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Furness Abbey, Barrow-in-Furness, Cumbria
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Alison Arnold, Robert Howard, Elaine Dunbar, Cathy Tyers and Peter Marshall

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SUMMARY

Dendrochronological analysis was undertaken on 43 samples obtained as slices from a series of timbers used as a foundation raft for the presbytery walls at Furness Abbey, these timbers having being removed as part of emergency conservation works. This analysis produced one dated site chronology comprising 32 samples and having an overall length of 182 rings (BIFESQ01). These rings were dated as spanning the years AD 975–1156. Interpretation of the sapwood on the dated samples would suggest the likelihood that all the timbers were cut as part of a single programme of felling (though perhaps not all at exactly the same time) in the period AD 1165–90, and are thus likely to represent part of the earliest work on the extant Abbey. A second site chronology, BIFESQ02, comprising nine samples could also be created, this being 161 rings long. This site chronology could not be dated by dendrochronology, but the results of a radiocarbon wiggle match suggest it is likely that the sequence is broadly coeval with BIFESQ01. The remaining two samples were rejected from the analysis.

CONTRIBUTORS

Alison Arnold, Robert Howard, Elaine Dunbar, and Peter Marshall

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Historic Environment Service, Environment Directorate, County Offices, Kendal, Cumbria, LA9 4RQ

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CONTACT DETAILS

Alison Arnold and Robert Howard
Nottingham Tree-ring Dating Laboratory, 20 Hillcrest Grove, Sherwood, Nottingham NG5 1FT
roberthoward@tree-ringdating.co.uk
alisonarnold@tree-ringdating.co.uk

Elaine Dunbar
SUERC, Radiocarbon Laboratory
Scottish Enterprise Technology Park
Rankine Avenue
East Kilbride G75 1QF
elaine.dunbar@glasgow.ac.uk

Cathy Tyers and Peter Marshall
Historic England
Cannon Bridge House
25 Dowgate Hill
London, EC4R 2YA
cathy.tyers@historicengland.org.uk
peter.marshall@historicengland.org.uk

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INTRODUCTION

Furness Abbey was originally founded by Stephen, Count of Boulogne (grandson of William the Conqueror) and King of England from AD 1135 until his death in AD 1154. The Abbey was initially established in AD 1124 at Tulketh, near Preston, in Lancashire, for the Order of Savigny, the first Savigniac monastery to be founded in England, but moved in AD 1127 to its present site in the Vale of Beckansgill just to the north of what is now Barrow-in-Furness (Fig 1). Following earlier archaeological work, as well as more recent investigation, the plan of the Savigniac church is known to have comprised an apsidal Presbytery flanked by two pairs of apsidal chapels. Elements of the Savigniac church survive at the west end of the Presbytery (Headland Archaeology Ltd 2012).

It is known from documentary sources that the church was not finished when the Scots raided and destroyed the Abbey in AD 1138, having chased off the monks. The monks returned in AD 1141, and began to rebuild the ornate church and erect more permanent buildings to create one of the great medieval English Abbeys. In AD 1147 the affiliation changed as the Savigniac Order merged with the Cistercians, and from this date Furness was a Cistercian house, the order gradually enlarging and rebuilding the original church.

During the twelfth and thirteenth centuries following the absorption of the Savigniac order by the Cistercians, the east end of the church was rebuilt with a square-ended Presbytery and three square-ended chapels opening off the north and south transepts. The majority of the current ruins date from this period. By the fifteenth century, it had been completely re-modelled and had become the second richest and most powerful Cistercian Abbeys in England, as well as one of the grandest. The Abbey was dissolved in AD 1537 on the orders of Henry VIII.

SAMPLING

The Grade 1 listed ruins are now a property in the care of English Heritage who has been carrying out emergency conservation work to stop the ruined Abbey church sinking into the soft ground. This follows earlier routine inspections which revealed serious cracks in the presbytery walls. It would appear that these walls are built up over a foundation raft of oak timbers, and that these timbers are now gradually giving way. A number of these timbers were retrieved from beneath the Presbytery during a programme of underpinning which took place in 2013 (Fig 2). This underpinning was performed by removing timbers from ‘slots’ beneath the walls, the slots then being filled with concrete. Initially, a number of these timbers were extracted without reference to their original locations (though they are believed to have been extracted from slots in area ‘C’) (Fig 3), though the locations of timbers extracted later were so identified.

From these timbers large off-cut baulk sections were taken and stored at the Abbey site. A dendrochronological analysis of these timbers was then requested by Tim Baldock, English Heritage National Projects Team, to provide independent dating evidence for the foundation timbers. Thus from the suitable baulks available a total of 43 cross-sectional slices were obtained with a chainsaw (Figs 4a/b), these slices subsequently being further reduced to radial slices. Each sample was given the code BIF-E (for Barrow-in-Furness, site 'E') and numbered 01–43 (Table 1).

ANALYSIS AND RESULTS

Each of the 43 samples obtained from Furness Abbey was prepared by sanding and polishing and their annual growth ring widths were measured. It was seen at this time that one sample, BIF-E18, had serious distortion to its growth which thwarted attempts to obtain reliable ring-width measurements. Similar issues were encountered with BIF-E24 with bands of narrow rings proving to impossible to measure reliably. A few other samples had slightly decayed or rotted outer sections and it was not always possible to measure the annual growth ring widths of these portions of the sample. It was, however, usually possible to determine the approximate number of rings these un-measured portion of sample might contain, this information also being given in Table 1, and used to help determine the likely felling date of the timbers. The ring-width data of all measured samples are given at the end of this report.

The data of the 41 measured samples were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), this comparative process producing two separate groups of cross-matching samples. The first group comprises 32 samples, these cross-matching with each other as shown in the bar diagram, Figure 5. These 32 samples were combined at their indicated offset positions to form site chronology BIFESQ01, this having an overall length of 182 rings. Site chronology BIFESQ01 was then compared to the full corpus of reference material for oak cross-matching with a number of these when the date of its first ring is AD 975 and the date of its last ring is AD 1156. The evidence for this dating is given in Table 2.

The second group to form comprises the remaining nine measured samples, these cross-matching with each other as shown in the bar diagram, Figure 6. These nine samples were also combined at their indicated offset positions to form site chronology BIFESQ02, this having an overall length of 161 rings. Site chronology BIFESQ02 was also compared to the full corpus of reference material for oak but in this instance there was no conclusive cross-matching and the nine samples must, therefore, remain undated by dendrochronology.

This analysis may be summarised as below:

Site chronology	Number of samples	Number of rings	Date span AD (where dated)
BIFESQ01	32	182	975–1156
BIFESQ02	9	161	------
Unmeasured	2	---	------

INTERPRETATION

Analysis by dendrochronology of the timbers of Barrow-in-Furness barn has produced a single dated site chronology comprising 32 samples, its 182 rings dated as spanning the years AD 975–1156. A further site chronology comprising nine samples has also been created, this being 161 rings long. This second site chronology, however, cannot be dated.

Site chronology BIFESQ01

None of the 32 dated samples in site chronology BIFESQ01 retains complete sapwood (the last growth ring produced by the tree before it was felled), this either having been removed by the original carpenters or decayed while the timbers were in the ground. As a result, it is not possible to indicate a precise felling date for any timber. Several of the samples do, though, retain the heartwood/sapwood boundary (this indicated by 'h/s' in Table 1 and the bar diagram), this meaning that only the outer sapwood rings have been lost from the timbers.

The average date of the heartwood/sapwood boundary on the 11 dated samples that certainly retain it is AD 1150. Allowing for the minimum and maximum numbers of sapwood rings the trees are likely to have had (the 95% confidence interval being 15–40 sapwood rings) this would give the timbers an estimated felling date in the range AD 1165–90. That these timbers are generally coeval, furthermore, is supported by the small difference in the position and date of the heartwood/sapwood boundary, this ranging by only 12 years from relative position 170 (AD 1144) on samples BIF-E21 and BIF-E36, to relative position 182 (AD 1156) on samples BIF-E07 and BIF-E19. Such similarity is indicative of a group of trees having been cut at a similar (though perhaps not identical) time to each other as part of a single episode of felling.

While it is very likely (allowing for estimates of unmeasured rings and the likely presence of the heartwood/sapwood boundary) that at least a few other timbers were cut as part of this later-twelfth century programme of felling, there are a number of timbers (those without the heartwood/sapwood boundary), where a likely felling date range cannot be reliably determined. The earliest possible felling may be represented by sample BIF-E15, though, with a last heartwood ring date of AD 1064 and allowing for a minimum of 15 sapwood rings, this is unlikely to have been before AD 1079. The latest timber without a heartwood/sapwood boundary is represented by sample BIF-E39, which, with a last heartwood ring date of AD 1141 and again allowing for a minimum of 15 sapwood rings, is unlikely to have been cut before AD 1156.

However, although it is possible that one or two timbers could in theory be earlier, or indeed later, than the majority, this seems unlikely given the high level of cross-matching between the samples, with values in excess of t=7.0, t=8.0, and t=9.0 being seen. Indeed, given that they cross-match with particularly high values, it is likely that samples BIF-E27 and BIF-E28 (t=16.7), BIF-E11 and BIF-E14 (t=17.0) and BIF-E07 and BIF-E08 (t=25.5), are pairs of timbers each derived from single trees, although in this instance it is feasible that some samples may have been derived from the same timber. However the overall level of cross-matching would suggest that all the timber has been derived from trees growing close to each other in a single woodland and are thus more likely to have been felled as part of a single episode of felling, albeit, possibly over a few years as work on the Abbey proceeded.

Site chronology BIFESQ02

Likewise, none of the nine samples in the undated site chronology BIFESQ02 retains complete sapwood or indeed the heartwood/sapwood boundary. It is thus difficult to be certain that the timbers are coeval. However, given again the levels of cross-matching between samples, it is probable that that all nine sampled timbers were derived from no more than three different closely grown trees (and possibly from a single tree) from a single woodland. As such it is very likely that, if more than one tree, they were cut at the same time as each other.

Radiocarbon dating sampling and analysis

Three samples from timber BIF-E40 that formed part of the 161 year undated site sequence BIFESQ02 were submitted for dating to determine whether the nine timbers in BIFESQ02 were contemporary with those in BIFESQ01. The three radiocarbon wiggle-match samples from the undated site sequence BIFESQ02 were selected from the beginning of the sequence (Table 3) in the expectation that they would fall on the 'steep' section of the calibration curve (Fig 7), if they were contemporary with BIFESQ01, and thus provide a more precise date for the last ring of the sequence than if samples from throughout the sequence had been submitted.

The three samples dated at Scottish Universities Environmental Research Centre (SUERC) were pretreated as outlined in Dunbar *et al* (2016), and dated by Accelerator Mass Spectrometry (AMS) (Freeman *et al* 2010).

The laboratory maintains a continual programme of quality assurance procedures, in addition to participation in international inter-comparisons (Scott 2003; Scott *et al* 2010). These tests indicate no laboratory offsets and demonstrate the reproducibility and accuracy of these measurements.

The results are conventional radiocarbon ages (Stuiver and Polach 1977; Table 3), and are quoted in accordance with the international standard known as the Trondheim convention (Stuiver and Kra 1986).

Radiocarbon dating

Radiocarbon dating is based on the radioactive decay of carbon-14 and can be used to date organic materials, including wood. A small proportion of the carbon atoms in the atmosphere are of a radioactive form, carbon-14. Living plants and animals take up carbon from the environment, and therefore contain a constant proportion of carbon-14. Once a plant or animal dies, however, its carbon-14 decays at a known rate. This makes it possible to calculate the date of formerly living material from the concentration of carbon-14 atoms remaining. Radiocarbon measurements, like those in Table 3 are expressed in radiocarbon years BP.

Calibration

Radiocarbon ages are not the same as calendar ages because the concentration of carbon-14 in the atmosphere has fluctuated over time. This is because, due to the fluctuations in carbon-14 in the atmosphere over time, a radiocarbon measurement has to be calibrated against an independent scale to arrive at the corresponding calendar date.

That independent scale is the IntCal13 calibration curve (Reimer *et al* 2013) is constructed from radiocarbon measurements on tree rings, plant macrofossils, speleothems, corals, and foraminifera. The calibrations which relate the radiocarbon measurements directly to the calendrical time scale have been calculated using IntCal13 and the computer program OxCal v4.2 (https://c14.arch.ox. ac.uk/oxcal/; Bronk Ramsey 1995; 2001; 2009). The calibrated date ranges quoted for each sample in Table 3, expressed as 'cal AD", were calculated by the maximum intercept method (Stuiver and Reimer 1986) and are rounded outwards to the nearest 10 years as recommended by Mook

(1986). The graphical distributions of the calibrated dates, shown in outline in Figure 9 are derived from the probability method (Stuiver and Reimer 1993).

Bayesian Wiggle-matching

Wiggle-matching uses information derived from tree-ring analysis, in combination with radiocarbon measurements to provide a revised understanding of the age of a timber; a review is given by Galimberti *et al* (2004). In this technique, the shapes of multiple radiocarbon distributions can be "matched" to the shape of the radiocarbon calibration curve. The exact interval between radiocarbon results can be derived from tree-ring analysis.

Although the technique can be done visually, Bayesian statistical analyses (including functions in the OxCal computer program) are now routinely employed. A general introduction to the Bayesian approach to interpreting archaeological data is provided by Buck *et al* (1996). The approach to wiggle-matching adopted here is described by Christen and Litton (1995).

Details of the algorithms employed in this analysis — a form of numerical integration undertaken using OxCal — are available from the on-line manual or in Bronk Ramsey (2009). Because it is possible to constrain a sequence of radiocarbon dates using this highly informative prior information (Bayliss *et al* 2007), model output will provide more precise posterior density estimates. These *posterior density estimates* are shown in black in the Figures and quoted in italic in the text.

The Acomb statistic shows how closely the dates as a whole agree with other information in the model; an acceptable threshold is reached when it is equal to or greater than An, a value based on the number of dates in the model. The A statistic shows how closely an individual date agrees with the other information in the model; an acceptable threshold is reached when it is equal to or greater than 60.

BIFESQ02

The chronological model for the dating of site sequence BIFESQ02 shown in Figure 8 shows good agreement between the radiocarbon dates and the relative number of years between them derived from the tree-ring analysis (Acomb = 92.8; An = 40.8; n=3). The model provides an estimate for the last ring of site sequence BIFESQ02 of *cal AD 1025–1065* (*73% probability*; *BIFESQ02_ring_161*; Fig 8) or *cal AD 1075–1110* (*22% probability*) and probably *cal AD 1030–1055* (*62% probability*) or *cal AD 1085–1095* (*6% probability*). Given that timber BIF-E40 along with the other timbers in site sequence BIFESQ02 only comprised heartwood rings this estimate simply provides a *terminus post quem* for their felling.

A potential last ring date for BIFESQ02 suggested by dendrochronology is AD 1038; with BIFESQ02 matching against reference for Lancaster Castle, Lancashire (AD 950–1404; *t*=5.4); Peterborough Cathedral transepts, Cambridgeshire (AD 921–1194; *t*=5.3) and Barton Coffins, North Lincolnshire (AD 785–1134; *t*=5.0; Tyers 2001). Incorporating the potential date for the last ring into the wiggle-match (Fig 9) shows good agreement (Acomb = 95.2; An = 40.8; n=3).

The average date (AD 1150) of the heartwood/sapwood boundary on the 11 dated samples that certainly retain it is not incompatible with the estimate for the date of the final ring of BIFESQ02 (Fig 10) and although unproven it is likely that the two sequences are broadly coeval.

CONCLUSION

It would seem very likely, therefore, that the majority of timbers examined in this programme of tree-ring and radiocarbon analysis, were cut as part of a single episode of felling in the later twelfth century specifically for the construction of the Abbey after the monks returned to the site in AD 1141 following earlier Scottish raids. Taken overall, the timbers have an estimated felling date in the range, AD 1165–90.

Woodland sources

As may be seen from Table 2, although compared with site chronologies from all parts of England, site chronology BIFESQ01 appears to generally cross-match best with references made up of data from other sites in north-west England. This would suggest that the timbers used for the foundation rafters are from relatively local woodlands.

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TABLES

Table 1: Details of tree-ring samples from Furness Abbey, Barrow-in-Furness, Cumbria

Sample number	Sample location	Total rings (+ estimate of unmeasured rings)	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
BIF-E01	Beam	105 (+60 nm to ?h/s)	no h/s	986	------	1090
BIF-E02	Beam	96 (+30 nm)	no h/s	985	------	1080
BIF-E03	Beam	166	h/s	988	1153	1153
BIF-E04	Beam	120 (+40 nm to ?h/s)	no h/s	988	------	1107
BIF-E05	Beam	80 (+80 nm to ?h/s)	no h/s	992	------	1071
BIF-E06	Beam	93 (+60 nm)	no h/s	976	------	1068
BIF-E07	Beam	170	h/s	987	1156	1156
BIF-E08	Beam	169	h/s	987	1155	1155
BIF-E09	Beam	153	h/s	997	1149	1149
BIF-E10	Beam	164	h/s	985	1148	1148
BIF-E11	Beam	170	h/s	976	1145	1145
BIF-E12	Beam	80 (+40 nm)	no h/s	984	------	1063
BIF-E13	Beam	137	no h/s	995	------	1131
BIF-E14	Beam	140	no h/s	995	------	1134
BIF-E15	Beam	70	no h/s	995	------	1064
BIF-E16	Beam	137 (+30 nm)	no h/s	975	------	1111
BIF-E17	Beam	148	no h/s	992	------	1139
BIF-E18	Beam	nm	---	------	------	------
BIF-E19	Beam	174	h/s	983	1156	1156
BIF-E20	Beam D5 B	132	no h/s	989	------	1120
BIF-E21	Beam D7 B	144	h/s	1001	1144	1144
BIF-E22	Beam D3 C	122	no h/s	998	------	1119
BIF-E23	Beam D8 C	106	no h/s	------	------	------
BIF-E24	Beam D4 B	nm	---	------	------	------

Table 1: Details of tree-ring samples from Furness Abbey, Barrow-in-Furness, Cumbria

Sample number	Sample location	Total rings (+ estimate of unmeasured rings)	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
BIF-E25	Beam D18 B	102	no h/s	------	------	------
BIF-E26	Beam D7 C	140	no h/s	988	------	1127
BIF-E27	Beam D3 D	108	no h/s	------	------	------
BIF-E28	Beam D9 A 1/3	116	no h/s	1014	------	1129
BIF-E29	Beam D22 1/16	114	no h/s	1025	------	1138
BIF-E30	Beam D6 C	128	no h/s	997	------	1124
BIF-E31	Beam D7 D	114	no h/s	------	------	------
BIF-E32	Beam D8 A	130	no h/s	998	------	1127
BIF-E33	Beam D5 C	168	h/s	985	1152	1152
BIF-E34	Beam D8 B	145	no h/s	986	------	1130
BIF-E35	Beam slot ‘X’ E	164	h/s	986	1149	1149
BIF-E36	Beam D A9 A 2/3	156	h/s	989	1144	1144
BIF-E37	Beam D6 D	110	no h/s	------	------	------
BIF-E38	Beam D17 E 2 pcs	144	no h/s	996	------	1139
BIF-E39	Beam D	92	no h/s	1050	------	1141
BIF-E40	Beam slot ‘X’ D	156	no h/s	------	------	------
BIF-E41	Beam D4 D	103	no h/s	------	------	------
BIF-E42	Beam D9 A 3/3	158	no h/s	------	------	------
BIF-E43	Beam slot ‘X’ C	108	no h/s	------	------	------

h/s = the heartwood/sapwood ring is the last ring on the sample
nm = rings not measured

Table 2: Results of the cross-matching of site sequence BIFESQ01 and relevant reference chronologies when the first-ring date is AD 975 and the last-ring date is AD 1156

Reference chronology	Span of chronology	*t*-value	Reference
Eastgate, Beverley, Yorkshire	AD 858–1310	7.5	Groves 1992
Lamb Hotel, Nantwich, Cheshire	AD 941–1276	7.1	Tyers 2004a
Second Wood Street, Nantwich, Cheshire	AD 932–1509	6.8	Tyers 2005
Annetwell Street, Carlisle, Cumbria	AD 930–1219	6.6	Groves 1990
Dundas Wharf, Bristol	AD 770–1202	6.6	Nicholson and Hillam 1987
Bowers Row, Nantwich, Cheshire	AD 920–1244	6.2	Hillam 1994 unpubl
Peterborough Cathedral nave, Cambridgeshire	AD 887–1225	6.2	Tyers 1999
Peterborough Cathedral transepts, Cambridgeshire	AD 921–1194	6.2	Tyers 2004b
Lancaster Castle, Lancashire	AD 950–1404	5.9	Arnold *et al* forthcoming
Oakham Castle, Oakham, Rutland	AD 923–1153	5.8	Arnold and Howard 2011

Table 3: Furness Abbey timber BIF-E40 part of sequence BIFESQ02– radiocarbon results

Laboratory number	Sample reference	Material & context	$\delta^{13}C_{IRMS}$ (‰)	Radiocarbon Age (BP)	Calibrated date – cal AD (95% confidence)	*Posterior Density Estimate -cal AD (95% probability)*
SUERC-58596	BIF-E40, rings 1–5	*Quercus* sp. heartwood, relative years 1–5 of chronology BIFESQ02, from BIF-E40 a waterlogged timber offcut from the Presbytery foundation raft	−26.3±0.2	1178±29	770–960	*865–905 (73%) or 920–950 (22%)*
SUERC-58597	BIF-E40, rings 20–24	*Quercus* sp. heartwood, relative years 20–24 of chronology BIFESQ02, from BIF-E40 a waterlogged timber offcut from the Presbytery foundation raft	−25.6±0.2	1081±28	890–1020	*885–925 (73%) or 940–970 (22%)*
SUERC-58598	BIF-E40, rings 36–40	*Quercus* sp. heartwood, relative years 36–40 of chronology BIFESQ02, from BIF-E40 a waterlogged timber offcut from the Presbytery foundation raft	−24.5±0.2	1127±29	770–990	*900–940 (73%) or 955–985 (22%)*

FIGURES

Figure 1: Map to show the location of Barrow-in-Furness and Furness Abbey (after Headland Archaeology Ltd) © *Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900.*

Figure 2: Views of a timber in-situ *(photograph Historic England)*

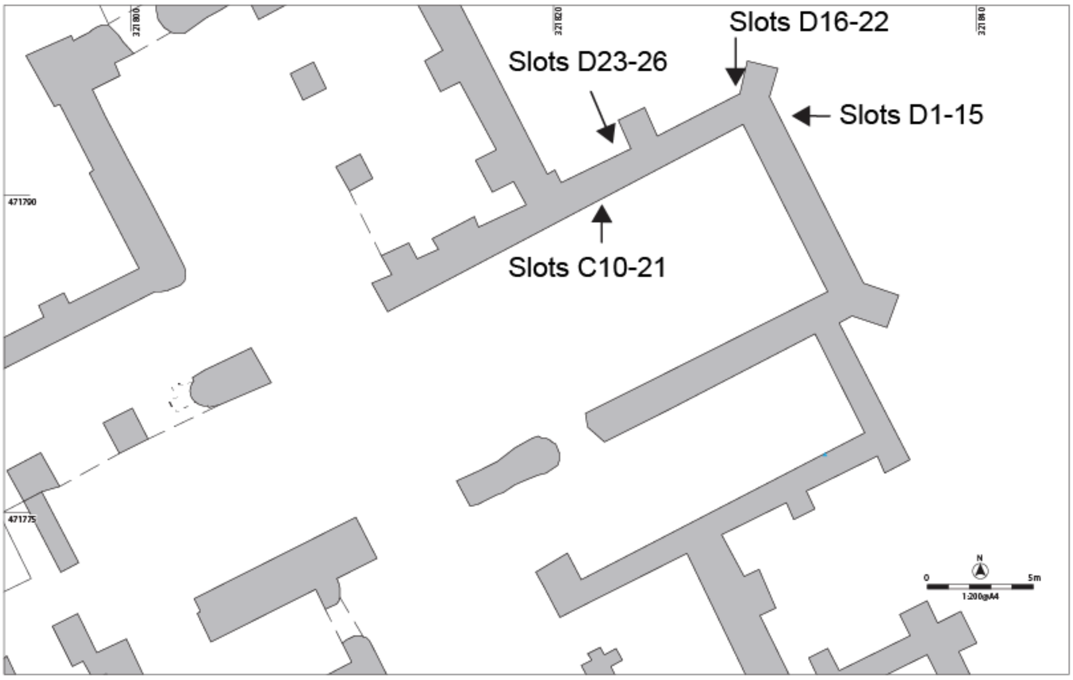
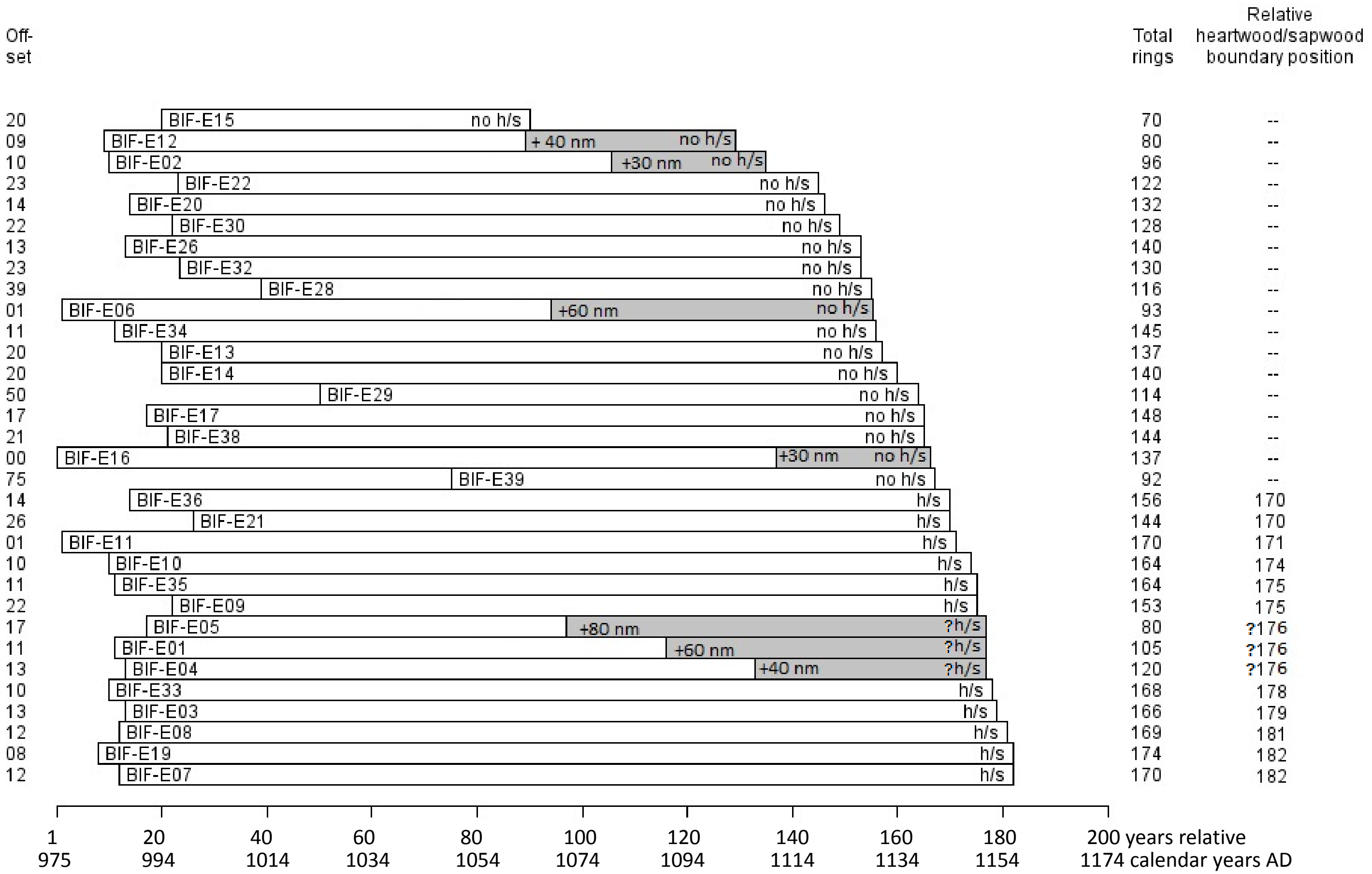


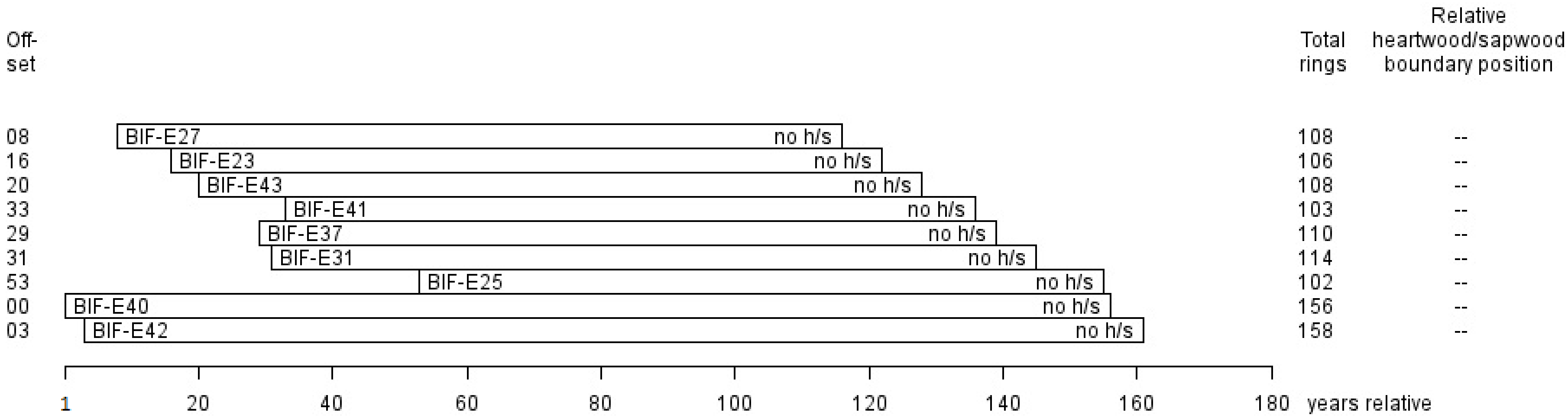
Figure 3: Plan of the Presbytery to show location of the underpinning slots (after Headland Archaeology Ltd) (after Headland Archaeology Ltd)

Figure 4a/b: Views of the timbers being sliced (photographs Robert Howard)



White bars = heartwood rings, shaded bars = estimate of rings not measured (nm); h/s = heartwood/sapwood boundary

Figure 5: Bar diagram of the samples in site chronology BIFESQ01



White bars = heartwood rings

Figure 6: Bar diagram of the samples in site chronology BIFESQ02

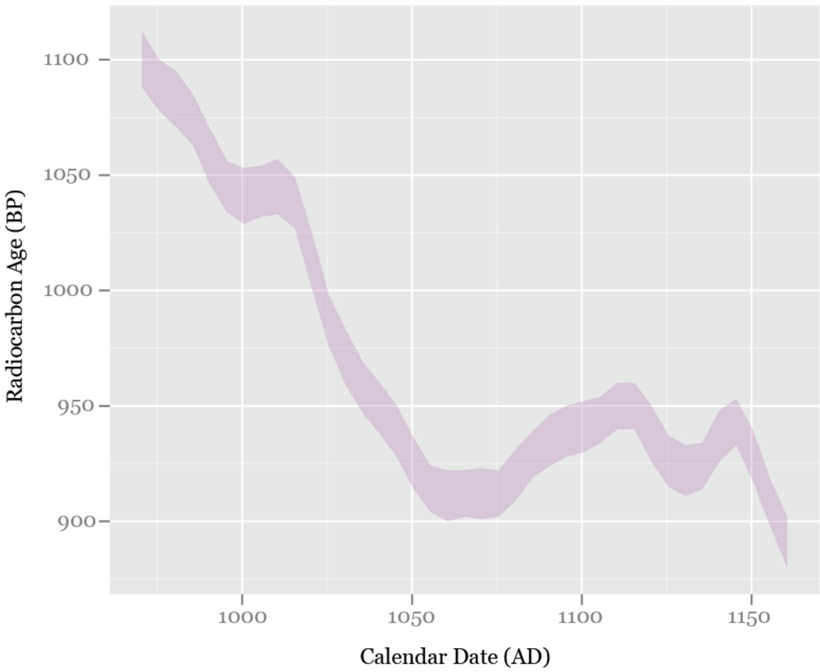


Figure 7: Radiocarbon calibration curve (Reimer et al *2013) for the period covered by the dated site sequence BIFESQ01 (975–1156 AD), illustrating why the three radiocarbon wiggle match samples from the undated site sequence BIFESQ02 were selected from the beginning of the sequence in the expectation that they would fall on the 'steep' section of the calibration curve*

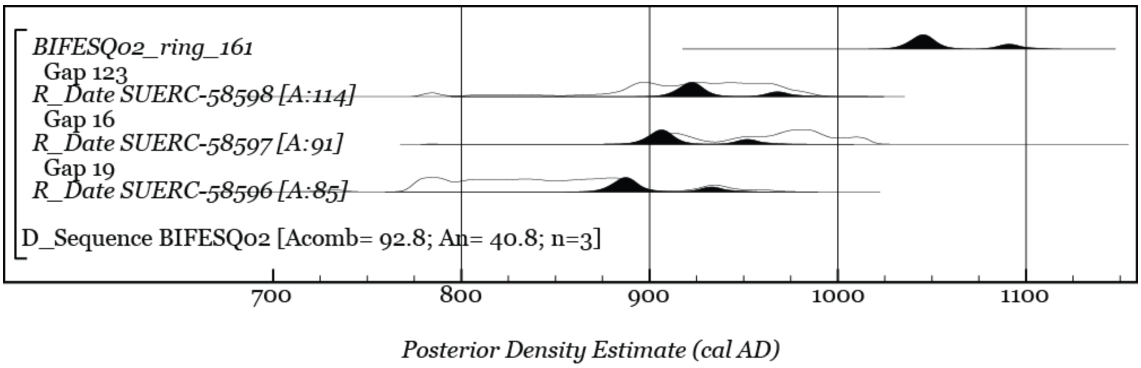


Figure 8: Probability distributions of dates from Furness Abbey site sequence BIFESQ02. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly

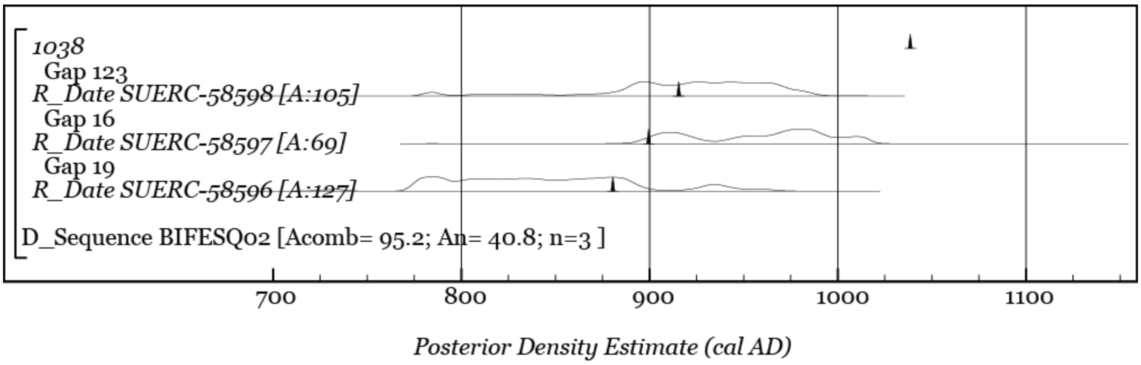


Figure 9: Probability distributions of dates from Furness Abbey site sequence BIFESQ02, incorporating the potential tree-ring date for the final ring of the sequence - AD 1038. The format is identical to Figure 9

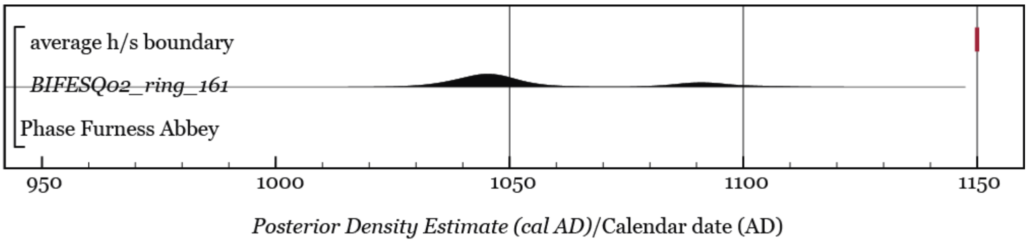


Figure 10: Summary of dating evidence for site sequences BIFESQ01 (average h/s boundary date) and BIFESQ02

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

BIF-E01A 105
254 219 181 200 189 152 219 168 131 161 163 161 209 132 132 176 142 136 69 38
55 90 126 133 155 190 174 118 117 103 75 80 89 82 86 82 67 153 132 132
161 148 191 164 160 96 115 118 146 198 172 257 243 210 190 233 196 87 59 66
81 121 79 106 126 106 96 121 76 89 68 114 97 118 150 131 120 128 96 60
109 103 73 66 116 97 104 75 76 179 123 123 148 135 92 53 46 40 48 101
145 146 100 147 91

BIF-E01B 105
259 231 176 205 192 171 192 182 150 155 157 165 189 144 132 179 144 134 64 44
51 93 131 139 146 180 176 132 100 100 74 78 91 71 94 87 67 157 139 128
157 152 191 155 178 87 117 107 162 187 170 234 251 225 187 220 193 89 67 65
98 116 107 129 150 107 110 112 73 85 60 108 99 115 151 134 107 117 93 72
114 107 61 63 114 111 100 83 118 158 142 132 127 126 95 53 47 56 68 96
134 150 109 152 96

BIF-E02A 96
196 228 163 108 138 144 142 132 134 106 169 156 187 221 192 184 257 202 154 139
61 45 60 117 107 107 139 120 122 96 80 46 53 61 46 98 93 93 116 149
107 150 102 174 84 114 65 105 70 104 153 112 264 325 309 246 320 209 104 105
88 164 160 95 162 230 182 209 207 114 128 101 162 196 199 153 170 151 135 142
85 166 170 59 73 125 134 150 132 176 271 218 240 178 126 139

BIF-E02B 96
169 200 154 109 134 141 151 172 149 111 173 189 201 242 205 178 237 176 140 122
60 45 61 117 102 107 128 122 127 108 96 45 58 60 56 81 84 86 125 146
113 144 126 155 114 110 75 83 108 100 162 109 259 314 293 237 320 212 95 96
98 170 160 96 158 231 184 209 200 114 128 100 157 203 198 165 169 146 140 139
76 160 169 67 68 120 150 164 115 190 284 212 223 232 103 134

BIF-E03A 166
212 224 208 174 184 205 230 246 228 207 168 179 216 189 146 167 108 65 58 75
99 129 83 81 156 117 89 82 52 42 46 45 96 76 75 116 60 48 57 53
62 64 69 45 41 49 71 45 56 53 71 65 60 77 49 39 54 26 43 54
48 121 100 82 95 106 56 64 32 59 62 46 57 59 67 56 77 37 42 44
23 35 42 56 39 32 45 56 45 50 46 45 35 22 25 35 29 42 34 50
64 43 48 35 45 43 53 40 52 45 43 43 40 75 93 50 65 62 40 42
40 36 33 39 37 39 85 123 76 78 39 39 35 68 70 67 82 79 70 63
37 30 50 30 56 65 135 106 71 32 37 43 64 81 87 62 93 83 84 53
45 51 73 121 109 107

BIF-E03B 166
185 232 230 184 179 229 227 238 235 209 194 164 203 186 136 164 119 67 46 84
107 125 91 82 161 111 92 85 53 42 43 49 92 82 66 121 60 46 53 59
53 64 70 42 42 56 70 47 50 59 68 60 65 73 46 39 57 28 45 51
49 118 113 75 100 109 59 56 40 53 64 46 57 62 60 62 71 32 48 36
34 42 40 45 39 35 39 58 44 49 48 40 34 26 20 35 32 42 32 63
56 51 42 38 39 39 62 48 53 42 43 40 46 68 106 39 68 59 35 59
34 37 26 37 45 45 79 131 80 78 30 40 34 64 83 69 82 79 65 65

37 30 51 31 58 56 135 104 78 31 35 43 59 85 89 59 90 90 83 45
49 55 69 128 110 103

BIF-E04A 120
225 172 195 238 416 390 242 389 164 139 148 130 134 149 228 277 155 111 59 82
135 100 146 140 97 139 125 123 67 103 114 62 71 47 53 100 84 107 95 108
101 121 137 104 85 51 98 87 67 84 110 107 123 100 110 60 98 92 50 65
50 65 70 70 82 106 98 139 89 173 132 117 167 126 114 98 100 70 129 112
84 81 70 89 71 61 122 128 140 136 157 68 82 83 67 46 53 54 60 46
45 66 47 53 74 73 48 68 52 58 58 73 70 45 91 136 94 115 104 63

BIF-E04B 120
216 167 204 236 393 384 260 355 191 164 136 132 131 149 198 270 165 113 56 85
135 100 139 146 92 135 121 122 64 102 111 67 74 39 53 99 85 100 97 104
94 124 137 99 86 60 92 95 62 85 96 109 122 93 106 69 92 89 54 60
51 62 72 69 81 103 90 139 95 168 128 112 156 135 121 95 93 89 127 111
81 90 76 75 73 61 117 129 134 135 154 56 82 81 67 43 50 54 62 42
45 65 43 60 65 73 45 70 64 48 51 53 63 62 37 98 131 100 93 99

BIF-E05A 80
326 344 399 660 432 560 194 154 162 173 144 152 102 72 69 75 134 189 186 138
183 145 97 117 64 138 152 116 75 64 85 107 155 192 175 164 173 173 236 167
115 140 162 173 109 113 153 196 131 85 120 79 82 87 84 57 103 128 122 135
136 177 117 203 155 187 223 164 192 171 125 81 88 76 154 176 95 109 109 156

BIF-E05B 80
300 340 376 663 435 569 177 148 164 171 157 155 100 67 62 87 140 171 203 138
182 135 96 140 69 136 150 124 78 56 85 107 139 185 184 169 162 181 235 153
110 134 164 175 112 107 167 192 125 85 115 81 85 82 84 59 107 119 123 135
126 187 111 204 159 167 228 171 182 164 142 90 71 79 154 160 107 93 103 168

BIF-E06A 93
420 363 343 317 221 210 244 397 296 401 397 373 373 378 409 234 278 299 253 382
392 373 232 217 286 228 142 121 53 54 35 62 87 66 78 75 115 88 78 95
50 43 45 43 56 62 100 142 116 128 140 92 79 89 117 60 71 70 76 81
75 131 151 110 123 151 167 92 45 53 48 62 64 114 148 154 164 163 103 111
87 163 175 134 164 211 122 138 134 96 115 146 79

BIF-E06B 93
423 372 339 339 199 205 269 389 317 391 394 346 344 369 385 257 270 295 244 389
390 384 226 212 279 232 137 137 49 50 39 60 87 71 82 75 115 85 76 80
35 48 48 45 70 51 98 154 115 114 121 82 84 90 134 75 60 70 75 83
86 125 147 123 117 143 164 84 41 36 50 59 64 123 139 175 172 159 100 102
78 163 172 131 161 208 113 135 133 79 115 142 80

BIF-E07A 170
424 283 232 341 330 396 386 423 410 325 269 255 171 145 175 107 80 59 47 38
58 91 82 73 65 95 64 75 64 35 36 30 29 46 48 60 71 90 75 95
42 46 41 51 60 56 34 51 58 56 71 70 64 56 37 35 33 29 32 28
50 37 154 170 190 177 235 131 176 98 148 193 215 290 137 110 86 94 48 68
57 57 59 68 84 81 78 81 89 98 95 80 52 52 56 46 37 46 59 76
62 68 68 57 48 65 65 58 75 70 51 43 50 54 40 68 132 81 142 110
89 90 46 68 61 94 90 93 181 149 107 99 56 63 81 112 106 134 87 96

101 62 53 109 81 130 105 128 196 159 84 69 101 113 134 103 140 139 85 133
115 84 84 135 165 155 175 134 200 237

BIF-E07B 170
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56 86 86 73 60 92 70 73 60 46 42 34 34 44 42 57 79 85 93 99
66 44 46 62 57 62 50 51 53 59 76 68 78 64 39 45 31 23 21 37
46 50 142 190 187 179 218 107 173 117 157 205 248 285 131 109 85 95 51 85
65 57 65 70 81 80 76 82 89 95 93 85 51 53 54 48 32 50 60 69
58 66 70 57 53 62 64 57 75 67 50 42 56 50 45 73 125 85 142 115
79 83 52 72 65 90 88 85 186 148 107 101 57 67 81 123 102 125 93 112
114 55 53 105 83 131 109 115 209 150 89 63 93 109 128 97 157 142 82 138
118 81 88 147 147 134 165 170 182 181

BIF-E08A 169
188 258 179 268 308 362 442 407 453 387 264 246 182 136 162 105 57 56 46 36
51 93 81 67 67 86 72 69 60 39 42 30 31 43 39 58 79 96 82 89
35 42 28 45 50 44 35 42 55 44 60 64 53 46 29 34 34 23 23 31
42 50 132 126 164 164 265 151 178 140 143 198 184 240 160 123 98 103 56 83
54 65 62 65 78 84 65 78 97 87 84 78 53 56 48 42 40 48 56 65
50 65 70 48 46 50 56 42 75 59 48 43 47 50 41 60 142 71 122 107
57 79 51 73 65 78 91 85 163 152 105 108 67 57 86 121 101 127 99 111
110 56 59 101 95 131 113 127 174 150 86 71 93 127 121 102 148 138 96 176
117 84 93 122 159 179 171 192 201

BIF-E08B 169
182 260 188 260 302 336 425 462 405 369 264 245 182 153 165 107 66 57 53 32
51 85 73 61 61 98 74 70 50 48 40 30 30 44 43 57 79 94 76 92
41 36 30 47 52 47 36 45 52 46 61 63 55 46 28 32 35 26 20 32
37 46 137 129 160 122 243 125 176 162 156 227 214 287 156 125 96 94 50 76
56 49 56 71 67 78 65 79 90 79 84 70 51 57 50 56 37 50 60 61
43 57 71 43 41 50 55 45 70 59 55 47 44 55 42 63 135 73 125 106
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118 52 61 111 85 135 106 111 196 145 84 65 103 116 139 94 144 134 107 167
109 77 81 121 143 171 179 165 240

BIF-E09A 152
129 143 219 213 188 207 136 101 114 161 128 75 67 78 96 144 73 76 62 37
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46 67 49 77 70 77 43 69 46 68 60 71 75 91 82 85 96 58 101 82
125 98 108 121 67 56 64 62 34 67 70 47 65 80 96 84 75 129 117 143
109 120 80 79 59 46 51 50 70 76 76 114 114 97 81 93 78 68 85 94
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130 121 89 55 81 91 83 82 91 105 92 126 101 88 119 106 107 139 232 195
168 81 98 87 101 77 112 134 145 82 135 228

BIF-E09B 153
118 157 209 216 196 204 130 94 117 149 123 78 63 84 86 107 74 61 63 55
39 56 50 66 65 64 87 71 51 55 50 67 46 56 40 50 55 57 47 48
48 73 50 64 71 62 47 61 49 58 63 71 83 85 77 92 93 52 101 96
109 101 109 126 63 60 61 57 53 60 67 46 69 78 93 85 68 142 117 134
117 115 78 74 70 32 39 56 71 82 72 118 107 89 89 87 89 73 90 81
73 60 80 75 66 123 134 100 104 78 57 90 65 57 46 85 106 82 140 123

131 115 75 71 73 92 89 76 92 100 99 125 96 95 115 101 111 135 219 143
129 104 89 77 78 90 109 153 130 137 130 151 189

BIF-E10A 164
326 414 393 308 402 407 323 355 379 374 340 360 328 253 219 207 173 117 140 92
62 48 82 135 154 106 101 184 123 79 81 34 32 31 39 64 60 58 112 65
56 70 60 62 52 66 45 46 71 71 59 53 67 76 62 56 50 52 32 40
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33 50 42 32 32 46 57 62 35 61 75 50 54 46 48 30 20 25 31 25
39 57 34 57 64 50 35 39 37 29 48 42 41 37 37 50 32 77 111 72
60 72 43 64 28 43 46 42 56 54 109 110 82 65 37 31 43 56 74 81
51 69 50 40 32 53 38 31 44 64 71 57 68 31 36 51 48 79 82 57
62 68 71 83

BIF-E10B 164
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31 41 49 28 80 109 93 89 112 50 44 37 43 62 39 48 59 63 46 68
40 47 42 29 40 40 54 60 34 57 68 52 53 46 39 28 20 26 25 31
32 55 33 59 70 54 34 29 37 30 50 41 35 37 51 41 33 68 106 68
62 70 35 53 34 57 31 46 48 49 100 112 77 75 35 29 37 64 75 75
62 66 56 42 46 42 29 37 44 55 81 51 71 42 40 38 52 68 90 56
57 70 63 90

BIF-E11A 170
313 355 204 350 337 182 387 359 234 311 211 306 186 191 254 186 140 189 178 186
178 185 138 155 167 147 130 149 118 84 45 59 98 116 80 99 135 146 82 79
42 45 42 31 62 53 64 96 71 56 101 82 112 89 92 59 57 74 65 67
78 85 132 103 93 71 73 53 75 60 60 78 71 183 209 124 125 125 60 91
72 79 100 71 79 76 82 79 112 54 65 73 39 66 64 83 84 54 104 128
108 110 76 56 74 36 40 65 46 90 117 90 156 138 91 59 46 78 56 108
90 94 81 71 62 49 104 118 61 90 67 39 60 37 54 38 50 67 65 115
153 106 88 46 49 49 78 98 122 159 107 86 75 49 60 54 41 77 54 137
96 75 44 34 37 50 52 46 62 87

BIF-E11B 170
246 332 235 315 343 213 351 355 237 291 216 277 198 190 265 181 162 188 184 186
182 191 128 161 169 147 128 146 117 98 59 64 109 117 78 96 146 139 74 78
56 40 40 40 59 54 53 104 78 55 99 87 110 91 85 74 59 64 54 82
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59 77 104 67 75 84 81 79 118 47 85 54 48 67 64 82 85 58 97 131
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84 93 81 80 63 46 100 121 64 98 70 43 53 34 56 43 44 62 76 116
153 106 96 38 40 55 75 103 115 172 87 93 78 46 68 57 39 72 56 127
103 78 46 34 45 44 59 56 56 77

BIF-E12A 80
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87 98 76 84 207 166 157 139 153 123 126 82 60 64 46 37 76 68 76 115
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BIF-E12B 80
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BIF-E13A 137
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162 196 190 270 243 231 165 137 75 124 108 139 160 166 150 193 154 139 154 86
118 79 146 128 118 171 157 132 145 229 109 136 159 68 87 112 81 121 79 140
131 123 154 125 68 75 52 31 86 95 84 114 71 90 118 76 96 62 76 53
152 81 48 56 51 45 41 65 62 43 56 46 46 47 50 43 40 46 58 63
65 81 100 129 50 59 78 128 135 160 170 165 92 75 79 65 105

BIF-E13B 137
294 171 229 211 171 282 219 276 185 146 179 109 176 274 300 210 192 335 272 232
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162 164 142 296 201 171 164 118 84 104 93 114 109 174 172 190 151 168 153 79
120 75 148 125 137 162 154 135 137 209 109 134 156 57 82 96 128 116 81 134
151 140 157 143 59 63 53 54 83 84 88 98 68 84 106 63 73 54 80 77
112 71 48 59 48 62 33 65 55 59 87 59 43 50 48 36 39 50 52 78
59 104 90 138 53 51 84 151 159 152 172 119 117 84 62 75 80

BIF-E14A 140
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139 55 39 41 34 75 64 62 134 65 79 92 97 116 86 83 50 52 78 96
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92 77 83 73 44 70 46 54 52 78 71 89 78 118 110 67 54 47 60 47
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93 118 69 83 34 37 42 69 85 89 78 60 39 29 25 43 29 30 56 34

BIF-E14B 140
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69 116 58 110 82 81 54 67 46 75 57 46 57 54 126 132 93 90 109 63
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87 97 84 67 42 34 30 65 101 87 79 57 39 32 23 37 31 40 41 45

BIF-E15A 70
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103 137 126 181 181 109 93 112 87 110 76 145 123 125 159 145 140 115 120 85
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BIF-E15B 70
241 430 400 505 335 437 376 360 262 214 165 104 226 288 221 202 145 214 215 192
175 108 123 178 164 143 106 156 181 173 145 182 140 137 123 142 132 85 84 124
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87 88 131 109 121 90 92 129 82 126

BIF-E16A 137
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93 91 112 126 119 69 50 89 84 70 84 76 73 75 81 81 42

BIF-E16B 137
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115 29 42 29 34 42 58 105 127 101 101 150 75 82 84 93 87 75 67 67
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BIF-E17A 146
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BIF-E17B 148
405 402 295 316 301 277 218 214 230 232 182 209 138 107 80 89 131 139 96 117
142 148 91 119 46 39 40 39 60 60 71 82 82 74 89 97 120 105 90 59
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118 107 65 89 65 92 96 65 71 84 85 104 128 65 92 81 42 73 68 101
100 71 114 134 135 119 110 68 92 41 46 65 42 97 142 95 148 143 95 75
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BIF-E19A 174
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31 28 26 52 42 42 123 128 138 128 139 60 78 51 81 84 104 115 97 75
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120 93 118 143 69 104 155 193 177 159 171 160 278 158

BIF-E19B 174
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120 85 79 75 45 45 50 62 56 49 37 43 51 61 57 81 58 40 34 51
34 28 29 42 57 35 121 132 126 124 131 66 82 51 76 92 101 113 98 78
71 98 46 64 73 65 49 65 78 109 85 96 118 115 138 102 61 112 70 54
61 58 124 108 88 114 118 71 76 75 104 55 59 56 40 43 45 62 41 97
146 86 109 88 84 62 52 59 53 58 68 81 137 124 84 81 51 54 69 131
92 118 117 100 78 85 52 59 60 92 86 57 61 33 35 47 74 68 101 123
121 101 120 132 70 109 152 190 186 154 170 159 269 152

BIF-E20A 132
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201 192 148 121 179 206 162 193 207 237 192 203 128 141 72 116 89 112 126 150
165 193 156 150 139 76 134 75 119 103 104 100 112 95 95 149 84 100 113 62
94 108 117 115 89 114 143 128 146 162 71 98 49 57 76 79 100 142 103 154
152 136 150 138 137 134 161 143 87 99 100 103 59 107 121 87 97 78 70 81
66 81 59 63 79 71 101 116 111 167 75 96

BIF-E20B 132
335 336 235 292 403 437 443 407 341 341 279 333 206 203 221 128 182 116 180 266
284 218 151 235 209 196 164 73 104 103 106 140 79 131 242 209 176 206 151 208
194 194 160 110 185 200 187 176 208 243 214 203 106 137 75 121 78 126 104 157
160 192 160 148 141 78 129 70 127 96 112 104 118 87 92 157 78 121 112 61
81 109 118 109 100 113 129 125 152 159 78 87 54 50 80 78 103 137 108 156
147 137 148 134 141 120 178 126 124 87 102 93 63 106 126 81 106 78 58 78
87 70 47 78 72 73 103 110 118 157 70 95

BIF-E21A 144
296 250 191 192 177 184 100 231 191 199 173 144 134 184 95 126 83 125 100 137
128 146 142 103 92 75 78 113 82 86 118 85 134 152 101 82 125 115 107 135
85 124 149 103 67 124 166 147 185 217 133 156 143 108 186 115 165 173 129 167
104 165 140 168 109 121 139 150 162 240 214 130 96 159 187 180 162 175 117 125
125 60 96 106 156 136 182 283 181 150 179 100 134 119 246 203 183 200 181 149
103 223 227 125 178 193 95 137 164 138 112 121 128 104 150 186 216 159 129 82
99 178 246 193 177 178 122 137 156 171 184 124 152 171 236 143 116 133 112 128
123 107 96 167

BIF-E21B 144
295 234 183 206 183 182 112 230 191 214 157 146 128 175 123 117 70 111 94 117
141 150 133 108 96 105 66 92 78 98 92 81 124 140 103 103 94 123 124 102
117 124 156 93 60 133 175 146 193 214 148 150 162 92 189 114 160 168 135 159
146 145 139 164 112 142 143 110 167 238 208 143 103 144 182 194 126 187 109 132
117 67 84 112 173 142 175 292 206 139 182 114 143 101 234 199 181 195 170 154
82 235 252 131 203 195 90 142 146 143 118 131 124 112 145 168 206 182 106 97
121 188 215 196 162 189 146 100 150 214 210 112 147 135 234 116 99 91 116 122
94 87 110 150

BIF-E22A 122
235 226 184 244 277 246 205 106 91 164 221 275 213 148 153 192 155 117 55 73
49 29 38 29 70 89 131 172 214 185 220 191 215 102 32 39 84 107 96 125
152 155 109 117 102 51 42 49 140 98 78 98 93 97 87 84 79 78 38 80
70 89 93 92 96 104 82 52 120 127 55 96 105 126 139 92 200 267 196 259
181 112 239 160 74 56 73 112 168 170 190 184 77 118 101 150 89 125 112 135
137 90 100 43 133 144 114 159 84 67 79 107 75 53 53 78 85 148 137 90

90 87

BIF-E22B 122
219 215 180 238 297 247 212 111 97 166 225 274 207 139 161 198 128 107 63 67
53 32 39 37 57 81 132 169 214 173 204 187 215 110 43 33 90 113 89 134
145 157 101 111 107 45 48 51 144 98 68 107 93 96 78 93 76 75 35 82
65 95 96 95 93 104 76 50 104 148 50 97 113 123 129 92 229 262 203 271
192 110 248 162 76 54 62 129 147 156 162 179 87 96 114 142 79 125 117 137
136 106 92 56 123 140 125 136 112 62 77 103 105 50 46 73 86 162 142 96
95 86

BIF-E23A 106
153 109 87 79 45 50 54 33 40 87 150 224 83 64 97 123 209 235 302 217
209 142 132 81 77 92 182 155 185 194 196 160 175 228 246 279 218 160 205 125
96 107 218 273 273 199 198 231 156 110 143 210 278 233 246 215 203 192 160 126
165 198 129 143 217 223 217 121 110 148 200 125 160 154 184 209 115 85 87 85
123 152 87 95 78 59 50 65 121 137 137 149 146 106 116 62 49 71 87 134
131 253 236 149 151 231

BIF-E23B 106
139 126 81 84 55 48 50 32 40 91 149 195 57 63 89 134 162 270 301 233
157 167 126 75 79 87 165 176 169 187 200 157 167 225 249 307 195 165 202 136
85 136 214 268 278 194 199 229 153 115 150 221 269 234 245 232 171 187 178 132
175 192 140 164 187 197 226 129 112 156 190 142 156 151 181 196 114 89 105 78
118 155 90 84 57 59 54 59 115 156 118 145 131 96 128 59 59 69 81 131
121 255 240 154 155 231

BIF-E25A 102
123 140 126 118 131 169 174 178 170 153 133 99 50 73 135 200 164 225 189 146
147 79 81 103 132 103 151 183 261 225 152 129 161 127 88 133 124 158 158 159
58 60 58 105 98 71 69 48 38 39 45 89 116 114 159 137 118 110 73 57
67 90 120 121 171 143 110 129 129 110 117 125 132 92 99 68 60 53 74 117
90 131 156 106 131 129 131 79 112 121 98 132 131 110 84 109 142 170 137 155
157 195

BIF-E25B 102
120 142 134 125 117 161 169 168 181 145 133 87 76 68 120 193 169 206 189 147
128 69 89 94 125 123 153 175 250 227 127 133 157 139 83 132 123 169 144 150
53 68 59 96 98 71 65 50 42 42 43 98 108 113 150 135 112 116 73 60
78 93 120 134 148 151 104 114 121 131 106 125 137 81 107 82 51 56 79 103
99 146 139 113 134 129 131 68 111 121 98 135 127 106 81 110 139 162 147 125
157 209

BIF-A26A 140
407 250 239 218 176 229 303 189 398 262 321 257 200 166 215 241 184 85 78 124
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175 92 151 54 68 74 104 87 123 184 175 184 178 209 182 107 64 92 115 145
106 118 110 137 128 168 137 154 100 96 86 95 137 115 153 101 125 85 132 150
47 70 52 67 93 54 81 116 145 107 92 76 99 69 46 48 56 85 100 95
128 113 112 103 114 147 139 138 124 113 79 88 103 75 112 156 93 131 109 98
96 87 118 81 87 112 83 150 143 109 59 64 51 61 68 153 113 182 178 110

BIF-A26B 140

301 200 238 230 195 265 237 205 382 314 174 353 231 160 165 225 184 62 82 132
125 98 108 139 177 148 129 118 89 88 72 42 57 58 98 126 123 138 156 150
152 121 133 74 62 78 85 114 123 167 196 189 168 210 188 95 73 85 129 149
86 125 109 128 143 170 127 146 98 103 106 76 120 131 137 108 121 85 142 139
65 56 57 70 85 53 85 121 137 106 78 70 106 68 49 69 51 64 99 84
131 121 104 104 113 149 134 134 125 140 88 85 112 56 129 138 109 134 87 96
81 93 128 96 95 85 90 147 143 121 103 93 76 81 121 131 174 156 100 102

BIF-E27A 108
376 172 75 100 167 299 375 484 217 155 155 117 67 69 51 42 37 85 166 236
82 56 85 151 115 150 208 166 117 129 63 32 46 51 100 109 107 125 139 107
103 147 145 178 134 116 104 70 65 67 114 193 178 182 134 143 79 65 89 129
189 199 231 200 164 107 92 96 120 140 107 96 135 268 204 166 158 167 134 123
167 139 165 187 181 86 139 118 114 63 95 46 64 54 65 100 140 151 234 214
143 138 126 92 139 170 197 278

BIF-E27B 108
352 157 84 104 175 293 364 471 239 151 137 119 83 62 48 33 46 89 160 262
85 56 71 141 135 150 194 155 137 136 64 52 42 54 92 117 114 135 124 111
107 147 139 189 150 106 90 71 73 62 120 178 126 171 140 146 81 76 84 134
191 184 237 185 165 121 101 90 102 135 94 101 153 306 227 153 154 120 151 130
157 140 171 192 181 85 157 129 120 73 84 53 56 51 67 97 138 167 221 227
156 156 129 93 146 171 209 272

BIF-E28A 116
140 202 108 196 102 100 109 217 207 229 186 150 146 106 128 130 169 214 149 191
205 212 131 185 196 210 228 185 157 162 135 101 201 248 211 235 222 160 181 235
126 223 134 120 241 208 206 210 181 201 232 145 157 175 91 111 212 268 159 96
139 231 215 178 245 129 245 139 79 109 160 210 238 191 315 203 205 218 166 171
125 265 252 226 225 270 240 157 293 257 153 255 185 96 187 174 204 141 209 219
166 225 177 228 160 128 132 103 177 223 175 196 217 192 175 243

BIF-E28B 116
185 212 131 173 150 87 129 223 198 236 191 164 146 100 135 154 201 210 116 194
217 209 136 181 203 203 238 168 149 182 121 103 217 255 191 215 214 181 190 248
153 225 135 131 231 210 195 220 176 217 242 129 156 171 87 118 220 269 188 110
154 231 217 190 234 134 235 143 88 106 164 219 275 158 309 207 218 246 155 182
131 245 246 245 246 256 264 134 301 253 160 218 195 143 175 196 210 217 155 201
189 223 190 178 189 132 98 112 132 244 159 199 203 206 203 262

BIF-E29A 113
265 196 118 167 121 187 135 117 100 91 133 100 165 189 265 191 238 214 142 80
86 117 101 83 116 135 174 139 180 131 141 88 110 135 122 126 117 139 157 176
101 148 128 71 59 65 69 70 67 92 117 151 149 140 123 148 104 82 67 80
110 117 103 153 182 123 150 117 132 114 131 117 132 78 98 93 68 100 131 100
90 103 39 48 87 79 81 61 74 95 62 131 135 90 98 51 74 67 64 82
103 101 96 75 57 46 88 56 57 54 67 78 107

BIF-E29B 114
260 186 116 171 118 185 138 116 95 76 123 104 171 182 262 201 242 217 141 89
96 118 110 93 105 125 198 125 183 133 125 101 107 134 102 115 115 134 150 182
120 134 117 79 58 67 73 73 56 93 132 145 153 151 123 136 99 85 70 74
97 109 115 149 167 113 153 125 124 101 137 118 115 92 93 101 66 94 130 99

117 89 43 45 81 79 87 64 81 94 58 129 128 100 86 76 50 64 73 84
101 100 109 79 71 50 62 65 53 61 75 75 89 104

BIF-E30A 128
363 285 254 210 234 130 160 160 178 96 153 219 197 148 127 183 224 117 162 117
166 135 84 108 166 207 217 162 152 121 107 143 151 151 189 126 176 168 179 135
201 173 186 236 168 150 144 140 118 215 243 194 180 217 175 181 187 146 263 176
119 227 171 225 160 163 173 194 118 178 192 96 139 234 251 177 113 155 189 210
144 158 116 152 90 54 68 98 175 257 221 260 188 171 200 90 150 147 216 205
194 191 202 183 149 276 246 131 228 198 165 123 160 110 92 90 181 170 188 134
173 164 81 89 104 168 175 201

BIF-E30B 128
321 282 250 222 225 137 157 171 169 103 166 221 215 166 162 212 232 147 185 124
153 146 89 107 158 191 229 138 121 157 118 146 125 170 183 130 193 159 165 134
214 168 184 234 184 151 139 159 107 196 239 218 182 220 167 159 203 150 272 163
142 229 176 223 167 152 197 210 111 181 215 85 151 209 231 159 95 131 192 221
151 136 115 169 90 63 71 103 178 221 207 229 186 166 178 109 156 158 219 180
218 176 196 202 153 269 231 149 188 205 193 106 165 112 87 90 184 162 168 150
174 157 103 89 103 156 190 221

BIF-E31A 114
124 140 166 301 171 173 142 79 55 59 90 171 214 184 257 219 141 100 216 185
250 175 144 167 117 66 101 155 228 235 182 151 150 82 49 56 119 160 160 189
167 146 137 109 82 104 116 93 101 137 161 165 96 95 95 104 95 92 96 108
138 95 56 62 75 74 79 43 65 50 52 39 57 85 104 90 137 120 93 121
51 46 79 84 125 125 156 170 107 112 134 137 189 150 173 134 115 93 90 89
95 182 140 159 175 136 193 118 120 65 55 78 82 130

BIF-E31B 114
117 150 173 243 207 164 152 82 53 72 76 173 228 185 217 217 135 108 217 216
212 190 140 168 106 89 83 154 227 225 175 156 159 101 59 65 111 192 175 191
197 162 126 123 89 90 137 89 103 106 173 184 103 92 95 106 85 89 93 134
103 99 66 65 70 69 67 57 61 50 48 42 59 82 103 92 143 113 90 121
60 50 70 90 118 120 159 150 113 126 132 143 190 142 169 119 128 103 90 87
95 170 145 168 169 119 202 118 112 84 56 78 80 112

BIF-E32A 130
103 258 167 192 243 280 169 159 84 169 172 293 163 137 146 189 153 121 54 71
86 77 21 32 92 97 121 134 176 173 185 164 210 121 41 39 83 85 135 111
192 167 100 119 98 28 37 53 122 76 67 118 88 106 91 111 84 110 60 75
89 143 125 115 98 104 96 70 143 167 59 87 110 135 140 92 184 279 192 246
204 103 223 164 66 63 59 124 150 133 150 166 78 101 89 145 81 120 122 132
117 122 106 82 90 138 125 146 113 76 68 83 91 62 50 77 103 155 168 96
105 35 57 44 85 75 115 141 178 132

BIF-E32B 130
110 242 206 200 280 240 189 144 98 171 187 301 150 155 178 159 148 115 60 71
100 57 25 34 90 92 124 150 170 175 184 167 214 102 36 42 82 103 122 108
185 169 100 117 94 46 38 47 126 79 68 115 78 92 96 109 82 104 53 68
99 151 129 123 103 109 100 71 163 170 51 82 100 143 131 104 195 273 176 246
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103 45 41 40 90 88 131 147 177 130

BIF-E33A 168
324 426 224 300 268 366 253 335 439 348 468 383 331 303 266 240 269 230 192 180
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110 93 79 98 104 100 135 87 129 140 110 99 153 123 128 201 124 163 165 131
90 141 209 215 196 203 139 168 159 121 220 134 184 165 131 203 159 171 184 218
119 190 181 109 150 235 254 175 110 163 162 181 146 209 109 140 100 53 74 93
149 145 157 250 167 171 159 93 121 138 179 204 160 178 140 124 91 205 225 117
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185 156 98 98 109 115 157 173

BIF-E33B 168
300 400 218 290 247 372 253 351 403 391 476 383 362 296 268 246 264 214 207 180
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101 103 73 110 94 95 123 84 128 153 101 82 152 125 127 185 142 145 160 131
87 121 204 217 202 201 159 163 157 115 198 108 163 171 157 204 146 159 187 214
128 186 193 90 150 230 261 188 100 175 174 188 140 199 123 125 90 49 86 93
134 150 145 257 189 164 141 92 153 106 200 204 187 156 143 149 75 187 209 134
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188 141 97 113 104 109 161 185

BIF-E34A 145
484 385 312 259 261 227 239 362 314 378 289 307 211 239 226 202 153 169 147 178
144 198 185 192 146 126 168 187 118 121 91 116 106 62 78 119 142 164 109 92
84 81 87 79 98 98 82 107 154 91 70 118 117 128 148 96 106 140 98 62
112 139 154 159 221 165 143 157 104 150 101 145 155 121 134 129 154 146 149 103
141 146 109 159 238 203 137 82 141 155 196 138 201 114 130 93 62 101 81 90
93 125 215 132 136 150 102 115 92 192 160 190 228 167 142 78 196 224 94 148
173 86 113 165 106 80 112 136 92 144 177 196 209 153 100 131 218 221 125 124
123 155 137 183 231

BIF-E34B 145
475 350 322 296 245 229 243 372 291 373 316 297 207 235 246 219 177 175 159 192
142 204 197 186 152 132 149 169 126 126 90 109 104 67 85 135 124 167 107 101
95 87 86 90 95 90 81 110 115 96 78 109 125 121 154 112 97 124 89 58
112 157 140 173 193 139 164 148 98 156 118 163 154 112 156 159 135 178 157 109
150 148 110 137 203 184 149 74 123 167 199 163 186 112 167 111 68 78 85 98
93 132 209 143 141 144 118 140 115 193 174 190 229 176 143 94 184 231 112 146
177 102 107 178 114 93 108 125 101 126 178 265 223 178 100 156 247 209 125 143
128 158 131 196 250

BIF-E35A 164
397 177 459 258 247 234 313 362 341 459 366 460 444 351 247 406 308 230 175 94
71 92 118 138 106 120 153 165 117 108 92 74 76 48 70 56 80 132 125 120
114 139 137 114 142 92 73 62 81 95 92 127 142 135 112 157 168 112 73 90
98 134 106 128 135 153 139 156 146 185 103 135 112 107 159 173 169 166 187 131
182 174 93 75 97 106 122 87 120 168 159 110 160 100 109 112 82 59 75 84
106 106 154 151 125 131 165 196 134 177 166 168 155 125 133 89 134 142 109 144
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147 96 75 52 89 89 56 68 90 101 93 104 106 112 137 145 156 106 118 118

112 100 153 168

BIF-E35B 164
362 212 290 438 197 235 329 389 307 485 357 481 403 337 238 388 317 246 164 92
80 82 124 128 122 124 150 169 121 90 79 91 76 53 73 57 79 118 126 128
121 139 135 104 151 104 60 67 83 96 85 124 145 135 125 157 160 110 82 87
98 126 104 125 146 150 150 132 162 184 90 140 84 113 167 189 166 168 187 112
216 183 65 68 81 112 119 84 132 158 159 114 162 98 118 118 93 66 56 87
120 113 157 156 125 140 162 203 147 162 187 162 140 115 139 96 129 158 96 156
96 63 78 65 87 75 56 108 65 150 139 132 104 69 68 69 78 128 99 121
139 97 87 55 81 100 57 68 62 90 77 107 110 118 129 132 163 126 115 113
110 108 143 175

BIF-E36A 156
219 243 239 254 350 288 264 380 398 335 200 148 216 225 162 89 42 42 32 135
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70 164 75 76 60 106 92 121 151 190 188 186 214 171 100 78 87 115 158 94
116 123 132 143 132 126 163 75 110 89 89 107 120 132 103 128 81 164 98 60
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60 113 87 70 54 93 197 202 174 142 75 96 118 179 153 131

BIF-E36B 156
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132 148 60 67 57 104 100 129 166 197 182 166 206 179 89 73 87 121 151 118
111 121 121 143 137 139 163 87 112 87 85 106 134 135 109 131 82 128 110 64
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BIF-E37A 110
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305 251 264 177 181 207 187 120 164 279 304 262 211 247 260 189 107 120 225 279
243 279 246 171 167 132 93 139 200 116 172 218 215 203 139 126 130 184 176 154
173 210 262 169 95 107 76 112 125 60 64 86 68 37 79 117 137 116 143 145
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56 55 67 109 130 106 104 161 156 162

BIF-E37B 110
129 100 130 165 200 192 175 173 100 117 78 75 98 155 223 226 230 245 250 223
278 257 278 195 174 235 165 106 147 327 282 253 220 215 270 173 95 123 234 267
250 265 226 179 175 131 92 140 173 126 143 200 196 214 133 139 208 113 183 161
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65 66 68 106 106 162 146 141 129 157

BIF-E38A 144
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80 52 76 88 78 60 72 74 63 70 82 66 57 84 69 90 98 107 90 95
62 76 75 73 79 93 121 134 133 80 104 85 45 64 48 76 57 57 70 114

112 109 96 70 106 73 49 43 48 76 81 89 144 135 91 116 110 75 95 118
81 98 87 82 89 68 76 121 104 85 90 65 81 71 87 67 64 81 51 78
109 143 99 74 63 53 75 83 122 150 140 93 56 53 77 78 59 50 60 90
82 113 106 132

BIF-E38B 144
455 437 408 425 312 216 228 201 187 150 89 82 78 136 167 92 146 155 105 78
80 71 76 42 37 41 53 74 77 100 82 91 83 92 74 100 57 42 44 50
77 59 74 94 72 74 75 69 60 66 75 67 59 82 79 117 85 98 83 95
68 80 116 62 56 99 128 127 160 48 90 102 50 47 70 82 64 40 70 118
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101 129 101 68 64 62 74 87 131 162 90 106 64 55 71 63 71 50 62 89
83 105 90 109

BIF-E39A 92
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77 105 87 89 86 90 85 77 63 78 82 64 78 100 84 89 78 67 64 89
50 59 95 100 79 125 132 78 88 60 64 69 87 85 95 106 95 106 60 68
89 67 48 76 69 92 106 82 82 90 67 107

BIF-E39B 92
131 164 175 184 135 167 105 109 141 117 144 132 110 131 159 116 128 110 64 66
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82 103 98 85 79 100 75 82 71 80 79 50 79 92 83 91 83 52 61 70
89 68 74 114 76 120 125 90 106 76 62 75 62 81 93 98 107 93 89 106
125 74 65 73 68 93 87 89 84 90 76 129

BIF-E40A 156
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46 68 126 162 137 167 157 117 146 195 191 215 190 151 153 103 75 67 184 234
188 225 173 185 106 62 91 162 217 214 250 209 170 156 123 93 114 139 107 134
154 295 243 144 133 141 144 110 135 131 178 159 159 67 68 59 105 85 68 65
54 40 44 56 80 87 109 157 158 131 102 86 59 75 90 96 128 149 155 144
128 137 112 138 130 124 95 120 72 62 56 71 106 115 146 168 84 134 138 106
75 120 118 84 132 158 109 91 118 138 159 171 125 154 171 238

BIF-E40B 156
475 359 354 388 402 319 407 383 259 126 57 44 53 129 153 177 192 143 119 129
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53 64 118 151 142 175 140 115 131 203 170 220 139 154 157 96 85 83 150 256
210 210 179 164 99 64 103 157 218 206 264 215 164 168 106 93 104 143 109 132
166 281 242 125 146 144 140 109 129 138 170 163 141 77 65 59 102 90 62 65
43 41 40 53 80 109 131 147 140 128 104 69 66 85 90 100 122 168 162 118
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83 106 105 103 145 153 115 90 106 135 167 169 125 162 172 228

BIF-E41A 103
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145 117 85 95 154 101 135 175 268 210 139 204 184 163 129 134 115 176 176 98

78 90 70 128 112 77 87 68 48 53 68 104 140 154 215 182 166 126 112 90
134 157 165 170 232 254 134 151 168 190 163 144 179 102 146 115 64 77 86 103
181 171 206

BIF-E41B 103
156 194 129 140 97 90 57 74 72 142 167 163 185 169 133 117 207 217 244 210
119 112 91 65 81 171 203 203 192 167 178 109 64 78 160 201 192 227 205 167
139 115 86 107 154 112 118 165 279 260 170 170 185 156 129 157 140 178 190 153
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177 171 202

BIF-E42A 158
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206 106 68 84 156 214 181 240 201 214 189 120 84 110 160 120 129 159 250 225
168 171 159 146 117 139 157 163 191 141 75 65 57 81 83 52 45 49 50 39
62 72 103 107 158 160 146 142 64 77 100 103 131 156 208 209 142 140 172 140
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94 146 153 98 90 112 138 171 170 146 129 159 186 81 83 102 134 234

BIF-E42B 158
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210 221 159 192 151 155 242 243 285 235 179 170 110 94 96 203 290 233 213 192
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165 170 160 160 92 148 156 162 185 139 84 73 52 87 87 45 51 43 50 43
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BIF-E43A 108
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115 66 55 72 100 120 131 197 163 146 174 82 95 119 115 181 181 287 245 232
158 184 123 196 125 150 106 152

BIF-E43B 108
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306 226 198 260 175 99 121 228 281 251 271 219 175 199 130 109 143 214 128 164
226 234 259 173 147 184 226 167 173 189 215 225 156 123 154 117 153 181 96 116
96 81 50 66 98 124 134 181 175 155 187 96 105 106 118 168 163 298 279 209
165 162 114 189 152 144 107 159

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

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

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

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

1. Inspecting the Building and Sampling the Timbers. Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can

sample *in situ* timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

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

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

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

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

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

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

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

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

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

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

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

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

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

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

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

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

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

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

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

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

7. Ring-Width Indices. Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form

they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Figure A7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

t-value/offset Matrix

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

Bar Diagram

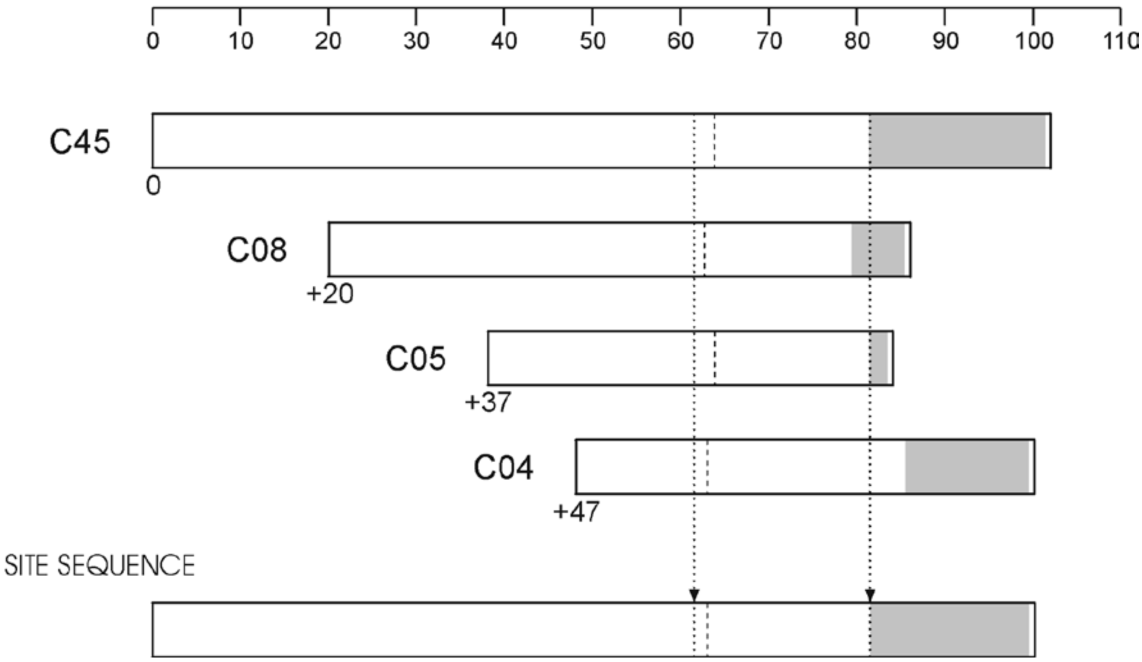


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

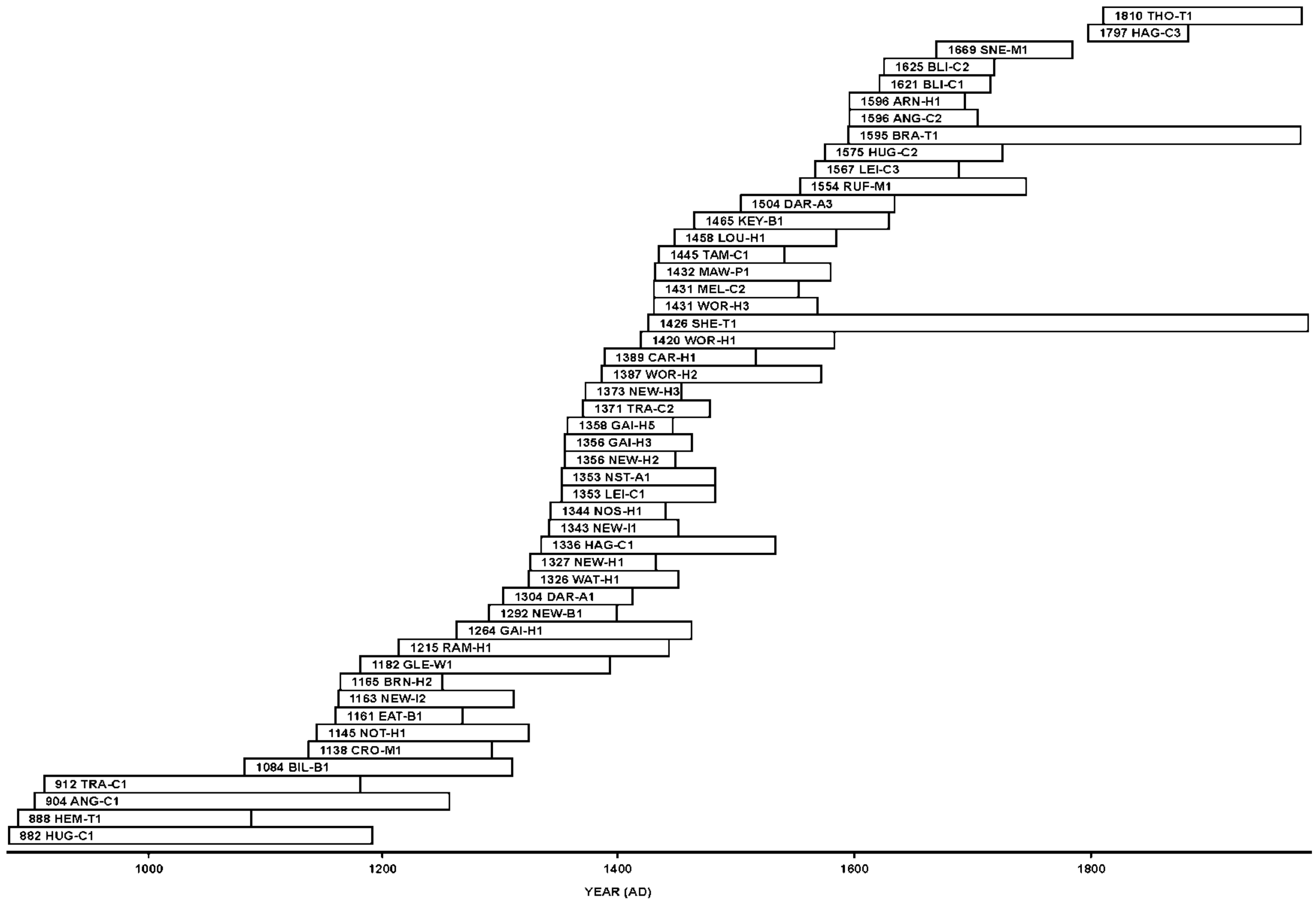
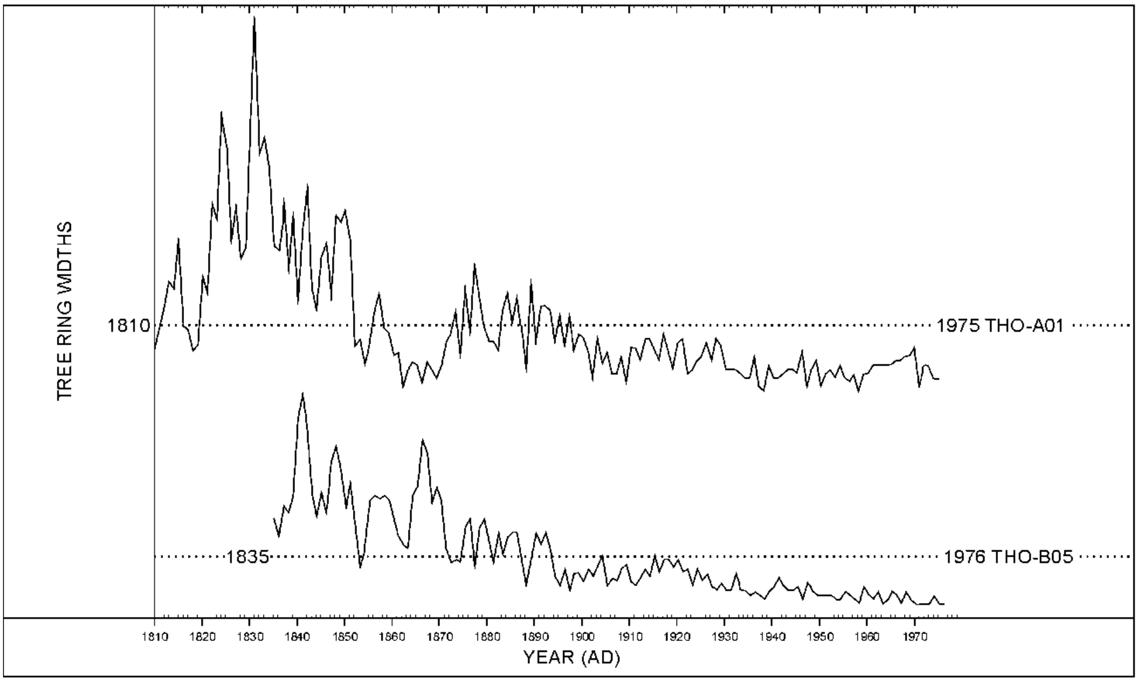


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

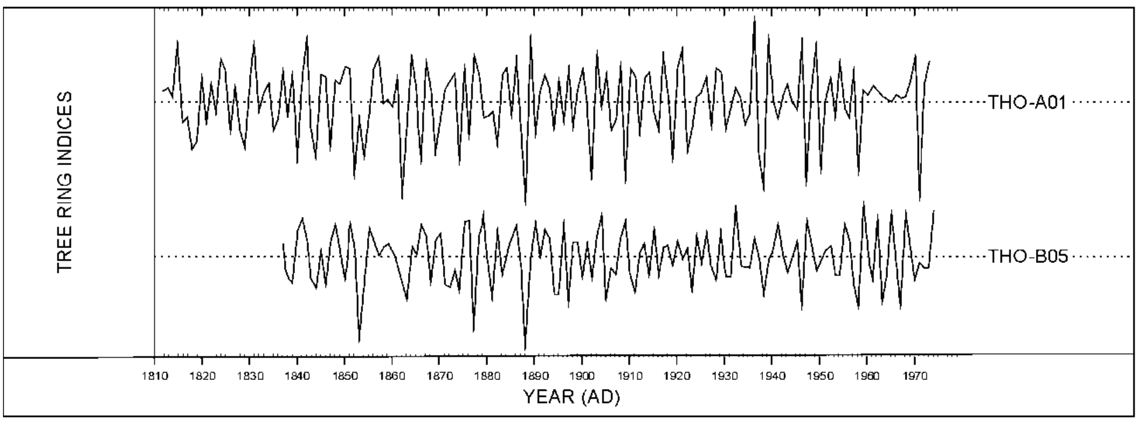


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known
Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences

Figure A7 (b): The Baillie-Pilcher indices of the above widths
The growth trends have been removed completely

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