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12 Broad Street
11, 13, & 13A High Street
Launceston
Cornwall

Tree-ring Analysis of Oak Timbers

Alison Arnold, Robert Howard, and Cathy Tyers

Discovery, Innovation and Science in the Historic Environment

Research Report Series no. 74/2022

Front Cover: 12 Broad Street, 11, 13 and 13A High Street, Launceston, Cornwall © Mr Byron J. Mason (cropped). Source: Historic England Archive IOE01/05130/23

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SUMMARY
Dendrochronological analysis was undertaken on 34 of the 42 samples obtained from different timbers in this building, eight samples having too few rings for reliable dating. This analysis produced a single site chronology comprising 14 samples from the roof and cellar areas. This site chronology is 88 rings long, these rings dated as spanning the years AD 1496–1583. A further single sample was dated individually, its 60 rings spanning the years AD 1468–1527. Although one timber from the cellar, estimated to have been felled in the period of AD 1542–67, might be earlier, other cellar timbers probably date to the last quarter of the sixteenth century; one cellar timber was certainly felled in AD 1582 with another cellar timber certainly being felled in AD 1583. The timbers of the roof have an estimated felling date of AD 1575–1600. Two other site chronologies, both comprising two samples each, and being 54 and 65 rings long respectively, were also created. Neither of these site chronologies could be dated, although it is likely that the timbers represented by each pair of samples are coeval. Of the 34 measured samples, 15 remain ungrouped and undated.

CONTRIBUTORS
Alison Arnold, Robert Howard, and Cathy Tyers

ACKNOWLEDGEMENTS
We would firstly like to thank Mr David Scott, of Scott and Company, Chartered Surveyors and Historic Building Consultants, who has had a long-term interest in these buildings, for not only permitting tree-ring analysis at this building, and for his enthusiasm and support for this programme of analysis, but also for his help in obtaining off-cut samples and for providing plans and drawings of the building. We would also like to thank Catherine Marlow, Historic England Inspector of Historic Buildings & Areas (Cornwall, The Isles of Scilly, Torridge, North Devon, West Devon and Torbay), for not only promoting this programme of tree-ring analysis, but also for help in arranging access to this building. Finally, we would like to thank Shahina Farid, Scientific Dating Coordinator for Historic England, for commissioning this programme of tree-ring dating and for her valuable contributions to this report.

ARCHIVE LOCATION
Historic England Archive
The Engine House
Firefly Avenue
Swindon SN2 2EH

HISTORIC ENVIRONMENT RECORD OFFICE
Cornwall & Isles of Scilly Historic Environment Record
Strategic Historic Environment Service,
Kresen Kernow,
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DATE OF INVESTIGATION
2022

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CONTENTS

INTRODUCTION

This Grade II* property (LEN 1206510 here) comprises two merchant's houses standing in the very centre of Launceston. An inscription on number 13 is dated 1555 and identifies Thomas Hicks, who was Mayor of the town in the sixteenth century at the time of the Reformation. Part of the roof structure has oak trusses with lap-dovetail collar joints and trenched purlins, and the building retains many seventeenth-century features including ovolo-moulded door frames. As such, the buildings represent an important element of the historic fabric of the town.

A much earlier origin has been suggested, however, and even the possibility of a twelfth-century core has been raised. The property is, nevertheless, multi period with many timber phases, and consists of a north block, south block, and rear kitchen block with cellars, ground-, first- and second floors and roofs.

SAMPLING

In advance of extensive renovations to this unique survival within the heart of Launceston, a comprehensive dendrochronological survey was requested to determine the date of the extant timberwork in the building. Tree-ring analysis was requested by Catherine Marlow, Inspector of Historic Buildings and Areas for Cornwall, The Isles of Scilly, Torridge, North Devon, West Devon and Torbay, to provide independent dating evidence to inform repairs and modifications required for the preservation and long-term care of this unique complex.

Prior to sampling, a thorough assessment was made of the extant and visible timbers for their potential for tree-ring dating. This showed that there was one accessible area of roofing, covering a small portion of the building, containing two principal-rafter with collar trusses, the trusses supporting single purlins to each pitch of the roof, these in turn supporting common rafters. Although the great majority of these common rafters were very modern replacements, a few appeared to belong to the same phase as the two trusses and possibly the purlins.

The roofs to other parts of the building were inaccessible, being totally ceiled-in, but the feet or lower ends of what appeared to be principal rafters could be seen from the second floor. Where visible (the feet of some principals being boxed-in), these appeared very square and regular in shape and did not seem to be historic timbers. They were also, potentially, some type of softwood. The second-floor rooms also contained a small amount of oak panelling, but, given that this was all firmly fixed in place with no plans to dismantle any of the sections, there was no potential for tree-ring sampling.

Of the first-floor rooms, only one had any visible timbers at the time of sampling. These comprised a few wall posts and studs, one ceiling beam, and a door lintel. The wall posts/studs were all set deeply into the walls, and most of the timbers appear to be derived from fast-grown trees, probably with insufficient rings for dendrochronological analysis. Two other rooms had ceiling beams, but these were boxed-in, and given other evidence of refurbishment and alteration to these rooms, were potentially modern timbers.

Similarly, the ground-floor rooms, presently used as commercial and retail premises, contained only a few ceiling beams, these again being boxed-in and presently inaccessible.

Of the cellar areas, all the joists to the northern cellar appeared to be very modern softwood replacements, with only the middle and southern cellar areas retaining what appeared to be historic timbers. In both these areas the timbering comprised two main ceiling/floor beams with common joists between. The common joists were of varied sizes, shapes, and lengths with some joists being chamfered, and possibly stopped, some being squared and shaped, while others appeared to be unshaped very small whole trees. Overall, the timbers here presented a very mixed series of characteristics. The cellars also contained a few 'Samson' posts. There were also some lintels to the lower door into the cellar, plus some studs/posts on the stairway down.

Thus, from the suitable material available, 38 timbers were sampled by coring, with a further four samples being obtained as off-cut sections of posts. Each sample was given the code LAU-N (for 'Launceston') and numbered 01–42. Samples were obtained from as many roof timbers as could be accessed which appeared to be suitable for tree-ring analysis. In addition, a selection of timbers to the ceiling of the cellar/ground floor-frame, and those to the steps leading down to them were also sampled. No samples were obtained from the ground floor.

Where possible (the exception being the four off-cut timbers whose original locations are a little uncertain, LAU-N39–42), the sampled timbers have been located by reference to a set of annotated photographs taken at the time of sampling, shown here as Figures 3a–c, and on a preliminary plan of the cellars kindly provided by David Scott, shown here as Figure 4. Details of the samples are given in Table 1.

ANALYSIS AND RESULTS

Each of the 42 samples obtained from timbers spread throughout this building was prepared by sanding and polishing. It was seen at this time that eight samples had very low numbers of rings, often less than 30, fewer than here deemed necessary for reliable dating purposes. These samples were rejected from this programme of analysis. The annual growth rings widths of the remaining 34 samples were, however, measured, these measured data being given at the end of this report. The 34 measured series were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix), this comparative process resulting in the production of three separate groups of cross-matching samples.

The first group comprises 14 samples, these representing timbers from the roof and from two parts of the cellars. These samples, combining at a minimum value of t=4.8, cross-match at the positions illustrated in Figure 5. These 14 samples were combined at their indicated offset positions to form LAUNSQ01, a site chronology with an overall length of 88 rings. Site chronology LAUNSQ01 was then compared with an extensive range of oak reference chronologies, this indicating a repeated series of cross-matches when the first ring of the site chronology dates to AD 1496 and the date of its latest ring is AD 1583 (Table 2).

The second group comprises two samples, both of them from timbers in the roof. These samples, combining at a minimum value of *t*=6.9, cross-match at the positions illustrated in Figure 6. These two samples were also combined at their indicted offset positions to form LAUNSQ02, a site chronology with an overall length of 54 rings. Site chronology LAUNSQ02 was also compared with an extensive range of oak reference chronologies but there was no satisfactory cross-matching and it must, therefore, remain undated.

The third and final group also comprises two samples, both of them from timbers in the south cellar. These two samples, combining at a minimum value of *t*=4.8, cross-match at the positions illustrated in Figure 7. These two samples were also combined at their indicted offset positions to form LAUNSQ03, a site chronology with an overall length of 65 rings. Site chronology LAUNSQ03 was again compared with an extensive range of oak reference chronologies but again there was no satisfactory cross-matching and this site chronology must also remain undated.

All three site chronologies were then compared with the 16 remaining measured but ungrouped samples, but there was no further satisfactory cross-matching. The 16 ungrouped samples were, therefore, compared individually with the same extensive range of oak reference chronologies, this indicating a cross-match and date only for sample LAU-N12, from a timber to the middle cellar. The 60 rings of this sample were dated as spanning the years AD 1468–1527 (Table 3).

INTERPRETATION

Dendrochronological analysis has thus successfully dated 15 of the 34 timbers from which samples were measured.

Cellar timbers

Two of the dated samples in site chronology LAUNSQ01, LAU-N16 and LAU-N20, both from joists to the middle cellar, retain complete sapwood. This means that they each have the last growth ring produced by the tree it represents before it was cut down (this being indicated by upper case 'C' in Table 1 and the bar diagrams Figs 5 and 8). In the case of sample LAU-N16, this last measured, complete, sapwood ring, and thus the felling of the tree represented, is dated AD 1582, while the last measured, complete, sapwood ring on sample LAU-N20, and thus the felling of the tree it represents, is dated to AD 1583.

The remaining seven dated samples from the cellars all have some sapwood present or at least the heartwood/sapwood boundary (h/s). The dates of the heartwood-sapwood boundary on six of these seven samples (the exception being sample LAU-N12) ranges from AD 1549 (LAU-N21) to AD 1566 (LAU-N23), not vastly different to that of the two samples with complete sapwood whose heartwood-sapwood boundary rings date to AD 1560 (LAU-N16) and AD 1559 (LAU-N20).

The average date of the heartwood/sapwood boundary ring on these six sample is AD 1558. Allowing for the minimum of 15 sapwood rings these trees might have had, and the maximum of 40 sapwood rings (the 95% confidence interval), this would give these trees an estimated likely felling date range of between AD 1573 and AD 1598. It will be seen that this date range nicely brackets the known felling dates, AD 1582 and AD 1583, of at least two timbers.

The exception amongst these cellar timbers is represented by sample LAU-N12, from a main beam to the south cellar. This sample has a heartwood/sapwood boundary date of AD 1527, somewhat earlier than that on all the other samples, and indeed the earliest of any dated sample from this site. Allowing for the minimum of 15 sapwood rings this tree might have had, and the maximum of 40 sapwood rings, this would give this tree an estimated likely felling date range of between AD 1542 and AD 1567.

Roof timbers

The five dated samples from the roof also have some sapwood or at least the heartwood/sapwood boundary, the dates of the boundary on these five ranging from AD 1556 (LAU-N07) to AD 1564 (LAU-N04), a variation of only eight years. The average heartwood/sapwood boundary ring on these five samples is dated to AD 1560. Using the same sapwood estimates as above, 15–40 sapwood rings, would give these trees an estimated likely felling date range of between AD 1575 and AD 1600. Interestingly, it may be noticed that this date would appear to be in keeping with the supposed structural sequence of the building, with floors presumably being constructed before roofs are completed.

Off-cut timber

The final dated timber is represented by sample LAU-N39, an off-cut from a wall post. This sample has a heartwood/sapwood boundary ring date of AD 1563. Using the same sapwood estimates as above would give this tree an estimated likely felling date range of between AD 1578 and AD 1603.

DISCUSSION AND CONCLUSION

Tree-ring analysis of timbers from this site has successfully dated 15 of the 34 timbers from which samples were measured. This analysis indicates that at least two cellar timbers were felled in the early AD 1580s, and while other cellar timbers are likely to be of at least a similar date, ie, later sixteenth century, at least one cellar timber might be a little earlier, dating to some time in the middle of the sixteenth century. A number of roof timbers, plus a probable wall post are also of later sixteenth-century date.

Woodland sources

As perhaps may be seen from Tables 2 and 3, although site chronology LAUNSQ01, and the individual sample LAU-N12, have been compared with reference material from every part of England, there is a distinct trend for them both to match best with reference chronologies made up of timbers from other buildings in the region, particularly with sites in Devon. While the source of the timbers used at these particular reference sites is itself unknown, it would suggest that the trees used for the timbers which have been dated here are from a similar, and relatively local, regional source.

Undated samples

As may also be seen in Table 1, 15 measured samples remain both ungrouped and undated. Although some samples with low ring numbers have been dated in this programme of analysis, the lack of dating for the others is probably caused but their low ring numbers. Other, longer, samples may remain undated because the source tree grew somewhere for which there is currently insufficient reference data available to provide secure cross-matching. It is also possible, particularly given the varied nature of the cellar timbers, that some timbers are in effect 'singletons', and while (as here) single timbers can sometimes be dated, this is often much more difficult than with collective groups of samples producing well replicated data. However, for whatever reason, it is a very common, if inexplicable, feature of tree-ring analysis to find that some samples will not date. This undated material will be reviewed periodically as further reference chronologies become available and these timbers may, in due course, also be dated.

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TABLES

Table 1: Details of tree-ring samples from 12 Broad Street and 11, 13 & 13a High Street, Launceston, Cornwall

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Roof					
LAU-N01	West truss, north principal rafter	48	h/s	------	------	------
LAU-N02	West truss, south principal rafter	59	h/s	1505	1563	1563
LAU-N03	West truss, collar	45	2	------	------	------
LAU-N04	East truss, north principal rafter	60	4	1509	1564	1568
LAU-N05	East truss, south principal rafter	54	8	1509	1554	1562
LAU-N06	East truss, collar	54	h/s	------	------	------
LAU-N07	North lower purlin, bay 1	49	h/s	1508	1556	1556
LAU-N08	North common rafter 1 (from west), bay 1	50	h/s	1512	1561	1561
LAU-N09	North common rafter 2, bay 1	67	3	------	------	------
LAU-N10	North common rafter 4, bay 1	nm	---	------	------	------
	Middle cellar					
LAU-N11	West main floor beam	72	11	------	------	------
LAU-N12	East main floor beam	60	h/s	1468	1527	1527
LAU-N13	Joist 2 (from north), west bay	75	20	1506	1560	1580
LAU-N14	Joist 3, west bay	54	h/s	1507	1560	1560
LAU-N15	Joist 7, west bay	40	no h/s	------	------	------
LAU-N16	Joist 10, west bay	56	22C	1527	1560	1582
LAU-N17	Joist 4, middle bay	nm	---	------	------	------
LAU-N18	Joist 10, middle bay	39	h/s	1523	1561	1561
LAU-N19	Joist 2, south bay	nm	---	------	------	------
LAU-N20	Joist 7, south bay	62	24C	1522	1559	1583
LAU-N21	Joist 9, south bay	49	4	1505	1549	1553
LAU-N22	Joist 10, south bay	nm	---	------	------	------

Table 1: continued

Sample number	Sample location	Total rings	Sapwood rings	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	South cellar					
LAU-N23	West main floor beam	71	h/s	1496	1566	1566
LAU-N24	East main floor beam	52	h/s	1501	1552	1552
LAU-N25	Joist 4, west bay	55	9	------	------	------
LAU-N26	Joist 5, west bay	54	10	------	------	------
LAU-N27	Joist 8, west bay	53	h/s	------	------	------
LAU-N28	Joist 9, west bay	35	h/s	------	------	------
LAU-N29	Joist 7, middle bay	39	h/s	------	------	------
LAU-N30	Joist 8, middle bay	49	no h/s	------	------	------
LAU-N31	Joist 6, south bay	33	h/s	------	------	------
LAU-N32	Joist 8, south bay	nm(28)	(10)	------	------	------
LAU-N33	Joist 10, south bay	56	6	------	------	------
	Middle cellar – steps and doorway					
LAU-N34	North door jamb	54	h/s	------	------	------
LAU-N35	Stair support beam	45	no h/s	------	------	------
LAU-N36	Lintel 1 (from west)	38	h/s	------	------	------
LAU-N37	Lintel 2	61	15	------	------	------
LAU-N38	Lintel 4	nm(29)	(h/s)			
	Miscellaneous off-cuts					
LAU-N39	Off-cut 1	45	h/s	1519	1563	1563
LAU-N40	Off-cut 2	50	h/s			
LAU-N41	Off-cut 3	nm(30)	(no h/s)			
LAU-N42	Off-cut 4	nm(30)	(no h/s)			

h/s = the heartwood/sapwood ring is the last ring on the sample; C = complete sapwood is retained on the sample, the last measured ring date is the felling date of the tree; nm = sample not measured

Table 2: Results of the cross-matching of site sequence LAUNSQ01 and relevant reference chronologies when the first-ring date is AD 1496 and the last-ring date is AD 1583

Reference chronology	Span of chronology	t-value	Reference
Godolphin House, Godolphin Cross, Cornwall	AD 1376–1620	8.4	Tyers and Tyers forthcoming
1–5 Bridge Street, Bideford, Devon	AD 1484–1706	8.2	Arnold and Howard 2012a unpubl
Sydenham House, Marystow, Devon	AD 1394–1654	7.3	Arnold *et al* 2015
Church of St Nectan, Stoke, Hartland, Devon	AD 1440–1697	7.0	Arnold and Howard 2013
Treludick House, Egloskerry, Cornwall	AD 1516–1630	6.8	Arnold and Howard 2007a
Docton Court, 2 Myrtle Street, Appledore, Bideford, Devon	AD 1440–1581	6.6	Arnold and Howard 2012b unpubl
Great Bidlake, Bridstowe, Devon	AD 1489–1599	6.3	Arnold and Howard 2011
Manor House, Templecombe, Somerset	AD 1486–1591	5.3	Howard *et al* 1997
Yarde Farmhouse, Malborough, South Hams, Devon	AD 1432–1603	5.3	Arnold and Howard 2009
Trerithick House, Polyphant, Cornwall	AD 1503–1673	5.3	Arnold and Howard 2007b

Table 3: Results of the cross-matching of sample LAU-N12 and relevant reference chronologies when the first-ring date is AD 1468 and the last-ring date is AD 1527

Reference chronology	Span of chronology	*t*-value	Reference
The Gildhouse, Poundstock, Cornwall	AD 1405–1543	8.1	Arnold and Howard 2007c
Church of St George, Modbury, Devon	AD 1343–1540	7.8	Arnold *et al* 2017
Church of St John the Baptist, Myndtown, Shropshire	AD 1420–1568	6.9	Arnold *et al* 2022
Sydenham House, Marystow, Devon	AD 1394–1654	6.7	Arnold *et al* 2015
Church of St Nectan, Stoke, Hartland, Devon	AD 1440–1697	6.3	Arnold and Howard 2013
Manor Farm Barn, Winterborne Clenston, Dorset	AD 1339–1515	6.2	Bridge 2014
Pool House, Blackborough, Devon	AD 1255–1366	5.9	Tyers *et al* forthcoming
Docton Court, 2 Myrtle Street, Appledore, Bideford, Devon	AD 1440–1581	5.7	Arnold and Howard 2012b unpubl
Alcester War Memorial Town Hall, Alcester, Warwickshire	AD 1374–1625	5.5	Arnold and Howard 2014 unpubl
Church of St Nicholas, Wilsford, Wiltshire	AD 1477–1575	5.5	Bridge and Miles, 2006

FIGURES

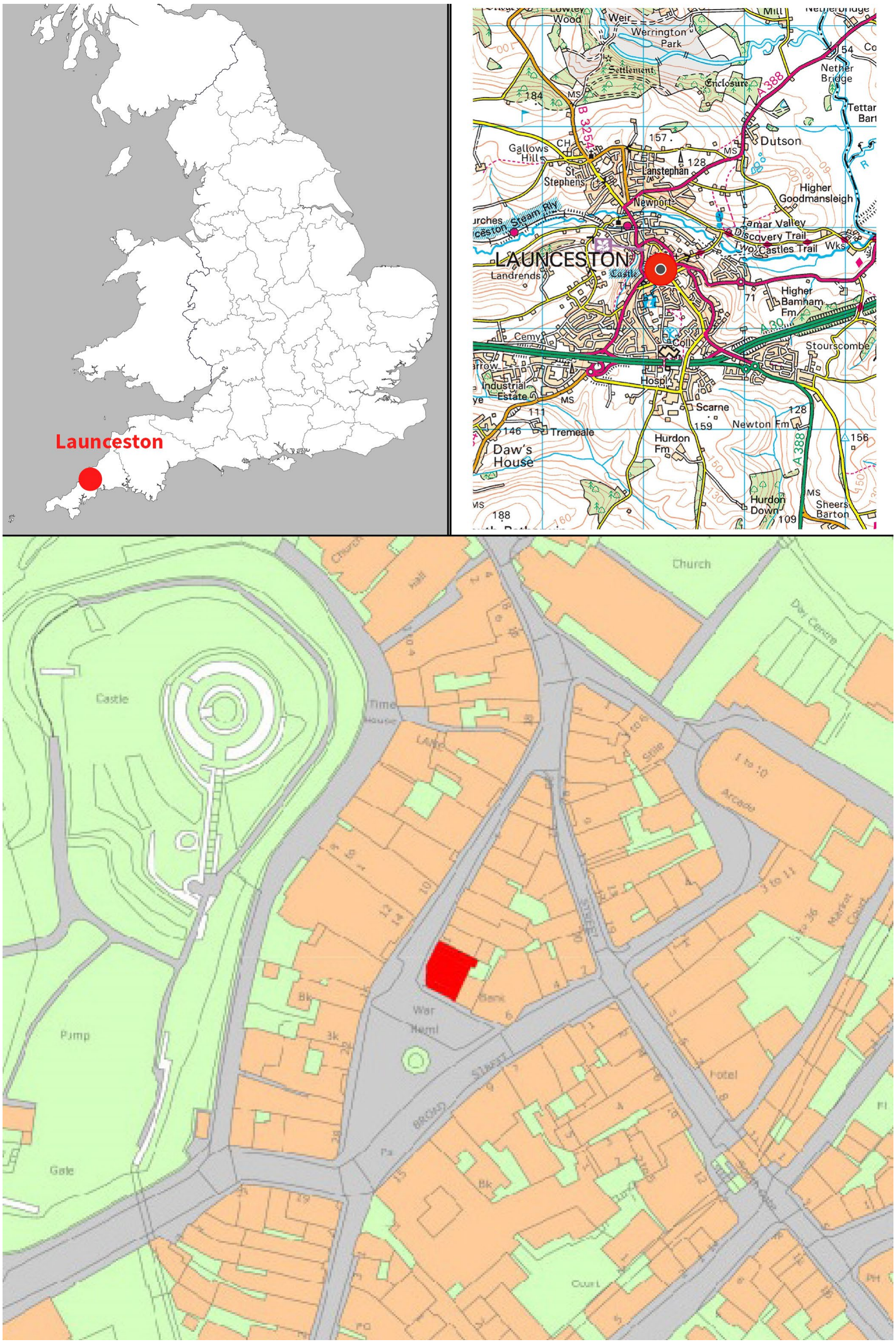


Figure 1: Maps to show the location of 12 Broad Street, 11, 13, & 13A High Street in Launceston, Cornwall marked in red. Scale: top right 1:50,000, bottom 1:1250

Figure 2a/b: General views of panelling to first-floor room (top) and corridor (bottom; photographs Robert Howard)

Figure 2c/d: General views of the middle cellar (top) and the south cellar (bottom), both viewed looking north (photographs Robert Howard)

Figure 2e/f: General views of the middle cellar (top) and the south cellar (bottom), both viewed looking north (photographs Robert Howard)

Figure 3a: Roof truss 1 viewed looking west to help identify sampled timbers (photograph Robert Howard)

Figure 3b: Roof truss 2 viewed looking east to help identify sampled timbers (photograph Robert Howard)

Figure 3c: Roof bay 1 viewed looking north to help identify sampled timbers (photograph Robert Howard)

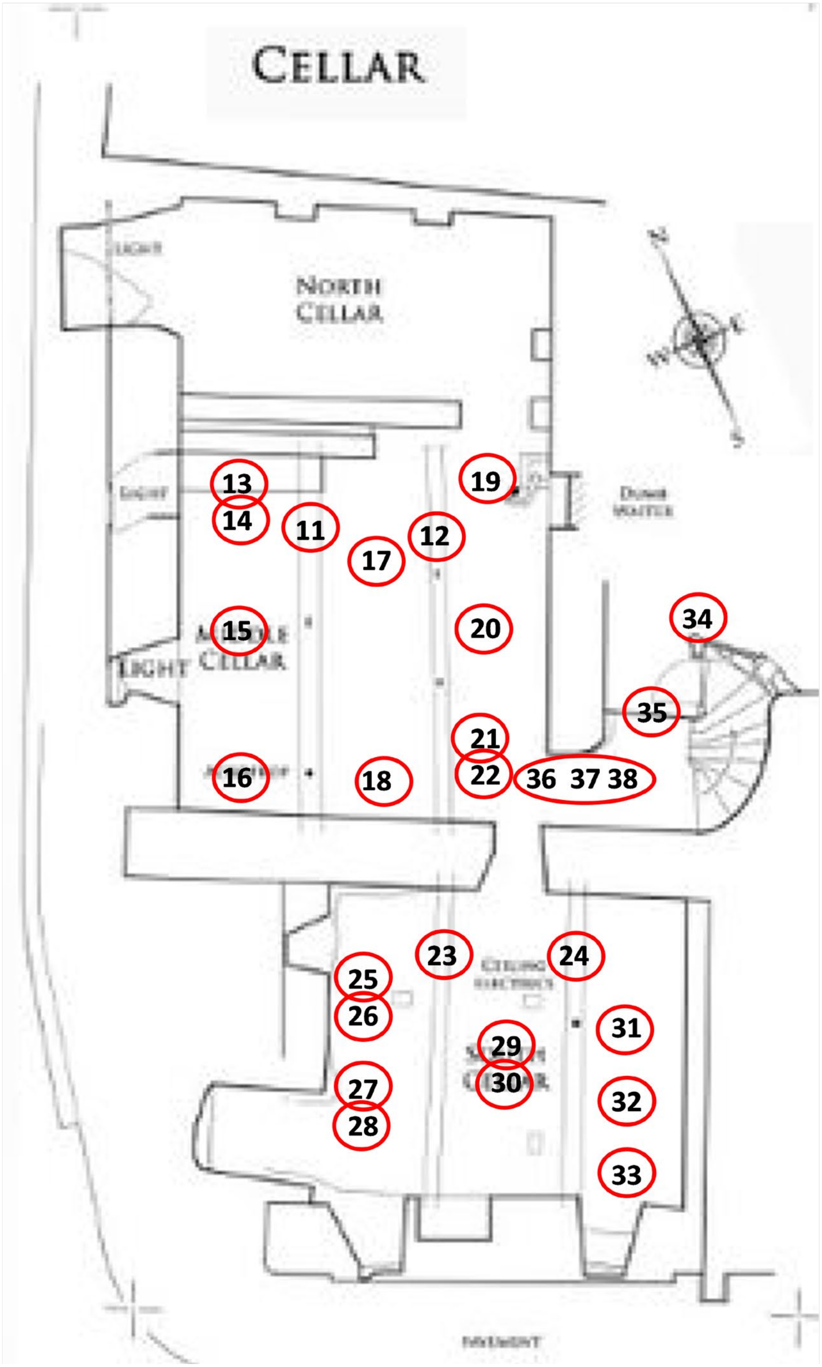
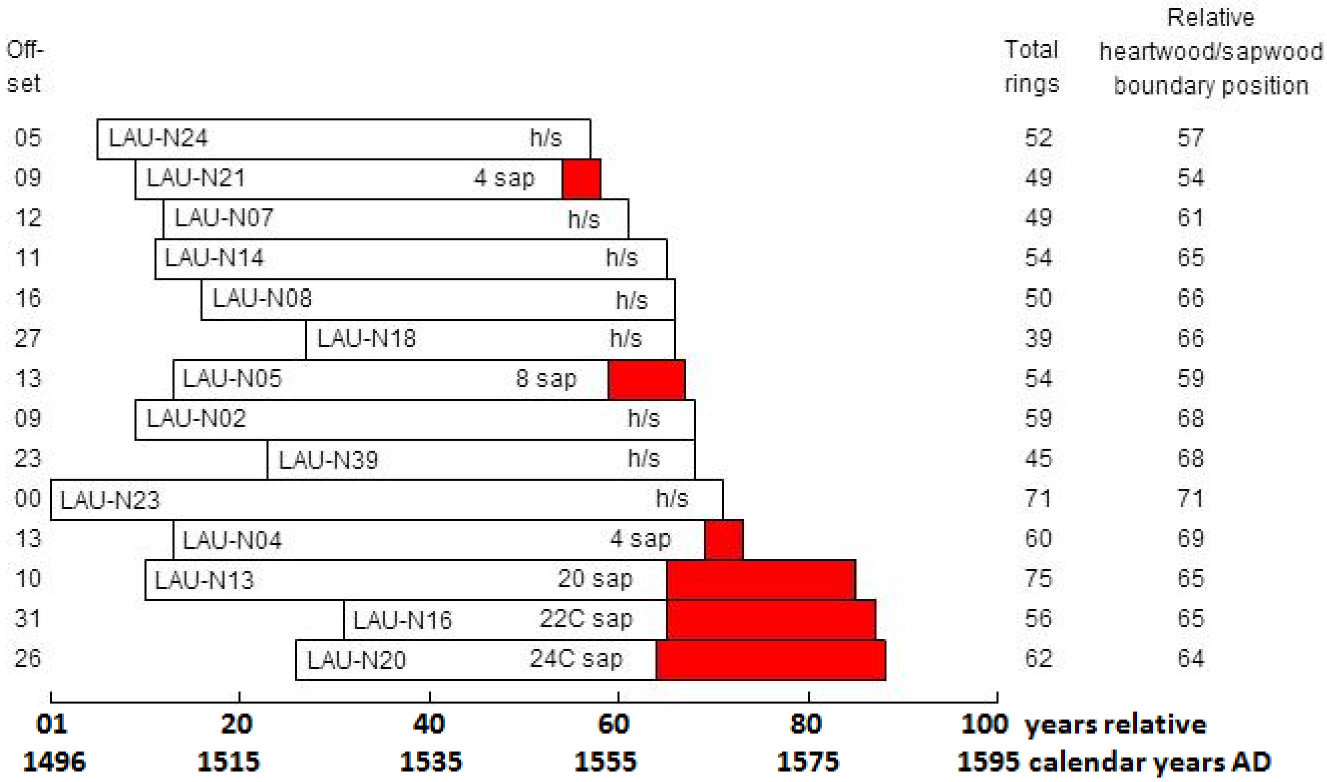


Figure 4: Plan at cellar level to help locate sampled timbers (after David Scott, Architects 2022)



White bars = heartwood rings; red bars = sapwood rings;
h/s = the heartwood/sapwood ring is the last ring on the sample.
C = complete sapwood is retained on the sample, the last measured ring date is the felling date of the tree

Figure 5: Bar diagram of the 14 dated samples of site chronology LAUNSQ01 arranged in last measured ring date order

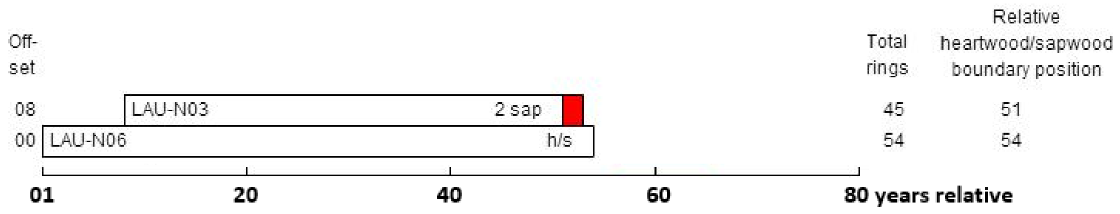


Figure 6: Bar diagram of the two undated samples in site chronology LAUNSQ02

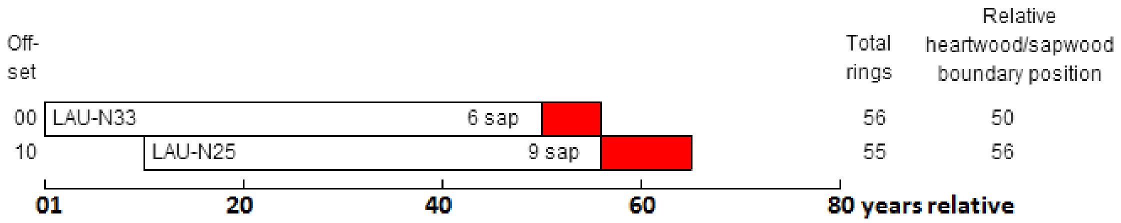
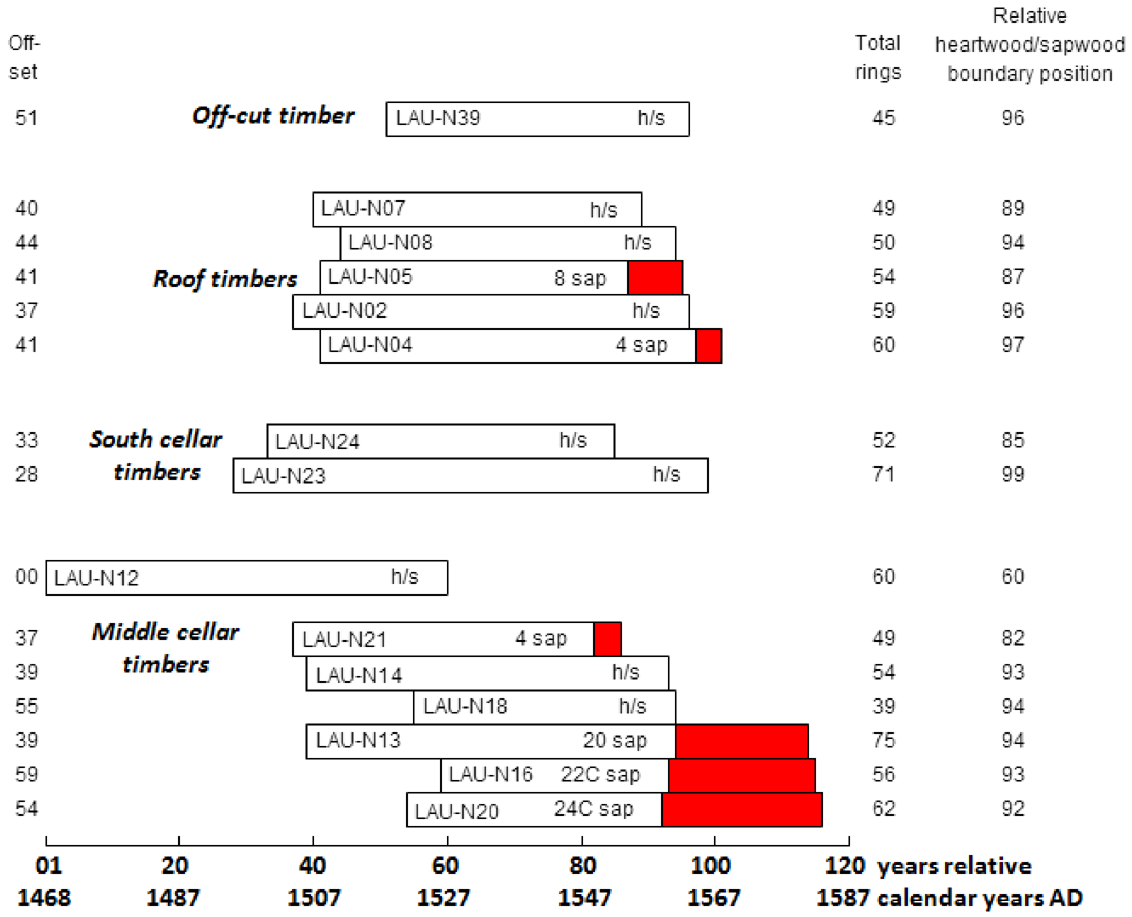


Figure 7: Bar diagram of the two undated samples in site chronology LAUNSQ03

White bars = heartwood rings; red bars = sapwood rings;
h/s = the heartwood/sapwood ring is the last ring on the sample.



White bars = heartwood rings; red bars = sapwood rings;
h/s = the heartwood/sapwood ring is the last ring on the sample.
C = complete sapwood is retained on the sample, the last measured ring date is the felling date of the tree

Figure 8: Bar diagram of all 15 dated samples grouped by timber location and arranged in last measured ring date order

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

LAU-N01A 48
747 581 328 482 311 325 358 387 369 285 178 229 243 323 232 168 188 135 154 135
117 167 79 132 200 298 184 204 196 175 139 199 125 198 162 194 140 197 180 151
175 104 93 131 137 127 167 207
LAU-N01B 48
770 565 335 602 287 310 346 402 339 288 161 221 223 300 229 161 162 140 160 146
124 159 89 121 203 296 175 204 195 165 128 175 153 182 166 182 145 225 154 146
142 107 84 136 134 129 158 199
LAU-N02A 59
405 327 282 250 225 269 207 256 229 254 138 111 170 135 154 130 172 164 113 125
110 120 167 221 145 103 100 93 187 173 104 97 104 95 132 121 172 119 168 117
103 123 135 125 131 165 148 115 122 124 131 93 134 140 154 173 138 146 168
LAU-N02B 59
382 316 275 243 239 258 221 242 204 255 126 125 178 146 163 121 174 168 114 107
124 128 153 221 153 103 96 103 184 165 110 78 117 84 140 112 188 122 151 131
93 120 134 118 142 150 143 124 122 130 128 103 120 135 146 171 132 154 153
LAU-N03A 45
314 206 280 289 205 192 232 334 230 209 221 228 240 289 257 171 161 230 201 203
160 150 130 193 221 241 273 180 121 175 169 156 172 155 175 173 158 160 161 194
119 210 196 236 310
LAU-N03B 45
281 219 284 283 217 200 224 332 241 207 255 216 246 290 204 176 147 234 189 192
160 153 142 200 217 193 265 189 131 177 181 146 178 151 173 171 155 168 167 187
121 203 194 232 305
LAU-N04A 60
290 198 246 286 234 305 243 191 223 234 178 230 235 278 268 229 314 276 333 407
293 239 360 275 234 160 307 123 196 175 223 206 262 198 179 150 214 134 179 212
190 168 173 134 134 145 146 109 93 119 142 124 105 91 78 115 184 153 140 170
LAU-N04B 60
252 190 253 297 237 292 263 195 207 231 188 218 234 279 264 216 292 335 339 401
320 227 340 270 235 160 293 184 165 165 218 216 255 189 171 165 196 135 176 206
181 170 170 125 150 137 140 108 107 112 156 118 103 93 78 128 175 154 163 196
LAU-N05A 54
375 384 455 488 494 540 414 355 318 316 313 328 436 457 304 320 371 322 302 400
300 187 379 326 326 262 440 204 295 276 309 282 296 186 206 231 195 140 170 213
203 190 175 110 155 269 187 187 214 253 262 237 171 274
LAU-N05B 54
369 390 527 496 490 573 408 385 282 325 316 375 426 484 314 287 391 318 314 357
306 187 385 320 326 267 423 222 290 270 305 279 278 197 208 229 193 154 173 188
207 188 170 101 171 267 188 185 206 247 256 237 175 269
LAU-N06A 54
426 285 363 399 447 346 323 337 495 321 349 310 341 283 325 335 235 215 225 195
189 187 166 140 101 185 168 167 145 136 82 130 147 149 145 139 76 110 81 114
89 101 128 128 110 112 112 145 98 170 159 200 179 185
LAU-N06B 54
422 293 431 372 407 360 333 338 489 325 344 318 323 300 314 332 242 207 225 203
204 185 165 142 110 181 169 166 146 138 92 139 154 129 148 129 85 100 96 111
89 97 123 122 110 114 116 145 89 170 159 195 180 179
LAU-N07A 49

338 337 406 388 403 421 508 260 186 224 307 225 221 234 196 101 98 100 113 182
195 139 139 170 151 137 160 132 100 117 89 124 154 120 104 151 118 95 107 107
81 70 98 128 131 132 143 147 99
LAU-N07B 49
341 348 402 385 399 428 503 268 179 224 314 232 224 223 190 104 111 103 112 171
178 133 133 177 141 147 149 131 100 118 84 127 148 115 110 152 110 100 104 100
92 63 100 136 135 135 130 150 100
LAU-N08A 50
314 295 292 167 140 204 200 142 225 232 207 170 218 240 248 279 248 157 153 229
211 208 182 210 119 210 232 237 175 175 153 164 126 125 109 142 112 98 155 194
89 124 159 168 112 140 132 144 137 165
LAU-N08B 50
313 271 303 150 150 200 229 145 201 230 225 185 207 245 236 259 236 191 150 218
210 210 189 217 121 213 229 246 172 159 168 162 129 126 112 160 103 103 150 195
99 123 142 162 123 137 139 151 146 162
LAU-N09A 67
114 130 134 108 62 99 118 81 129 134 113 119 111 83 125 89 163 173 183 162
150 148 83 75 88 89 108 77 48 93 39 103 91 78 92 90 114 60 63 47
67 75 79 118 160 135 71 67 71 97 105 134 141 207 116 172 238 166 156 123
175 121 117 212 185 220 234
LAU-N09B 67
117 119 143 105 63 93 112 96 127 135 117 109 115 83 115 92 187 173 173 153
144 150 88 71 84 86 112 73 50 88 46 101 90 73 100 90 119 67 65 49
66 71 80 117 156 134 73 69 72 89 114 132 145 200 113 164 249 170 160 123
187 120 128 198 187 233 235
LAU-N11A 72
158 179 120 117 108 138 81 203 224 217 175 282 305 268 183 91 121 146 78 199
303 282 276 293 282 295 318 367 321 303 301 279 260 198 214 190 156 123 162 226
307 206 289 262 264 345 309 306 292 217 214 210 212 262 198 215 292 217 155 173
118 183 200 198 228 183 121 165 212 195 186 280
LAU-N11B 72
154 181 127 113 105 149 88 202 226 222 184 271 309 263 197 100 128 132 89 200
308 297 289 288 284 299 307 384 322 300 299 275 269 196 222 175 172 127 137 228
296 215 282 235 253 354 315 296 301 220 235 218 218 257 201 206 300 213 162 163
131 165 208 195 222 181 122 180 195 203 187 274
LAU-N12A 60
206 149 169 151 138 100 145 156 150 92 143 175 141 170 153 169 204 209 209 200
151 132 175 160 96 107 92 124 214 150 78 153 159 103 100 126 115 101 131 80
129 164 98 153 108 84 106 53 84 105 106 126 96 126 106 90 79 73 90 120
LAU-N12B 60
199 142 173 150 149 91 136 166 140 93 143 183 139 176 163 153 219 208 205 188
175 131 171 132 100 112 108 132 222 161 96 157 161 102 92 132 108 100 131 78
143 159 96 160 103 69 119 53 82 87 112 123 101 106 110 76 84 79 92 117
LAU-N13A 75
137 142 142 168 117 137 135 84 142 98 92 103 84 93 114 92 91 67 87 162
126 133 132 150 73 174 194 250 321 494 265 315 414 335 281 210 146 176 109 114
87 124 65 40 79 107 64 97 115 112 108 130 142 160 151 156 221 175 161 223
140 187 131 181 317 260 135 131 215 220 102 136 93 125 260
LAU-N13B 75
135 110 141 166 116 142 126 87 150 100 84 102 58 96 111 99 89 62 96 162
125 132 146 121 89 170 197 254 316 503 245 333 410 344 278 217 139 191 98 118
95 112 62 42 85 109 65 96 110 119 117 113 154 170 162 148 235 151 173 241
128 184 150 175 324 209 154 135 226 232 96 130 92 145 242

LAU-N14A 54
164 208 219 150 180 236 224 265 160 83 84 90 112 91 126 119 89 64 66 97
147 147 101 60 80 80 87 81 75 55 118 135 167 146 103 89 89 77 35 60
60 64 74 87 99 124 132 89 92 95 67 82 86 105
LAU-N14B 54
168 213 223 151 188 247 226 258 161 78 90 108 105 91 139 114 90 59 57 89
146 142 115 64 77 89 85 75 80 50 129 150 157 142 105 86 91 71 39 48
56 59 71 95 93 125 140 102 88 78 86 78 87 99
LAU-N15A 40
104 119 311 333 300 256 414 160 292 266 293 137 173 159 240 182 214 95 117 123
161 203 192 232 260 189 152 149 75 115 157 149 118 126 120 183 309 146 104 157
LAU-N15B 40
100 122 311 342 293 242 418 183 284 255 307 130 171 158 242 193 203 104 112 133
153 210 192 228 265 194 142 146 86 102 150 146 130 136 102 159 359 150 112 156
LAU-N16A 56
339 362 248 110 148 158 150 196 254 125 220 360 342 264 296 193 249 207 219 132
130 130 95 110 201 96 135 235 210 187 164 258 245 159 93 171 98 170 135 129
105 109 196 218 211 155 128 131 182 152 112 103 109 163 128 151
LAU-N16B 56
338 351 255 103 159 156 150 207 248 130 210 332 334 276 287 182 255 221 223 142
153 131 96 113 200 96 121 250 209 168 207 262 264 157 104 176 107 159 137 114
110 103 206 220 193 168 123 139 173 134 96 96 132 159 125 163
LAU-N18A 39
186 268 292 379 322 384 294 273 294 276 260 210 343 166 213 159 286 198 250 210
235 146 156 153 151 164 197 230 247 210 167 221 262 206 139 215 200 178 209
LAU-N18B 39
184 261 295 378 343 384 287 246 292 282 259 200 339 174 220 148 288 196 249 181
254 139 149 150 150 168 203 230 260 182 190 214 246 207 131 221 195 176 211
LAU-N20A 62
356 264 204 259 270 246 251 180 128 216 149 194 118 217 91 169 106 147 166 196
129 147 114 158 156 165 158 177 182 242 114 139 156 169 142 119 156 197 146 179
153 132 112 187 150 162 148 156 157 181 138 145 189 187 159 162 120 189 150 142
104 144
LAU-N20B 62
352 252 190 259 253 261 259 185 135 195 157 198 133 214 86 175 103 138 169 186
144 148 123 158 155 160 153 177 178 202 106 152 140 180 143 125 150 190 145 182
143 139 118 182 162 161 148 151 150 178 118 151 180 193 165 156 134 175 168 134
103 150
LAU-N21A 49
498 343 238 180 175 193 378 244 242 318 198 99 137 143 117 93 134 89 61 62
71 76 133 148 110 75 74 42 81 76 96 54 77 111 150 160 110 118 128 109
65 100 53 80 107 92 173 160 175
LAU-N21B 49
480 301 216 177 172 191 317 264 246 357 162 98 134 153 111 94 132 96 53 65
78 99 146 160 110 92 76 57 79 85 89 43 74 108 154 152 110 116 117 105
77 96 57 71 81 121 176 157 184
LAU-N23A 71
183 372 372 333 404 335 351 268 397 371 260 219 201 273 257 293 338 261 492 346
198 226 154 240 229 318 205 185 138 206 219 255 270 260 218 205 185 179 239 262
143 203 267 310 265 290 172 221 132 180 137 195 156 275 212 199 146 105 125 138
84 112 147 189 187 134 194 115 105 115 152
LAU-N23B 71
182 367 381 330 396 334 346 274 396 367 258 224 195 276 253 278 335 269 478 339

182 228 159 234 229 303 209 165 143 195 198 242 284 271 230 200 189 184 200 253
140 198 259 314 265 292 178 215 135 164 118 194 155 267 214 206 157 115 126 128
96 106 146 187 181 137 188 125 96 121 153
LAU-N24A 52
212 258 196 298 405 350 201 205 242 220 437 393 330 285 171 107 162 129 107 157
156 157 125 82 82 88 110 125 110 110 167 128 146 140 151 150 167 139 160 185
143 98 135 146 86 106 140 109 127 194 202 173
LAU-N24B 52
197 260 200 291 403 364 200 198 244 191 458 385 327 284 157 110 167 129 92 152
163 171 121 82 73 85 118 123 125 102 174 136 144 146 149 153 167 134 154 187
136 113 150 131 82 112 140 120 126 193 206 177
LAU-N25A 55
250 434 437 411 400 250 237 191 132 157 174 134 167 139 110 118 189 234 201 246
173 153 158 174 250 170 229 125 156 169 131 139 200 179 177 96 192 169 175 189
151 212 200 203 187 220 263 177 224 259 248 225 317 288 328
LAU-N25B 55
241 428 405 418 396 278 238 184 129 143 163 151 153 150 108 127 205 233 205 252
167 167 152 177 259 158 242 116 156 159 145 139 187 187 173 101 182 172 181 176
156 213 196 198 200 206 259 202 211 229 261 223 353 290 325
LAU-N26A 54
200 233 296 253 331 259 202 314 223 234 239 328 191 164 235 338 325 235 275 229
203 203 219 254 150 182 116 145 159 142 117 189 159 170 114 239 212 185 190 225
212 187 212 207 187 217 220 326 389 232 242 246 246 293
LAU-N26B 54
190 221 294 239 342 266 248 289 216 230 240 337 174 182 234 329 321 232 275 229
234 215 235 243 146 182 101 134 168 122 98 215 153 187 104 254 220 214 171 191
182 215 204 185 201 206 209 268 345 214 265 237 260 293
LAU-N27A 53
287 446 406 284 261 312 284 285 312 301 271 279 446 428 396 348 379 301 278 333
248 223 156 204 153 243 167 212 262 204 178 217 217 331 284 310 325 343 279 304
225 296 422 341 271 377 364 258 237 274 228 244 242
LAU-N27B 53
286 451 401 284 273 325 268 297 314 305 272 282 443 417 395 335 368 314 281 348
237 220 171 195 157 240 162 226 252 200 161 217 229 338 280 323 318 306 314 326
220 307 420 352 271 379 364 285 239 284 228 253 252
LAU-N28A 35
180 318 240 368 413 426 536 574 511 421 478 416 436 360 421 443 557 351 495 568
512 534 518 423 450 829 538 331 288 393 435 307 485 396 379
LAU-N28B 35
185 323 238 363 412 448 500 553 502 418 479 410 442 350 424 442 566 319 522 564
504 531 510 404 459 825 553 335 285 403 427 303 480 384 377
LAU-N29A 39
569 555 448 297 336 319 266 230 141 194 405 464 408 307 374 345 191 181 257 321
251 195 163 242 146 156 210 143 91 107 92 81 93 53 129 110 126 115 107
LAU-N29B 39
567 552 461 295 328 312 282 230 122 184 421 452 396 304 387 353 196 175 268 310
272 209 156 256 148 160 202 139 91 94 98 87 98 48 154 115 128 117 104
LAU-N30A 49
373 346 217 332 345 348 426 434 354 244 273 374 333 378 446 375 268 213 239 50
43 46 64 66 120 174 144 160 175 203 185 228 217 149 158 276 206 279 128 85
87 167 129 239 173 200 193 252 293
LAU-N30B 49
376 330 266 319 334 371 428 425 355 259 260 374 316 407 437 380 282 200 234 53

29 37 71 57 120 171 137 161 182 201 167 237 190 168 143 282 198 289 132 78
84 151 140 234 176 205 185 247 299
LAU-N31A 33
123 150 136 111 158 128 110 92 172 184 199 108 122 246 142 198 235 203 194 156
183 150 239 171 119 171 132 100 146 194 197 169 195
LAU-N31B 33
118 132 154 103 141 113 111 99 163 190 200 109 125 241 178 212 230 213 185 162
185 146 239 164 132 164 141 105 157 196 195 165 195
LAU-N33A 56
771 668 623 260 214 289 146 132 152 221 291 385 252 260 286 377 339 183 160 320
254 258 470 523 272 159 315 235 293 280 177 65 57 103 165 79 148 83 125 135
137 129 109 193 60 33 42 81 76 71 77 96 115 126 169 147
LAU-N33B 56
769 631 602 266 209 276 137 151 134 228 296 374 236 253 285 357 313 203 164 318
253 275 457 485 256 162 320 245 301 268 179 64 60 101 167 95 154 75 135 137
143 141 105 181 51 42 48 73 80 70 95 100 121 126 167 143
LAU-N34A 54
374 293 300 289 301 337 380 396 264 268 238 207 103 92 139 145 120 134 137 112
121 69 50 35 82 41 29 29 28 70 178 266 300 300 357 298 398 285 275 210
230 193 268 240 207 178 160 203 267 262 296 273 375 345
LAU-N34B 54
365 301 332 270 314 334 375 396 269 255 241 201 103 106 142 131 109 138 121 105
120 76 44 37 76 44 28 30 28 65 167 264 289 309 360 298 393 284 285 195
231 195 260 239 212 182 157 203 267 246 282 275 374 345
LAU-N35A 45
163 189 160 192 171 225 175 309 162 328 296 179 173 334 312 382 312 400 352 340
517 569 597 643 414 420 275 168 245 335 328 364 443 200 296 206 217 243 177 207
217 304 204 170 224
LAU-N35B 45
159 189 150 197 161 236 169 304 157 321 300 180 190 326 309 378 314 401 343 335
531 564 601 629 417 406 278 182 231 318 358 344 381 212 276 209 224 245 179 201
221 299 201 173 230
LAU-N36A 38
451 306 238 259 467 428 313 589 468 432 367 330 314 351 392 199 99 141 112 213
152 195 137 147 109 165 156 143 263 215 162 150 138 171 121 154 120 176
LAU-N36B 38
441 316 231 254 469 441 329 615 499 434 403 346 328 381 374 196 108 142 124 186
165 209 150 123 117 157 167 151 245 217 167 153 135 170 121 160 119 172
LAU-N37A 61
108 118 81 133 126 118 93 91 101 142 104 66 67 91 201 209 182 191 144 140
146 148 189 87 123 84 114 150 142 114 117 134 86 86 141 142 147 156 168 218
184 110 132 115 53 117 128 81 79 107 51 90 71 92 87 75 71 78 73 85
90
LAU-N37B 61
109 120 94 154 158 171 131 112 99 136 103 76 61 80 212 198 190 182 156 145
139 150 196 82 137 92 101 149 164 96 110 125 81 82 112 135 122 164 169 210
171 118 128 110 57 138 125 85 92 116 51 87 96 92 75 100 71 68 65 71
89
LAU-N39A 45
132 120 160 157 146 191 139 142 166 178 137 96 138 221 242 197 201 123 191 201
205 169 157 125 125 114 57 92 82 124 153 167 185 125 191 178 222 185 196 146
199 182 145 168 170
LAU-N39B 45

127 120 150 159 145 196 169 159 199 242 166 95 144 205 225 167 226 108 180 189
210 162 160 113 131 96 69 94 96 128 141 165 172 117 184 187 220 193 192 140
196 192 165 167 167
LAU-N40A 50
215 418 303 390 319 248 177 142 189 167 162 171 200 165 164 137 123 119 150 132
95 103 118 46 107 160 121 135 125 132 139 102 73 64 105 82 68 85 82 67
77 77 98 96 110 116 131 123 113 107
LAU-N40B 50
204 438 309 370 305 239 175 128 218 186 182 184 196 167 169 138 112 131 148 119
86 85 104 53 96 128 116 141 125 131 150 94 67 64 92 75 64 75 78 76
82 74 96 82 100 121 143 106 114 110

APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

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

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

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

1. Inspecting the Building and Sampling the Timbers.

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

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

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

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

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

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

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

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

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

2. Measuring Ring Widths.

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

3. Cross-Matching and Dating the Samples.

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

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

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

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

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

4. Estimating the Felling Date.

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

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

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

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

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

5. Estimating the Date of Construction.

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

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

6. Master Chronological Sequences.

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

7. Ring-Width Indices.

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

t-value/offset Matrix

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

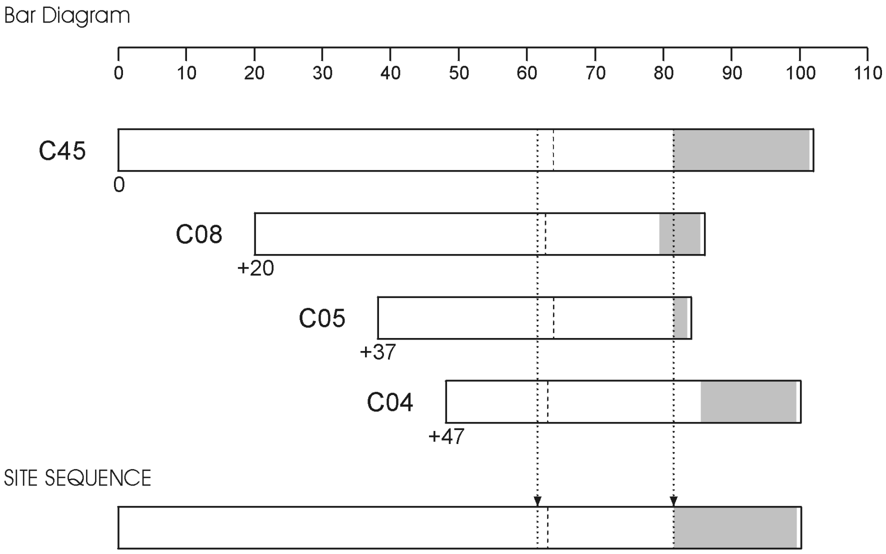


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

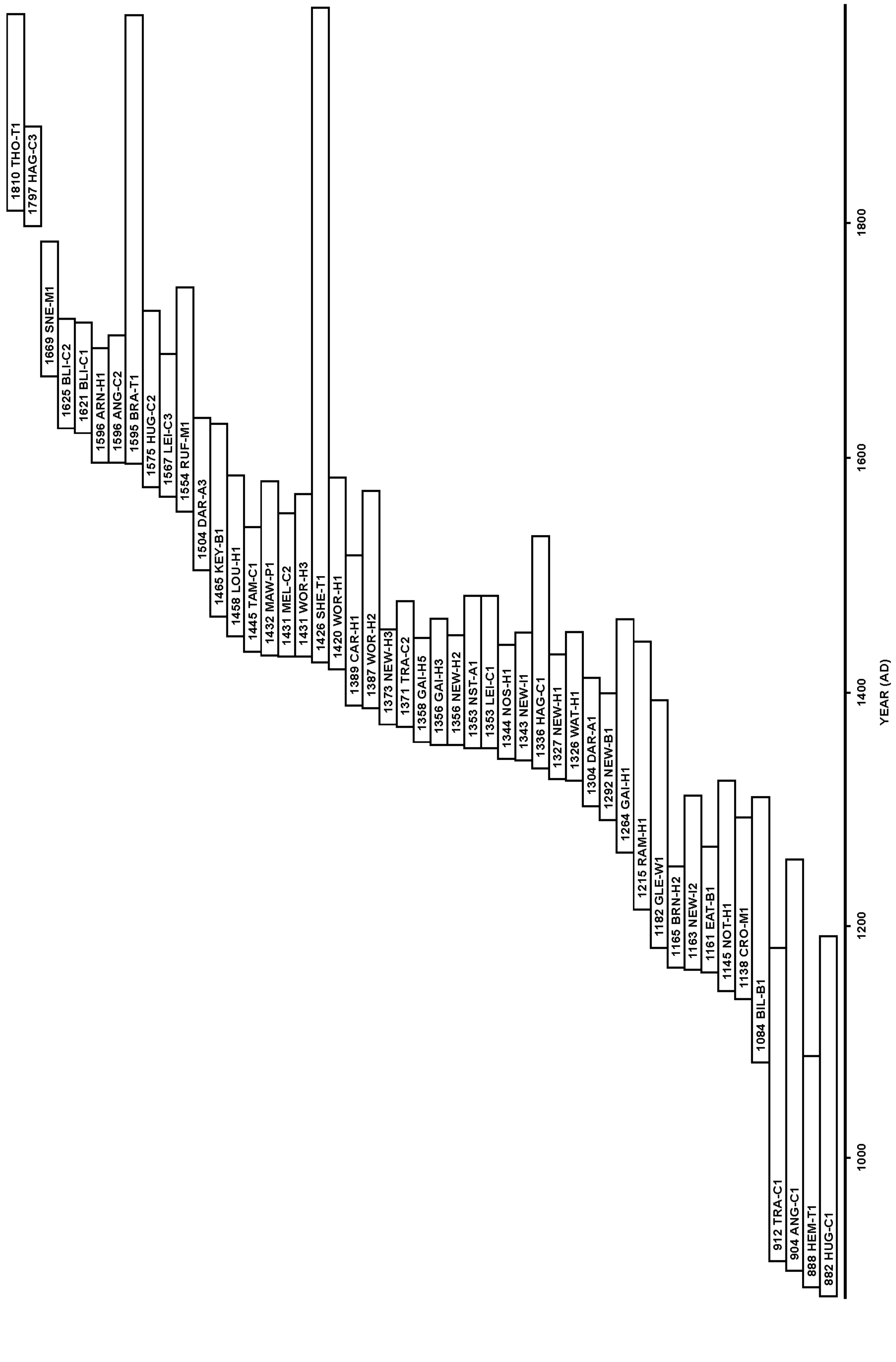
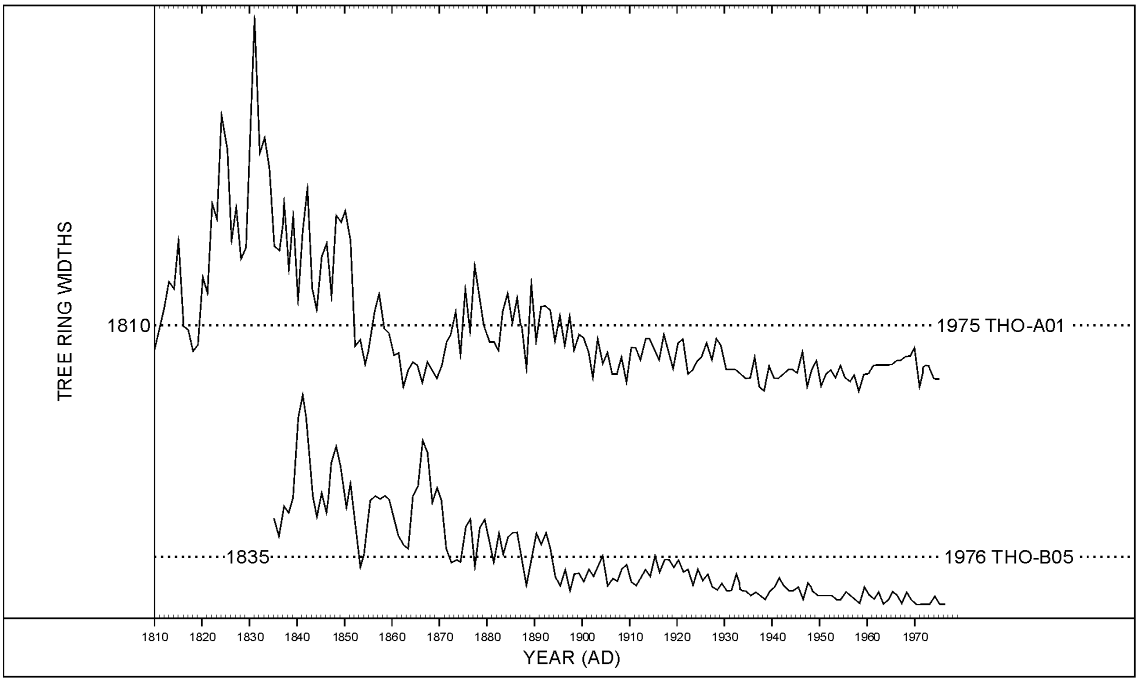


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

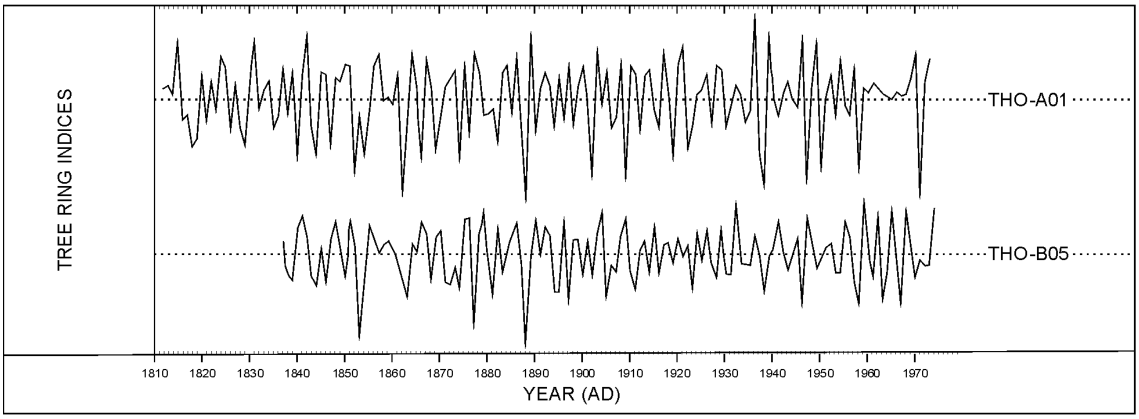


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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

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

The growth trends have been removed completely

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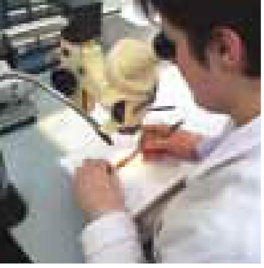
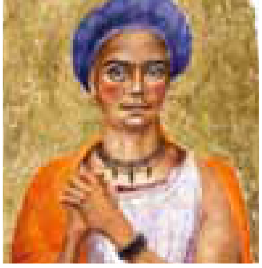


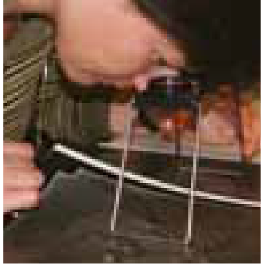


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