on sampling and wood storage c) establish contact between specialists (excavator, dendrochronologist, technologist, conservator) d) discuss time tabling, costings, and production of a research design e) discuss the need for spot dates
2 Fieldwork	a) one or more site visit by dendrochronologist, if necessary; most effective if technologists and conservator also present b) advice on sampling c) liaison between specialists d) ask for spot dates if results will help direction of field work e) sampling f) reassess the assessment strategy: is a pilot study necessary?
3 Assessment	a) timbers are assessed by dendrochronologist or someone approved by dendrochronologist for: • approximate number of rings • oak or non-oak • presence of sapwood/bark b) list of timbers for conservation given to dendrochronologist c) prioritise samples on basis of suitability for dendrochronology and ability to answer archaeological and other research priorities d) pilot study of further spot dates, if necessary
4 Analysis	a) sort out samples in order of priority b) analyse top priority samples c) provide results to excavator and other specialists and obtain feedback d) process is repeated with next priority samples and so on
5 Dissemination	a) write archive report b) incorporate comments from project leader and other specialists c) assimilate report into publication d) publication text sent to dendrochronologist to check interpretation of tree-ring results



FIG 16 Coring a large tiebeam in the Great Kitchen at Windsor Castle (English Heritage Central Archaeology Service)



FIG 17 Coring equipment (photo: J Hillam)

It is essential that the user contact the dendrochronology laboratory at the start of a project so that the potential of the timbers, costings, and timing of the tree-ring work can be discussed and agreed. If a need for dendrochronology arises unexpectedly during excavation or recording, a dendrochronologist should be consulted immediately. A list of contacts is given in Appendix 1.

2.1.1 Standing buildings

If a building is being repaired, the dendrochronologist should be approached before building work commences. Detailed plans and background information about the building, including its national grid reference and the name of the owner or other contact, should be provided. Warning should be given if the timbers have been treated with chemicals at any time. Other safety factors should also be discussed at this stage (see below, section 2.2).

Before sampling, the person requesting the dendrochronology should ensure that all the relevant permissions have been obtained, for example scheduled monument consent or listed building consent. Where a building is scheduled and listed, only scheduled monument control applies. Confirmation should be obtained in writing if the view of the controlling authority is that consent is not required. The contractor should check this with the person requesting the dendrochronology as he/she may be liable to prosecution if the works are undertaken without consent.

If a building is being restored, the project organiser should make sure that the building contractors are aware of the importance of sapwood. Sandblasting and other forms of cleaning not only damage the surface of the timbers by removing tool marks, graffiti, and carpenters' marks, but they also damage the sapwood and **some felling dates have been less precise than they should have been because the sapwood was removed by overzealous builders** (eg Hillam and Groves 1991).

2.1.2 Archaeological Projects

Users should provide the dendrochronologist with general information about the site and the timbers at the fieldwork stage, and ideally the dendrochronologist should visit the site at least once. Plans can then be made about sampling for assessment.

2.1.3 Art-historical objects and living trees

Projects involving art-historical objects or living trees should be discussed individually with the dendrochronologist since each project is likely to have special requirements.

2.2 Sampling

2.2.1 Health and safety

Dendrochronologists should carry out their work under a defined health and safety policy and observe safe working practices at all times. Risk assessments should be carried out and documented where necessary. On building sites and archaeological excavations, dendrochronologists must also comply with the health and safety policies of the contractor. For further information see the bibliography.

2.2.2 Standing buildings: access

Safe access to the timbers should be arranged with the project organiser or the building contractor. Some of the factors that must be considered are:

- The provision of scaffolding or lightweight staging for access to timbers above head height, since sampling from ladders can be dangerous.
- Any flooring should be checked and made safe.
- An electricity supply or a generator should be available. Electrical appliances should be run off a 110 volt supply, using a transformer if necessary.
- Two people should be present at all times during sampling.
- Hard hats, goggles, dustmasks, ear defenders, and adequate protective clothing should be worn where necessary.
- Insurance, including public liability and Professional Indemnity, is the responsibility of the dendrochronologist or his/her employer.

If safety precautions are not adequate, sampling should not be carried out.

Where a building is being renovated, the dendrochronologist must always report to the foreman in charge when arriving on site and comply with procedures laid down by the contractors. He/she should try not to interfere with the work of other contractors.

2.2.3 Standing buildings: assessment

An initial assessment of the timbers should be undertaken by the dendrochronologist. Whether this is done on a previous visit or carried out immediately prior to sampling will usually depend upon the complexity of the building. It is valuable if the first tour of the building is made with someone with a detailed knowledge of that building such as the archaeologist or building historian. The examination should establish some or all of the following:

- number of phases
- the identification of the wood type (usually oak but other species are sometimes present)
- the cross-sectional dimensions of the timbers
- the orientation of the annual growth rings
- how the timber was converted from its parent trunk
- the presence of bark and sapwood – crucial for the production of precise dates
- whether a timber is suitable for dating purposes (generally those with more than 50 rings)
- any evidence that the timbers have been seasoned
- any evidence of reuse

This first tour of the building will also make it possible to look at safety factors, light, power supply, and so on. It can be useful to have an assessment check list (Table 4), particularly if several buildings are being assessed during a day.

The initial assessment will lead either to the sampling of the timbers, or, if the timbers are unsuitable for dating purposes, to the abandonment of this aspect of the project. In the latter case, the initial assessment should still provide some information about the timbers.

2.2.4 Standing buildings: types of sample

If timbers have to be replaced during repair work, they should be labelled with their precise locations in the structure and kept for dendrochronology, since complete slices are always preferable to cores. If possible, a section of 50 – 150mm thickness should be cut from the timber. Where complete slices are not available, sampling will



FIG 18 600mm corer used for large timbers; space is needed around the timber before this corer can be used (photo: J Hillam)



FIG 19 Core being taken at the bottom of a timber so that the resulting hole is less obvious (photo: J Hillam)

generally be by coring (Figs 16 – 19). End sections of timbers can sometimes be polished and either photographed or the rings measured *in situ*. Photography and *in situ* measurement become particularly important when timbers in furniture and panelling are examined. For these procedures to be successful it is very important that the cross-sections are well-prepared, otherwise the rings will be unmeasurable.

Cores are taken using a hollow tube, sharpened at one end and attached to an electric drill (650 watt or above is recommended) at the other (Fig 17). Their extraction leaves a hole between 13mm and 15mm in diameter depending on the specification of the corer. The holes can be left open or can be filled with dowels if required.

Where possible, at least eight to ten timbers should be sampled per building or, for more complex buildings, per phase. This allows for one or two samples being unsuitable or undatable and therefore increases the chances of producing a site master curve. The selection of timbers for sampling will depend upon accessibility as well as on the results of the initial assessment. For example, space is needed around the timber since it may be necessary to attach a corer up to 600mm in length in order to obtain a complete core (Figs 17 and 18). Extra timbers might be sampled if some of the timbers are thought to be reused, for example, or if information is required about the number of trees used in a building.

The position of the samples should be recorded with sufficient accuracy to allow their location to be traced at a later date. Ideally, their position should be marked on plans made available by the project organiser. If these are not available at the time of sampling, a sketch should be drawn with the location of the samples marked (a compass is indispensable for this purpose). The location of the samples can also be described. For example, where trusses are labelled numerically from west to east, the first principal rafter on the north side of the building would be: Truss 1, north principal rafter. The CBA Handbook *Recording timber-framed buildings* (Alcock *et al* 1996) is a useful aid in describing timber buildings.

Care must be taken not to disfigure the building and it is therefore important that a skilled operator takes the cores. Sampling should be as discreet as possible, for example at the bottom of a timber rather than at head height (Fig 19), and the coring of mouldings or other decorative features should be avoided. Normally only one core per timber should be extracted but sometimes

it might be necessary to take two so as to obtain the longest ring sequence and/or sapwood. Unnecessary coring and damage to decorative features are likely to contravene scheduling and listing controls.

Coring is a slow process, often taking half an hour per core, because care must be taken to remove the sawdust as the corer penetrates the timber. Failure to do so is likely to result in a shattered core. It can also result in the timber overheating. These problems are exacerbated in damp timbers, which are difficult to core successfully.

The core is usually extracted starting at the outer edge of the timber, including sapwood if present, and progressing towards what was the centre of the tree (Fig 16), or occasionally *vice versa*. The aim is to extract a core that is parallel to the medullary rays of the timber and includes the maximum number of rings.

Sapwood can be very difficult to core successfully since the worm-eaten wood often turns to dust. Generally the older and the damper the timber, the more difficult it is to extract complete sapwood. The problem can sometimes be overcome by cleaning up the sapwood in a mortise or on an end section and counting the number of sapwood rings.

A note should always be made if some of the sapwood is lost during coring. Where bark edge is present, loss of sapwood can be detected by marking the entry point of the corer on the timber with a felt tip pen. If the pen mark is no longer visible after coring, rings have been lost and the outer measured ring will not be the bark edge.

TABLE 4 Suggested prompt sheet for the assessment of standing buildings. Some adaptations may be needed for specific building types such as bellframes and crucks

1 The building BUILDING CONTACT INFORMATION	(outstanding feature which distinguishes the building inserted here, eg fierce dog, carved ceiling) NGR TEL SURVEY/REPORT/PLANS/NONE																																															
2 Access PARKING KEYS EASE OF PERSON ACCESS EASE OF EQUIPMENT ACCESS LADDERS/STAIRS POWER POSITION OF POWER POINT AVAILABILITY OF POWER LENGTH OF CABLE REQUIRED LIGHTING FLOOR SAFE CLEAN VENTILATION BIRDS BATS	Y/N Y/N GOOD/POOR GOOD/POOR 240v/110v/N ALWAYS/LOCKED/KEY GOOD/POOR/NONE Y/N/BOARDS REQUIRED Y/N Y/N/POOR/EXCESSIVE Y/N Y/N																																															
3 The timbers LOCATION SPECIES NO OF TRUSSES NO OF TIMBERS ACCESSIBLE NO SUITABLE RE-USED CONVERSION SAPWOOD BARK	<table> <tr><td></td><td></td><td></td><td></td></tr> <tr><td></td><td></td><td></td><td></td></tr> <tr><td></td><td></td><td></td><td></td></tr> <tr><td></td><td></td><td></td><td></td></tr> <tr><td></td><td></td><td></td><td></td></tr> <tr><td></td><td></td><td></td><td></td></tr> <tr><td></td><td></td><td></td><td></td></tr> <tr><td>Y/N/HS</td><td>Y/N/HS</td><td>Y/N/HS</td><td>Y/N/HS</td></tr> <tr><td>Y/N</td><td>Y/N</td><td>Y/N</td><td>Y/N</td></tr> <tr><td></td><td></td><td></td><td></td></tr> <tr><td></td><td></td><td></td><td></td></tr> </table>																																Y/N/HS	Y/N/HS	Y/N/HS	Y/N/HS	Y/N	Y/N	Y/N	Y/N								
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COMMENTS																																																

2.2.5 Waterlogged wood

Wood found on waterlogged sites should be kept in the same condition in which it was found. That is, wet wood should be kept wet, but if it has already dried out, no attempt should be made to re-wet it since this may destabilise it. Before sampling, the assemblage should be drawn and photographed and, where possible, examined by a wood technologist (for further information, see English Heritage 1996).

The presence of bark and/or sapwood should be noted. **Care should be taken of the fragile sapwood, which can be easily brushed off or damaged.** The wood can be cleaned gently with water; but sharp tools should never be used. Project managers should emphasise this point to avoid enthusiastic staff trowelling off the sapwood. Failure to do so will severely reduce the effectiveness of the dendrochronology results.

Any samples requiring conservation should be set aside, although these may later be sent for analysis once they have been examined in the conservation laboratory (see section 2.3).

The remainder of the timbers, or the proportion agreed by the excavator and the dendrochronologist at the planning stage, should then be sampled on site. Sampling off the site, apart from problems of transport and storage it may involve, can lead to loss of information and/or damage to the timbers. If there is doubt about the timber having enough rings, it should still be sampled – the dendrochronologist can check this during assessment. Similarly, although routine dating in the British Isles is still confined to oak, an assemblage of non-oak timbers may be useful for research purposes. The usefulness of any non-oak samples should be checked with the dendrochronologist concerned before sampling.

Sampling is usually carried out under the direction of the excavator. Complete slices of 50 – 150mm in thickness should be taken through the widest part of the timber, incorporating sapwood where present. If there are only a few timbers, or the timbers are not oak, they can be sawn by hand. For larger assemblages of oak timbers, it is advisable to use a chain saw. To comply with current Health and Safety regulations (see bibliography), operators should have a current chain saw license, and protective clothing and ear protectors should be worn.

The edges of delicate samples – those with sapwood and any that are in danger of splitting – can be bound with masking tape or bandages for protection. Samples of charcoal can be consolidated by surrounding the charred remains in foam or by wrapping with a bandage previously soaked with a fast-drying car body-filler or equivalent (Baillie 1982, 171 – 2).

For health reasons, samples must not be treated with biocides.

All samples should be sealed in clear polythene bags, and labelled inside and out (see also English Heritage 1996). One bag per sample is adequate unless the sample is very large and, provided air is excluded when the bag is sealed, it is not necessary to add water. Dymo labels are a convenient method of labelling for inside the bags, but **they should not be nailed or stapled to the sample.** The outside of the bags should be clearly labelled with a waterproof marker pen. If they cannot be transported to the laboratory immediately, they should be stored in their sealed bags in cool conditions.

Full details of each sample should accompany the samples in a separate envelope. As well as general information about the site, the following information should be included where applicable:

- context and sample number
- description of the context with plans
- function of the timber
- details of associated timbers
- presence of bark
- any signs of reuse
- approximate date
- whether the sample can be discarded after analysis

Knowledge of the approximate date is used, not as prior evidence, but to save time during the crossmatching process. All the Roman timbers, for example, can be grouped together; and time will not be wasted in comparing Roman sequences against medieval chronologies. Of course, if no date can be found in the Roman period, then the search will be extended to chronologies from other periods.

Samples are normally kept after analysis. However, the absence of a national strategy for the retention of waterlogged wood samples means that **pressure from lack of storage space may lead to samples being discarded if there are no instructions to the contrary.**

2.2.6 Art-historical items

For obvious reasons, these cannot be sampled. Instead, the end sections of the wooden items need to be accessible. These can be carefully pared or sanded, and the ring widths photographed or measured *in situ*. The same procedure applies to other objects, although, if they are large enough, it may be possible to remove a core of wood and return it after analysis.

2.2.7 Living trees

These are sampled using a Swedish increment corer, available from forestry suppliers, which removes cores of 5mm diameter. The corers were designed for use with softwoods and therefore care must be taken when using them on hardwoods such as oak, since the corers may break during coring. There has been some debate as to whether the holes should be filled after core removal but general consensus seems to be that the holes should not be plugged. Trees sampled in the Sheffield area in 1987 were not filled and in each case the tree remains healthy with the hole completely grown over. There seems to be no preferred season when the trees should be cored. It is advisable to take at least two cores per tree, particularly if the study is aimed at extracting ecological or climatological information.

Since minor damage is caused by coring, it is important that a tree is cored only to extract information that will answer predetermined questions. Trees grown for their timber should not be cored since possible discolouration and/or callusing will reduce the value of the timber.

2.3 Conservation of waterlogged timbers

Timbers set aside for conservation may also hold valuable chronological information. There are several methods of sampling these, each of which alters the appearance of the timber to a different degree. The use of a body scanner to produce sectional radiographs, for example, is totally non-destructive but is expensive and tests so far have not been very successful (Tyers 1985). V-shaped wedges can be removed, analysed in the dendrochronology laboratory, and then returned for replacement in the parent timber. This method worked successfully for the Hasholme log boat from North

Humberside, but was less successful for the timbers from the medieval revetment at Billingsgate Lorry Park in the City of London. It is more successful when the ends of timbers or even complete slices are removed and sent to the dendrochronology laboratory. They can be returned after analysis to be conserved and joined up with the rest of the timber. Any effect on the timber's display potential can be offset by an information board explaining why the samples were removed and what results were achieved.

In some cases, removing a sample slice from a display timber may be the only way of obtaining a precise date for a site. The analysis of a section through a fine oak plank from the Caldicot Castle Lake excavations in Gwent, for example, produced a precise felling date of 998/997 BC for the timber platform when analysis of all the other timbers had failed. Other examples can be seen in Denmark at the Roskilde Ship Museum and the National Museum where timbers from Viking ships and Bronze Age coffins, respectively, have been sampled, dated, and displayed. It is not easy to detect where the sample was taken!

From a dendrochronological point of view, samples have been successfully measured and dated before and after conservation, although treatment with PEG (polyethylene glycol wax) can sometimes make measurement difficult, while freeze-drying may make the wood over-brittle. If a waterlogged sample is to be examined before conservation, it will usually have to be frozen prior to measurement. Freezing makes it easier to plane the cross-section by consolidating the wood. It is also possible to clean the whole surface rather than an edge or single radius, which is all that can be achieved on a non-frozen sample. The freezing of a wood sample therefore is more conducive to accurate ring measurement, but it is unpopular with some conservators because of possible cell damage, which makes it impossible to conserve the sample by the freeze-drying method. In such cases, it may be necessary to decide which is more important – a precise tree-ring date or optimum conservation.

Cores can be taken from waterlogged timbers using a Swedish increment corer, normally used for living trees. Results from these have been mixed. They often they tend to break and are unusable, but where the wood is stable, good results can be obtained. The timbers from the brine tank and pump support mechanism at the salt-making site of Upwich in Droitwich were precisely dated following successful coring.

2.4 Assessment

Waterlogged structural timbers from archaeological projects should be assessed following MAP2 guidelines (see above, section 2.1). Other dendrochronological projects such as those relating to standing buildings are usually assessed by the dendrochronologist prior to sampling.

Assessment of samples from waterlogged structural timbers does not have to be carried out by the dendrochronologist. This could be done by a member of the project staff after discussions with, and training from, the dendrochronologist. The samples to be assessed will be that proportion of the total assemblage agreed by the excavator and dendrochronologist during the fieldwork stage. The first stage of assessment will be to divide the samples into those that have potential for dendrochronology and those that do not. The latter have no value for dating purposes. If the assemblage is large, it may be worthwhile recording basic information about these samples. The samples can be discarded once this has been recorded unless they are required by other specialists.

For the categories that are potentially datable, information on the species, approximate number of rings, and presence or absence of sapwood and bark is necessary so that the samples can be ranked according to their dendrochronological potential. Top priority will be given to those samples with long ring sequences, which will enable a site master chronology to be constructed. Next will come those with sapwood, if they have not already been included in the top priority group. These data will then be combined with information from the excavator and wood technologist based on stratigraphic and technological details such as reuse. This will allow priority lists to be drawn up based on all the available information and according to the research interests of all the parties involved. At this stage liaison between the excavator, wood technologist, and dendrochronologist should ensure that the best material is selected for analysis.

2.5 Spot dates

The full analysis of a large assemblage of timbers takes a long time. Sometimes the user may need results within weeks rather than months or years and 'spot dates' have been introduced to meet this need. They are not intended to replace standard analysis but rather to augment it. Although spot dates are generally used for large assemblages of waterlogged wood (eg Tyers and Boswijk 1996), they might also prove useful when dealing with complex standing buildings.

'Spot dates' can vary in complexity. If the dating of a particular context is important to the interpretation of a site, a group of 4 – 6 timbers might be sampled and analysed after assessment, and the results sent to the excavator prior to the main analysis stage. Because no report is required at this stage, tree-ring results are usually available 4 – 6 weeks after receipt of the samples. Where a site has little stratigraphy to aid phasing, a series of spot dates may be carried out. In extreme cases, where there is no other dating evidence, the bulk of the tree-ring analysis may initially be in the form of spot dates. Spot dates can, if necessary, be carried out during the fieldwork stage. There is a danger here that timbers with poor dendrochronological potential or even reused timbers will inadvertently be selected. However, it is a way of providing dating information, which may help to guide the progress of the excavation.

2.6 Analysis and dating

2.6.1 Standing buildings

Samples that are unsuitable for dating are rejected at this stage. Samples with fewer than 50 rings, knots, or very narrow rings fall into this category. Out of the minimum eight to ten samples taken, often only four or five samples per phase are suitable.

Examination of the cores prior to measurement can be useful. Similarity in ring pattern might indicate an origin in the same tree, while alternate bands of narrow and wide rings could be the result of pollarding. Such occurrences should be noted and followed up once the rings have been measured and the tree-ring graphs plotted.

When relative dating has been achieved, the matching ring width data are combined into a phase or building master curve, which is then tested against dated reference chronologies for the period AD 404 to the present. Local reference chronologies will be used first, followed by those from further away, and finally, if no dating can be obtained, non-British chronologies will be used in case the timbers were imported.

Since dendrochronology is an independent dating method, the acceptance of a tree-ring date should be based on the quality of the match between the master curve and the reference chronologies. External factors such as the architectural style of the building should not be allowed to influence this decision. For example, examination of cores from a barn near Leominster, thought on stylistic grounds to be thirteenth century in date, proved without possible doubt to be late fifteenth/early sixteenth century (see above, section 1.3.6). That is, there was only one acceptable match and it was in the late fifteenth century.

2.6.2 Waterlogged wood

Samples will have been assigned priorities during the assessment phase. Those most suitable for dendrochronology will be examined first so as to establish a site chronology, if this was not already done during analysis of spot date samples. The dating framework for the timbers can then be expanded by examining the other timbers in order of priority until the questions posed in the research design are answered. In some cases, results will prompt new areas of research, perhaps relevant to another project. For example, the information that timbers have been imported from the Baltic region might be incidental to the project with which they are associated. But the resultant tree-ring chronology might enable the dating of several structures from another project. It may therefore become important to analyse more timbers from this context than would otherwise be necessary. Such additional analyses may have to be funded by a separate research project.

The pattern of analysis will vary depending on the complexity of the site. If it is a single structure, such as a well lined with ten timbers, the analysis will follow the rules set out in the section on standing buildings above (2.6.1). On the other hand, if it is a large, multi-period site with many timber contexts, such as a complex urban site, analysis will be more complicated. For convenience, the

samples from the oak timbers will probably be processed first by period, then by phase, and finally by structure and context. As the analysis continues, however, and a well-replicated site master is constructed, sequences from structures examined later in the analytical process may be tested directly against the site master rather than first making a master for each structure. This worked well during the analysis of 500 samples from Billingsgate Lorry Park in London, but not for those from Annetwell Street, Carlisle, which showed much more local variation within their ring patterns. The only way to ensure reliable results from the Carlisle site was to treat each structure as a separate site. Any non-oak samples with dating potential will be analysed after the oak samples have been examined, and any resulting non-oak chronology tested against the oak site master.

2.6.3 Art-historical items

Analysis of timbers in this category differs from those above in that there will often be only one sample. Even if, for example, panels from four paintings are examined together, the timbers are not likely to be related and each sample will have to be treated as though it were a separate 'site' (Hillam and Tyers 1995). This means that a replicated site master cannot be constructed, and the potential for dating will be lower.

A further problem is that the origin of the timber will not be known, unlike timbers found in standing buildings and archaeological sites, which are often local in origin. Boat timbers pose the same problem, or any structure containing timbers that are likely to be imported. Much panelling was imported as boards from the Baltic area; Salzman (1979) documents examples of this. As there are several chronologies available for this region, the dating of imported boards is now fairly routine. However, there must be sets of tree-ring data that remain undated because they were imported from areas where little or no tree-ring research has been carried out.

2.6.4 Living trees

Cores from the same tree should be measured and averaged to give a single ring sequence containing information about that tree. This ring data can be combined with data from other trees in the same woodland to produce a site-specific master curve, which will provide ecological and climatological information about that particular woodland.

2.7

Dissemination of results

The tree-ring results should be presented as an archive report that is intelligible to the layman as well as specialist; this report may be edited for inclusion in the final project report. Its suggested form and content are outlined below. It may not always be possible to give a step-by-step account of how each timber from a complex building or archaeological site was dated, because too many stages of checking and cross-checking are involved.

The primary function of the report is to present the results of the analysis of the timbers in such a way that they could be replicated by another dendrochronologist. For historic buildings, the survey of the building and accompanying plans will normally be the subject of another, separately commissioned report. Any inferences about dates of construction given in the tree-ring report are interpretative dates and may be dependent on other factors. Interpretation of tree-ring dates for standing buildings, for example, will be dependent on the quality of the building recording work. If phases of repair or reuse are undetected during a survey, the resultant tree-ring dates may well be misrepresented.

Where art-historical items are concerned, the report should include a disclaimer to the effect that the tree-ring dates relate directly to the wood, but not necessarily to the work of art (see above, section 1.5.2).

Archive reports for tree-ring analyses funded by English Heritage are submitted for inclusion in the Ancient Monuments Laboratory Report Series. These reports make available the results of specialist investigations in advance of full publication, and are available on request from the Ancient Monuments Laboratory (see Appendix I for address). Lists of tree-ring dates from standing buildings are published each year in summary form in the journal *Vernacular Architecture*. At present no such vehicle is available for the publication of results from waterlogged sites or art-historical material.

The user should always send a draft of any written work that includes tree-ring results back to the dendrochronologist for checking. This will avoid any misrepresentation of tree-ring results.

2.7.1 The tree-ring report

The complexity of a tree-ring report will depend upon the number of samples taken and the number of phases of construction or repair; but its basic form should include the following sections:

a) Summary

b) Introduction: archaeological and historical background, location including National Grid Reference, and circumstances and purpose of study.

c) Methodology: how the samples were taken and processed, from sample preparation and ring measurement through to absolute dating if this has been achieved; brief details of the crossdating statistics and the sapwood estimate. For the non-specialist, a general reference to dendrochronology is useful (eg Baillie 1982; these guidelines).

d) Results: an account of the results should be preceded by a description of the contextual location of the timbers. The description and/or plan should be accurate enough to allow the user to identify the location of the tree-ring samples. Nomenclature for timber-framed buildings should follow Alcock *et al* (1996). Where possible, the dimensions of cross sections and orientation of rings should be included. The dating results should be supported by statistical analysis, and a list of the independent reference chronologies used to establish crossdating. The results should also include any useful non-chronological facts that have been established such as:

- the size and age of the parent tree(s)
- how the timbers were converted and which part of the trunk was used (the dendrochronologist is in a unique position to determine this)
- which timbers, if any, are from the same tree (the criteria used to establish this fact should also be explained)
- whether one or more woodlands were exploited
- whether any of the timbers were imported from abroad

e) Interpretation: the preceding section describes the results obtained by independent scientific investigations, ie the dates of the tree-ring sequences. Dendrochronological interpretation of the tree-ring dates will result in the production of estimated felling date ranges, or *termini post quem*, for felling, in the

absence of bark edge. This is also independent of other dating evidence but the felling dates or felling date ranges given will depend on the sapwood estimate employed.

f) **Discussion:** when the dates of felling have been established, further inferences may be made about the timbers' date of use, based on the felling dates and on any other dating evidence. If merited, discussion of the academic significance of the results and suggestions for future work may also be included.

g) **Conclusion:** summary of main results (not always necessary for single phase structures).

h) **Acknowledgments**

i) **References**

j) **Figures should include (where appropriate):**

- a plan of the site or building showing the locations of the samples
- a bar diagram showing the relative positions of each ring sequence and, where present, the position of the heartwood – sapwood boundary (eg Figs 12, 13, and 15)

k) **Tables should include:**

- details of each sample, including the total number of rings, average ring width, the presence of any unmeasured rings, number of sapwood rings, presence of bark edge, date span of the rings of dated timbers, and estimated felling dates
- a *t* value matrix showing the level of crossmatching between timbers
- ring width data of any master chronologies and/or undated timbers
- *t* values between the master chronology and independent reference chronologies to show how the chronology was dated

2.8 Quoting tree-ring dates

Tree-ring dates are often mis-quoted in the literature (Miles forthcoming). Sometimes the end and start dates of the tree-ring chronology are confused with felling dates. Other problems tend to arise where an allowance has to be made for missing sapwood (see above, section

1.3.10). If a sapwood estimate of, for example, 10 – 55 rings is applied, it indicates that there is a 95% chance of there being more than nine missing sapwood rings and fewer than 56. The 10 – 55 estimate has a skewed distribution and therefore the felling date estimate should not be represented as a – figure around the mid-point of the range since this is statistically incorrect. For example, if a felling date range is given as 'AD 1500 – 1540' by the dendrochronologist, it should **not** be quoted as 'felled in AD 1520 – 20' or, even worse, 'felled about AD 1520'. Both these interpretations add a statistically unjustifiable amount of precision to the felling date range. This is true regardless of which sapwood estimate is used.

A first attempt is made here to produce a convention for the quotation of tree-ring dates (Table 5). It will no doubt evolve with use.

2.9 Data archiving

The National Geophysical Data Center in Boulder, Colorado, USA, houses the International Tree Ring Data Bank (ITRDB). This contains tree-ring data from all over the world although most of these are from living trees. The data are available free to contributors or for a small charge to non-contributors, or it can be accessed through the Internet (<http://www.ngdc.noaa.gov/paleo/treering.html>). The ITRDB also runs an electronic discussion forum, which currently has over 500 members from all over the world.

There is no national tree-ring database in Britain or elsewhere in Europe, nor is there a national agenda for the storage and safekeeping of wood samples. It is up to individual laboratories to ensure that their data are carefully archived with full sample and site information. As a initial solution to the absence of a European databank, an initiative to collect information about European tree-ring chronologies was launched at the 1993 Workshop for European Dendrochronologists in Nottingham. This European Catalogue of Tree-Ring chronologies will list information about the chronologies, **but not the data themselves**. Anyone requiring data for research purposes must contact the dendrochronologist who produced the chronology. Under a working party consisting of André Billamboz, Esther Jansma, Georges Lambert, and the author, the following objectives were established for the Catalogue:

- to promote communication and cooperation between European dendrochronologists
- to encourage the exchange of data
- to document the vast amount of data that now exists in Europe
- to inform about the research aims of each laboratory
- a long-term aim to further cooperation on data storage

The European Catalogue is still in its infancy but the first lists have already been drawn up and circulated to contributors (Hillam forthcoming (b)). It is envisaged that the full Catalogue will eventually be available on the Internet, although summaries will be published in *Dendrochronologia*. Further information can be obtained from the author (see address in Appendix 1).

TABLE 5 Proposed convention for the publication and quoting of tree-ring dates. The Sheffield sapwood estimate of 10–55 rings is used in these examples, but it can be replaced by other published estimates

TYPE OF TREE-RING DATE	EXPLANATION
date span AD 900 – 1066 (Sheffield, 1995)	date of the first and last ring of the ring sequence (laboratory, date result produced). Should not be confused with felling dates
felled AD 1066B (Sheffield, 1995)	bark edge present; last ring incomplete – felled late spring/summer of AD 1066 (laboratory, date result produced)
felled AD 1066/1067B (Sheffield, 1995)	bark edge present; last ring complete or season of felling indeterminable – felled winter/early spring of AD 1066/1067 (laboratory, date result produced)
felled AD 1066/1067B? (Sheffield, 1995)	bark edge probably present – probably felled in AD 1066/1067; definitely not before (laboratory, date result produced)
felled AD 1066 – 1096 (Sheffield, 1995; Hillam <i>et al</i> 1987 for 10–55 sapwood estimate)	25 sapwood rings but no bark edge; sapwood estimate applied; there is a 95% chance of the timber being felled in one of the years within this range laboratory, date result produced; details of sapwood estimate). Should not be quoted as 'AD 1081±15' or 'about AD 1081'
felled AD 1066 – ?1111 (Sheffield, 1995; Hillam <i>et al</i> 1987 for 10 – 55 sapwood estimate)	heartwood-sapwood boundary probably present; sapwood estimate applied – the timber being felled after AD 1066 and possibly before AD 1111 (laboratory, date result produced; details of sapwood estimate)
felled AD 1066+ (Sheffield, 1995; Hillam <i>et al</i> 1987 for 10 – 55 sapwood estimate)	no sapwood; unknown amount of heartwood may missing – timber felled some unquantifiable time after AD 1066 (laboratory, date result produced; details of sapwood estimate)

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Glossary

I am much indebted to Michele Kaennel, whose work I have adapted for many entries in this glossary. A full version of her multilingual glossary of dendrochronology has now been published (Kaennel and Schweingruber 1995). Not all the entries are found in the text; some are included should the reader want to read more widely on the subject.

Asterisks refer to entry terms defined elsewhere in the glossary; alternative terms are given in brackets.

absolute chronology A set of ring width series or other ring parameters that have been *crossmatched, and *crossdated against another dated series.

***annual growth layer** A growth layer produced in one year; in cross-section, appears as an *annual ring.

annual ring (annual growth ring; tree-ring) Cross-section of an *annual growth layer.

bark All the tissues outside the *vascular cambium.

bark edge Edge of the timber underneath the bark.

calibration, radiocarbon The process of converting a radiocarbon measurement into a distribution, or range, of possible calendrical dates, expressed as Cal BC and Cal AD.

cambium see **vascular cambium**

14C (carbon 14) A radioactive isotope of carbon with atomic mass 14.

chronology building The *crossmatching and processing of ring widths or other indices from several samples from a given site or region to produce long chronologies used for *crossdating and for deducing past climates; the number of samples will vary depending on the availability of samples and length of chronology.

complacency 1 Lack of ring width variability, which theoretically indicates that the growth of a particular tree is relatively unaffected by variation in climate. 2 Tree-ring sequence with little variability.

core see **increment core**

correlation coefficient A statistic that expresses the amount of interdependence or association between two data sets without regard to dependency; it usually ranges from +1, which indicates perfect and direct correlation, to -1, which indicates perfect and inverse correlation; a value of 0 indicates a complete lack of interdependence.

crossdating The procedure of matching variations in ring widths or other ring parameters against a dated ring pattern, allowing the identification of the exact year in which each *annual ring was formed.

crossmatching The procedure of matching variations in ring widths or other ring parameters.

date, to In *dendrochronology: to determine the date of an *annual ring.

dendrochronology The science of dating *annual growth layers of wood (tree-rings) to their exact year of formation.

dendroclimatology A sub-field of dendrochronology that utilises dated tree-rings to reconstruct and study past and present climate.

dendroecology A sub-field of dendrochronology that utilises dated tree-rings to study ecological problems and the environment.

dendrogeomorphology A sub-field of dendrochronology that utilises dated tree-rings to study geological processes such as avalanches or glacier movements.

dendrohydrology A sub-field of dendrochronology that utilises dated tree-rings to study hydrological problems such as river flow, sea level changes, and flooding history.

dendroprovenancing The use of dendrochronology to determine the provenance of a timber.

detrend, to To remove a *trend in a curve, whatever the origin of the trend (eg long-term climate change, age of tree).

diffuse-porous species Species (eg alder, beech, birch) with little or no decrease in *vessel size throughout the ring. Most European trees are diffuse-porous species.

earlywood (springwood) Wood produced during the early part of the growing season.

false ring A change in cell structure within an *annual ring, which resembles the boundary of a true annual ring, making it appear to be two rings instead of one.

felling date The year, known or estimated, when a given tree was felled.

floating chronology A set of ring width series that have been *crossmatched and averaged, but not *crossdated against an absolute chronology; a chronology to which absolute dates have not been assigned.

frost ring Distorted tissue damaged by freezing in the growing season during which the cells were being formed.

Gleichläufigkeit A non-parametric measure of the year-to-year agreement between the yearly intervals of two ring series, usually expressed as a percentage of cases of agreement.

growth layer A layer of wood produced during one growing season.

growth rings A layer of cells, seen in cross-section, identified by a change in cell structure between each ring.

hardwood A conventional term for broadleaved trees and their timber.

heartwood The inner part of a tree, often distinguishable from the *sapwood by a colour change, which no longer contains living cells;

provides mechanical rigidity for the stem and support for the crown of the tree.

increment corer or borer An auger-like instrument with a hollow bit and an extractor used to extract *increment cores from trees.

increment core Thin cylinders of wood extracted radially from a tree or timber using an *increment corer.

independent date A date derived by methods that are totally independent of archaeological or historical context.

latewood (summerwood) Wood produced later in the growing season after the production of *earlywood.

limiting factor A factor that controls the rate of growth; this can be external (eg water; temperature, soil minerals) or internal (eg available minerals, enzymes). A tree's rate of growth cannot proceed faster than that allowed by the most limiting factor.

marker date A date that seems to occur and recur in the archaeological record.

master chronology A dated or undated chronology for a given area, constructed by averaging overlapping series of matching ring-widths or indices; can be used to crossdate new ring sequences.

mean Sum of values divided by the number of items summed.

missing ring An *annual ring that is discontinuous around the stem so that it is absent along certain radii.

pith The central core of a stem.

radiocarbon see ¹⁴C.

radiocarbon dating The determination of the age of old carbonaceous materials carried out by measuring the content of *¹⁴C.

reference chronology Dated *master chronology used to date new ring sequences or chronologies.

replication Sampling and *crossmatching ring sequences from more than one timber per site, or

more than one radius per tree, in order to improve and check the information content in a chronology.

reused timber One that has been salvaged from an older context and used in a more recent one.

ring porous species Species (eg oak, ash, elm) with an abrupt change in cell size from the large *vessels of the *earlywood to the smaller, denser vessels of the *latewood.

ring width Width of an *annual ring.

ring width index The transformed value of a *ring width after *standardisation.

ring width series or sequence

A set of *ring widths plotted as a function of time; also known as a tree-ring curve.

running mean Ring width average for a given number of successive years, the sequence being moved ahead by one year each time the average is computed; each average is assigned to the year of the central ring in the sequence.

sapwood The outer part of a tree, often distinguishable from the *heartwood by colour; containing living cells, which transport water and store food reserves.

sensitivity 1 Presence of ring width variability, which theoretically indicates that the growth response of a particular tree is 'sensitive' to changes in climate. 2 Ring pattern that shows ring width variability.

signature year A year in which a significant proportion of ring sequences show the same increase or decrease in width from the previous year.

softwood A conventional term for coniferous trees and their timber.

spot dates Tree-ring dates produced for a small group of timbers in advance of routine analysis.

standardisation or indexing Removing long-term variations from a series of ring widths, thereby creating a series of ring width indices.

Student's *t* test A means of testing the significance of the *correlation coefficient by taking into account the length of overlap; in dendrochronology, a *t* value of 3.5 or above indicates a match if the visual match between the tree-ring curves is acceptable (Baillie and Pilcher 1973).

***t* value** see **Student's *t* test**

terminus post quem Archaeological term, used dendrochronologically to indicate the earliest possible felling date; for example a *terminus post quem* of AD 1066 indicates the tree was felled after 1066.

tree-ring see **annual ring**

tyloses intrusive growths of the cell walls, which invade the *vessels of oak heartwood but not the sapwood.

vascular cambium Layer of cells underneath the bark responsible for the increase in tree girth; it divides each year to produce new wood to the inside and inner bark to the outside.

vessel Tubular cells in *hardwoods which are stacked vertically and used for conducting water; seen as holes in cross-section. The large spring vessels of oak are responsible for its well-defined annual rings.

waney edge Edge of timber underneath the bark; also known as *bark edge or cambial surface.

wiggle-matching Comparison of a series of radiocarbon dates, produced from samples of wood separated by intervals of real years, against a radiocarbon calibration curve to produce a more precise date in the absence of a tree-ring date.

Appendix I

Contact addresses; funding for dendrochronology

Contact addresses

English Heritage

23 Savile Row
London W1S 2ET
Alex Bayliss 020 7973 3299
Alex.Bayliss@english-heritage.org.uk

Sheffield Dendrochronology Laboratory

Research School of Archaeology
& Archaeological Science
University of Sheffield
West Court
2 Mappin Street
Sheffield S1 4DT
Cathy Groves 0114 276 3146
c.m.groves@sheffield.ac.uk

At present advice from the above is available to all, free of charge. Addresses of contractors who may be willing to undertake dendrochronological work are given below. Please note that inclusion in the list is no commitment to provide help, nor does it indicate that English Heritage endorses the organisation listed or their results.

AOC Scotland Ltd

Edgefield Industrial Estate
Edgefield Road
Loanhead
EH20 9SY
Anne Crone, Coralie Mills
0131 440 3593
admin@aocscot.co.uk

Belfast Tree-Ring Laboratory

Palaeoecology Centre
Queen's University
Belfast BT7 1NN
Mike Baille 028 90335147
m.baillie@qub.ac.uk

Dave Brown 028 90335143
d.brown@qub.ac.uk

Bridge, Martin

Institute of Archaeology
University College London
31-34 Gordon Square
London WC1H 0PY
020 7679 1540
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MarBrdg@aol.com

Nayling, Nigel

Department of Archaeology
University of Wales, Lampeter
Lampeter
Ceredigion
Wales SA48 7ED
01570 422351
n.nayling@lamp.ac.uk

Nottingham University Tree-Ring Dating Laboratory

Department of Archaeology
University Park
Nottingham NG7 2RD
Robert Howard 0115 951 4837
roberthoward10@hotmail.com
Cliff Litton 0115 951 4960
cdl@maths.nott.ac.uk

Oxford Dendrochronology Laboratory

Mill Farm
Mapledurham
Oxon
RG4 7TX
Dan Miles 0118 9724074
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research.oxford.ac.uk

Sheffield Dendrochronology Laboratory

Research School of Archaeology
& Archaeological Science
University of Sheffield
West Court
2 Mappin Street
Sheffield S1 4DT
Ian Tyers 0114 222 5107
I.Tyers@sheffield.ac.uk

Switsur, Roy

School of Applied Sciences
Anglia Polytechnic University
East Road
Cambridge
CB1 1PT
01223 417712
V.R.Switsur@anglia.ac.uk

Tree-Ring Services

23 Fairbank Avenue
Orpington
Kent
BR6 8JY
Andy Moir 07961 435044
akmoir@tree-ring.co.uk
www.tree-ring.co.uk

Funding for dendrochronology

The British Academy: Fund for Applied Science in Archaeology

These provide support to non-site specific projects which involve the application of established scientific techniques. Further details and application forms are available from:

The British Academy

20-21 Cornwall Terrace
London NW1 5QP

English Heritage

Anyone with a project in receipt of English Heritage funding may request dendrochronological work; forms are available from Alex Bayliss at the address given above.

The Heritage Lottery Fund

Anyone with a project in receipt of funding from the Heritage Lottery Fund may include dendrochronology as part of the project.

Appendix 2: First aid for dendrochronology

Most archaeologists are familiar with the publication *First aid for finds* (UKIC and RESCUE 1988). Although it deals with waterlogged wood to some extent, it does not specifically mention dendrochronology. Some of the most important 'rules' are therefore summarised below. If in any doubt about what to do, telephone your dendrochronologist.

Buildings under repair

- ensure sapwood is not removed during renovation (eg defrassing, power hosing)
- do not throw away timbers replaced during renovation
- fully record and label timbers that have to be removed with their original location

Waterlogged wood

- keep the timber wet
- do not use sharp tools
- if necessary, clean surfaces gently with water
- photograph and draw before sampling
- sample on site
- take as many samples as possible
- keep sample wet (unless they have already dried out, in which case no attempt should be made to re-wet them)
- sample thickness 50 – 150mm
- protect edges with tape or bandages if fragile and/or sapwood is present
- bag and seal sample; avoid nails and staples
- label inside and out
- do not use biocides

Charcoal

- if fragile, surround with foam and do not attempt to sample
- if solid, cut out slice 100–200mm and protect with foam



ENGLISH HERITAGE

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