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DEWAR’S LANE GRANARY, BERWICK-UPON-TWEED, NORTHUMBERLAND
TREE RING ANALYSIS OF TIMBERS

SCIENTIFIC DATING REPORT

Alison Arnold, Robert Howard, and Cathy Tyers

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SUMMARY

Dendrochronological analysis was undertaken on 51 samples taken from oak and pine timbers of this building. Site sequence BWKASQ03 was successfully dated to the period AD 1701–1825. This site sequence contains four pine samples, one from the central framework, one from the west framework, and two from floor joists. All four samples have last measured ring dates in the first quarter of the nineteenth century, showing that none of them relate to the likely original construction of the building in the mid to late-eighteenth century. They appear broadly coeval and it is likely that they are associated with the post-AD 1829 reconstruction, following a fire in AD 1815. The likely source of these timbers is Scandinavian, possibly south-east Norway. Although a number of other small groups of timbers were identified none of the resultant site sequences, either oak or pine, could be successfully dated.

CONTRIBUTORS

Alison Arnold, Robert Howard, and Cathy Tyers

ACKNOWLEDGEMENTS

The Laboratory would like to thank John Smithson of the Berwick-upon-Tweed Preservation Trust for arranging access. Various dendrochronologists from Scandinavia and countries around the Baltic Sea have kindly either carried out cross-dating procedures or made reference data available. Reference data has also been obtained from the International Tree-Ring Data Bank based in Boulder, Colorado, funded by the National Geophysical Data Center (part of the World Data Center). The survey drawings, used in Figures 3–9, were produced by Bain, Swan Architects.

ARCHIVE LOCATION

Northumberland SMR; NTRDL

DATE OF INVESTIGATION

2006-7

CONTACT DETAILS

Alison Arnold and Robert Howard
Nottingham Tree-ring Dating Laboratory
20 Hillcrest Grove
Sherwood
Nottingham NG5 1FT

Cathy Tyers
Sheffield Dendrochronology Laboratory
University of Sheffield
West Court
2 Mappin Street
Sheffield S1 4DT

CONTENTS

INTRODUCTION

Dewar's Granary is located in the Northumberland town of Berwick upon Tweed (NT99815274; Fig 1); to the east it faces Dewar's Lane and the west, an open yard which has access to the Quayside by a tunnel through the Quay Walls. The building measures *c* 38.7m by 8.7m and is constructed of roughly-coursed sandstone blocks. Since its erection, the whole building has developed a dramatic westward lean. With the exception of the blocking up of a number of windows, alterations to some of the ground-floor doorways, and the addition on the west elevation of three massive full height concrete buttresses to counteract the lean of the building, externally it does not appear to have been changed a great deal since construction. This construction is thought to have occurred in the mid-to-late eighteenth century, based on its similarity to a warehouse in Hull dated to AD 1745.

Internally, the building consists of four storeys plus attic. Each floor is supported by joists that span the full width of the building, their ends lodged within the east and west walls. These joists are supported mid-span by a central arcade, consisting of axial beams resting on timber pads and chamfered storey posts (replaced in steel at basement level and partly replaced at first-floor level). On or just inside the line of the internal face of each side wall there is a free-standing timber frame, of posts and rails, which also supports the floor joists (Fig 2). The 1991 RCHM(E) survey of the building concluded that the central structure was likely to be part of the original construction whilst the freestanding framework running along the inside of the walls was later, added in an attempt to strengthen it. The positioning of this latter timberwork is thought to demonstrate that the building had already begun to lean at its insertion, ie at basement level the posts of the eastern are set well clear of the wall, whilst those of the western are embedded in its face. However, documentary evidence uncovered since 1991 has shown that the Granary suffered a serious fire in December AD 1815, at which time the building was said to have been 'reduced to ashes'. If this is the case, it suggests that all the internal wooden structures seen today are likely to date to the post-AD 1829 reconstruction or later. The roof structure consists of paired rafters with collars and is thought to date to the early twentieth century. The above building description is based the surveys by Peter Ryder (Ryder 2004) and the RCHM(E) (1991).

SAMPLING

Prior to the discovery of documentation referring to the fire it was assumed that the central timberwork and floor joists were part of the original construction and that the timber frame along the inside of the walls was later, added in an effort to counteract the leaning of the building. Although it is now thought that all internal timberwork must post-date the fire AD 1815, it is still unclear whether it is all contemporary, dating to the post-AD 1829 reconstruction, or represents various phases of construction. As such, during sampling the different groups of timbers were treated as potentially separate phases. The posts, pads, and axial beams located along the centre of the building being one (the central framework), the posts and rails located just inside the walls being a second (the east and west framework), and the floor joists being a third.

Sampling and analysis by tree-ring dating was commissioned and funded by English Heritage. The building is being redeveloped by the Berwick-upon-Tweed Preservation Trust and tree-ring dating was requested by Catherine Dewar, Historic Areas Adviser at

English Heritage's Newcastle office to inform a Listed Building Consent application. The purpose of the analysis was to produce dating evidence from the timbers that may aid the interpretation of the historical development of the building.

In addition, this structural assemblage was dominated by conifer timbers, and hence provided a good opportunity to further the English Heritage research programme on the dendrochronological analysis of conifers. This ongoing research project has, when the opportunity has arisen, been investigating the viability and value of analysing conifer timbers from historic contexts (Groves 2000). The primary aim is to extend the scope of British dendrochronology to allow the production of dating evidence for conifer structures, the timbers of which, according to documentary evidence, forest history and recent dendrochronological studies (eg Groves 2002, Groves and Locatelli 2005, Howard *et al* 2006), are most likely to have been imported. Successful analysis has the benefit of not only providing dating evidence for the building under investigation, but also information relating to the source of the timber and hence the trade in timber.

Due to the potential difficulties associated with the analysis of imported conifers (eg Groves 2000; Groves 2004), a more extensive sampling strategy is usually applied. With this in mind, and in accordance with the specifications of the brief a total of 53 timbers were sampled. Each sample was given the code BWK-A (for Berwick-upon-Tweed) and numbered 01–53. The majority of the timbers associated with the central framework are pine (*Pinus* spp) although some of the pads are oak (*Quercus* spp). Twenty-five of these central timbers were sampled, 19 pine (BWK-A03–18 and BWK-A20–22) and six oak (BWK-A26–31). The timbers of the eastern and western framework were also seen to be pine and 21 of these were sampled (BWK-A32–41 and BWK-A43–53). Finally, seven of the joists, again all pine, were sampled (BWK-A01–02, BWK-A19, BWK-A23–5, and BWK-A42). The position of samples was noted at the time of sampling and has been marked on Figures 4–7. Further details relating to the samples can be found in Table 1. Timbers from all structures have been numbered from north to south.

ANALYSIS AND RESULTS

At this stage it was noticed that two of the samples (BWK-A48 and BWK-A51) taken from timbers of the east framework had too few rings to make secure dating a possibility and these samples was rejected prior to measurement. The remaining 51 samples were prepared by sanding and polishing and their growth-ring widths measured. The samples were divided into oak and pine and samples from each type compared with each other by the Litton/Zainodin grouping procedure (see Appendix). Oak sample measurements are given at the end of this report. As this analysis forms part of a wider research project to enable the dating of imported Baltic conifers in England, the ring series from the conifer timbers will be fully published and discussed as part of the final project publication.

Oak samples

At a least value of t=5.0, two groups had formed. Three samples matched each other and were combined at the relevant offset positions to form BWKASQ01, a site sequence of 152 rings (Fig 10). The remaining three oak samples matched each other and were combined at the relevant offset positions to form BWKASQ02, a site sequence of 305 rings (Fig 11). Attempts to date these two site sequences by comparing them against a large number of reference chronologies for oak, both from this country and other north European countries, proved unsuccessful. Bearing in mind the potential date of these sequences they were also tested against available North American oak reference data.

Pine samples

At a least value of *t*=4.5, 33 samples had formed ten groups. Four samples matched and were combined at the relevant offset positions to form BWKASQ03, a site sequence of 125 rings (Fig 12). This site sequence was then compared against a series of relevant reference chronologies for pine where it was found to have a consistent match at a first-ring date of AD 1701 and a last-ring date of AD 1825. The evidence for this dating is given by the *t*-values in Table 2.

The other nine site sequences (Figs 13–21) formed from small groups of matching samples were also initially compared with an extensive range of European pine reference chronologies, including those available from Scottish sites, which consist of both native and imported timbers, and subsequently with chronologies from Canada and the north-eastern area of the United States of America. No satisfactory cross-matching was identified for these remaining site sequences, nor was there any conclusive cross-matching for any of the ungrouped pine samples.

Details of all site sequences constructed:

Site Chronology	Species	No of Samples	Rings	Date span/undated
BWKASQ01	Oak	3	152	Undated
BWKASQ02	Oak	3	305	Undated
BWKASQ03	Pine	4	125	AD 1701–1825
BWKASQ04	Pine	6	217	Undated
BWKASQ04	Pine	3	175	Undated
BWKASQ05	Pine	5	119	Undated
BWKASQ06	Pine	4	145	Undated
BWKASQ07	Pine	2	79	Undated
BWKASQ08	Pine	2	164	Undated
BWKASQ09	Pine	3	175	Undated
BWKASQ10	Pine	2	148	Undated
BWKASQ11	Pine	2	188	Undated
BWKASQ12	Pine	3	143	Undated

DISCUSSION AND CONCLUSION

The tree-ring analysis has successfully dated only four of the pine timbers, one from the central framework (a fourth floor post), one from the west framework (again a fourth floor post), and two floor joists, one from the fourth floor and one from the first floor. Unfortunately, none of the samples have complete sapwood so it is not possible to prove whether all four represent a single felling. Given the great variation in number of sapwood rings in pine trees (eg Zetterberg and Hiekkanen 1990; Howard *et al* 2006), it is also not possible to calculate a felling date range, as would be the norm for oak, for these timbers. It can be said, however, that these samples are broadly coeval and, with all four having last measured sapwood ring dates in the nineteenth century, that none of them can be from the original mid-to-late eighteenth-century construction but that they probably all post-date the AD 1815 fire. Although it has therefore been possible to demonstrate the presence of some nineteenth-century timber likely to be associated with the post-AD 1829 reconstruction, the lack of dating evidence for the majority of the timber framework prevents the dendrochronological analysis showing whether or not the entire internal timber framework is the product of a single felling and construction event. The site sequence BWKASQ03 matches well against reference chronologies from south-east Norway, suggesting that these four timbers may have originated in this part of Europe (Table 2). This has the additional benefit of confirming that they are also therefore Scots Pine (*Pinus sylvestris* L.).

The failure to date any of the other pine samples is clearly disappointing, particularly in the light of the recent successes with various conifer assemblages (eg Howard *et al* 2006, Arnold *et al* 2007). However, dendrochronological dating of conifer timber in this country is in its infancy and the lack of success here should not be regarded as discouraging. One of the potential problems with the material from Dewar's Lane Granary is the possibility that the material represents multiple sources, as reflected in the number of small groups of cross-matched samples, and may also incorporate material of different date. This clearly hampers the successful production of well-replicated, and hence more readily dateable, site sequences. Erratic growth patterns where the ring widths change suddenly, either becoming very narrow or very wide, will also reduce the dating potential. Conifers, in particular, are subject to 'missing rings' where a tree either lays down a partial ring or fails to grow at all, false/shadow rings, and rings that wedge out (Schweingruber 1988, 47), all of which reduce the chances of successful cross-matching. Whilst the measured ring sequences and samples have been systematically checked for these potential measurement difficulties, it remains a possibility that at least some of the sequences could have unrecognised problems.

Although neither of the oak site sequences is particularly well-replicated both are long ring sequences which would ordinarily have been expected to have a reasonable chance of being dated successfully. It may be that the trees involved were subject to non-climatic growing conditions which have unduly influenced the growth pattern decreasing the dating potential. The oak samples were certainly derived from very slow grown trees with average ring widths ranging from 0.65mm to 1.08mm but they don't particularly suffer from erratic growth patterns. However, it is notable that very little oak reference data exists for the post-medieval period in this region and it remains a possibility that the oak timbers are imported from an area for which reference data is not readily available. The Laboratory have encountered difficulty in the past when trying to date timbers from the north-east of the country thought likely to be post-medieval in date (ie Mount Grace Priory Guesthouse, Arnold *et al* 2004; Ripon Cathedral, Arnold *et al* 2005).

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TABLES

Table 1: Details of tree-ring samples from Dewar's Granary, Berwick-upon-Tweed, Northumberland

Sample number	Sample location	Total rings*	Sapwood rings**	First measured ring date (AD)	Last heartwood ring date (AD)	Last measured ring date (AD)
Central framework (pine)						
4th Floor						
BWK-A03	Post 2	108	58	1701	1750	1808
BWK-A04	Post 6	94	21	----	----	----
BWK-A05	Axial beam, 2–3	61	36C	----	----	----
3rd Floor						
BWK-A06	Post 9	125	--	----	----	----
BWK-A07	Post 10	166	--	----	----	----
BWK-A08	Axial beam, 5–6	173	26	----	----	----
BWK-A09	Axial beam, 7–8	163	02	----	----	----
BWK-A10	Axial beam, 9–10	137	--	----	----	----
BWK-A11	Pad 10	102	42	----	----	----
2nd Floor						
BWK-A12	Post 1	140	28	----	----	----
BWK-A13	Post 8	206	38	----	----	----
BWK-A14	Post 5	344	75	----	----	----
BWK-A15	Axial beam, 1–2	94	41C	----	----	----
BWK-A16	Axial beam, 3–4	117	05	----	----	----
BWK-A17	Post 3	129	--	----	----	----
BWK-A18	Post 4	102	09	----	----	----
1st Floor						
BWK-A20	Axial beam, 6–7	126	29C	----	----	----
BWK-A21	Axial beam, 5–6	105	08	----	----	----
BWK-A22	Axial beam, 3–4	166	31	----	----	----

Central framework (oak)						
4th Floor						
BWK-A26	Pad 4	66	--	----	----	----
BWK-A27	Pad 9	179	14	----	----	----
3rd Floor						
BWK-A28	Pad 1	199	02	----	----	----
BWK-A29	Pad 7	122	09	----	----	----
2nd Floor						
BWK-A30	Pad 11	100	--	----	----	----
BWK-A31	Pad 2	201	--	----	----	----
East and West framework (pine)						
4th Floor						
BWK-A32	East post 3	58	27	----	----	----
BWK-A33	East post 4	86	24	----	----	----
BWK-A34	West post 11	103	41	1723	1784	1825
BWK-A35	East post 9	108	75C	----	----	----
3rd Floor						
BWK-A36	East post 4	55	--	----	----	----
BWK-A37	West post 7	132	48	----	----	----
BWK-A38	West post 9	112	33	----	----	----
BWK-A39	West post 10	93	12	----	----	----
BWK-A40	West rail, 9–10	76	14	----	----	----
BWK-A41	East rail, 3–4	147	--	----	----	----
2nd Floor						
BWK-A43	West post 2	81	05	----	----	----
BWK-A44	East rail, 3–4	111	20	----	----	----
BWK-A45	East post 4	60	--	----	----	----
BWK-A46	East post 8	124	45	----	----	----
BWK-A47	East rail, 2–3	75	--	----	----	----

BWK-A48	East post 9	NM	--	----	----	----
BWK-A49	West post 10	109	22	----	----	----
BWK-A50	West post 1	90	16	----	----	----
1st Floor						
BWK-A51	East rail, 9–10	NM	--	----	----	----
BWK-A52	West post 8	62	--	----	----	----
BWK-A53	East rail, 7–8	61	33	----	----	----
Joists						
4th Floor						
BWK-A01	Common joist 6 (from north)	55	04	----	----	----
BWK-A02	Common joist 5 (from north)	93	29	1716	1779	1808
3rd Floor						
BWK-A42	West joist 46	104	46	----	----	----
1st Floor						
BWK-A19	Common joist 35	72	43	----	----	----
BWK-A23	East joist 41	162	52C	----	----	----
BWK-A24	East joist 39	98	27C	----	----	----
BWK-A25	West joist 34	68	39	1738	1766	1805

*NM = not measured
**h/s = the heartwood/sapwood ring is the last ring on the sample
C = complete sapwood retained on sample, last measured ring is the felling date

Table 2: Results of the cross-matching of site sequence BWKASQ03 when the first-ring date is AD 1701 and the last-measured ring date is AD 1825

Reference chronology	*t*-value	Span of chronology	Reference
Norway Jondalen	10.66	AD 1605–1981	Briffa *et al* 1986
Sweden Dalarna	7.04	AD 1001–1852	Bartholin pers comm
Norway Hurdal	6.93	AD 1678–1981	Briffa *et al* 1986
Norway south-east	6.49	AD 871–1986	Thun pers comm
UK Imports:			
Wallace Collection, London	6.69	AD 1604–1773	C Tyers pers comm
Crucible Works, Sheffield	6.57	AD 1650–1804	I Tyers pers comm
Millers House, Bromley by Bow, London	6.16	AD 1607–1762	Arnold *et al* forthcoming
Godolphin House, Cornwall	4.06	AD 1528–1769	Tyers and Tyers forthcoming

FIGURES

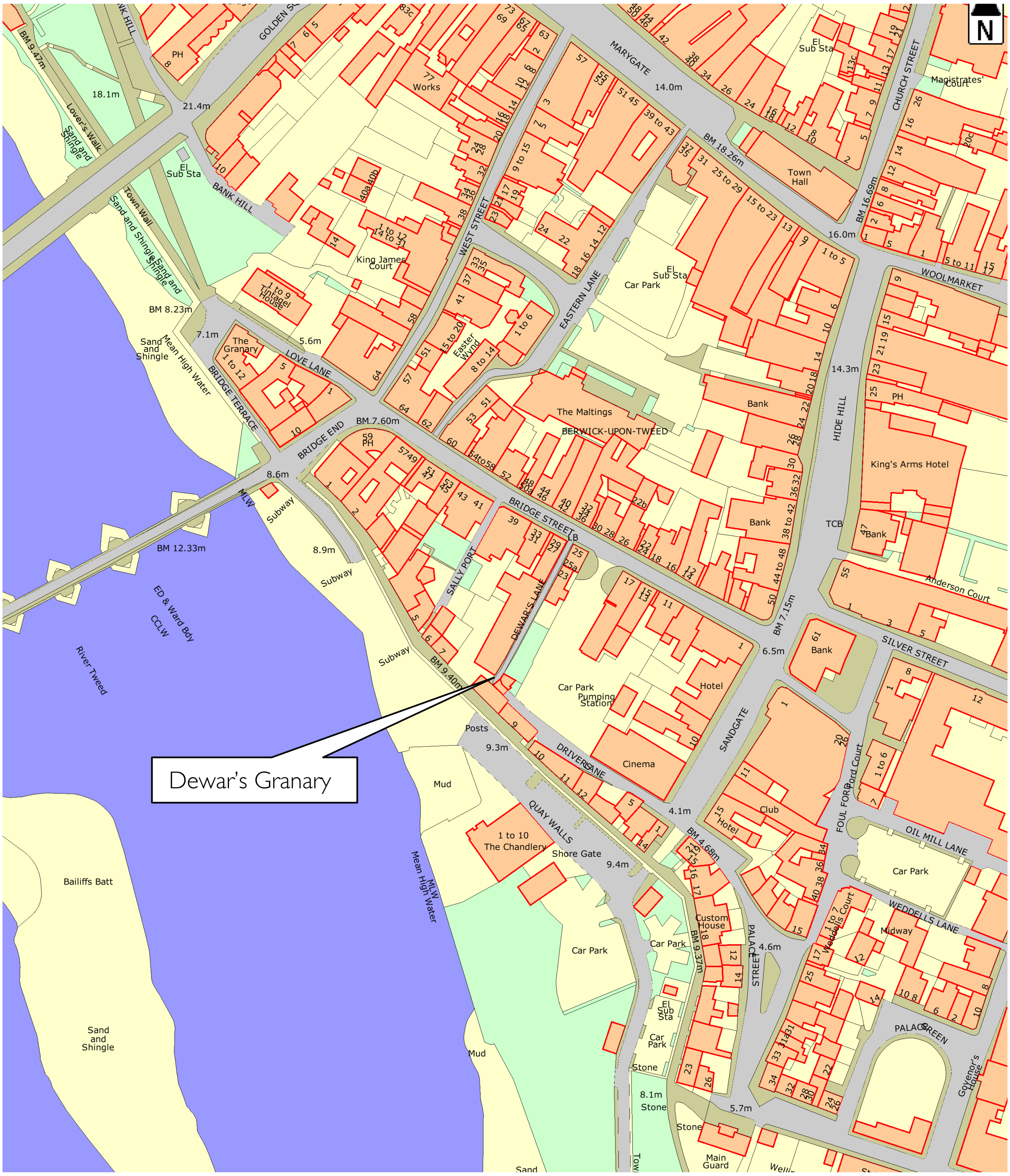

Figure 1: Map to show the location of Dewar's Granary, Berwick-upon-Tweed, Northumberland

Based on the Ordnance Survey map with permission of the Controller of Her Majesty's Stationery Office, © Crown Copyright

Figure 2: Second floor, looking north

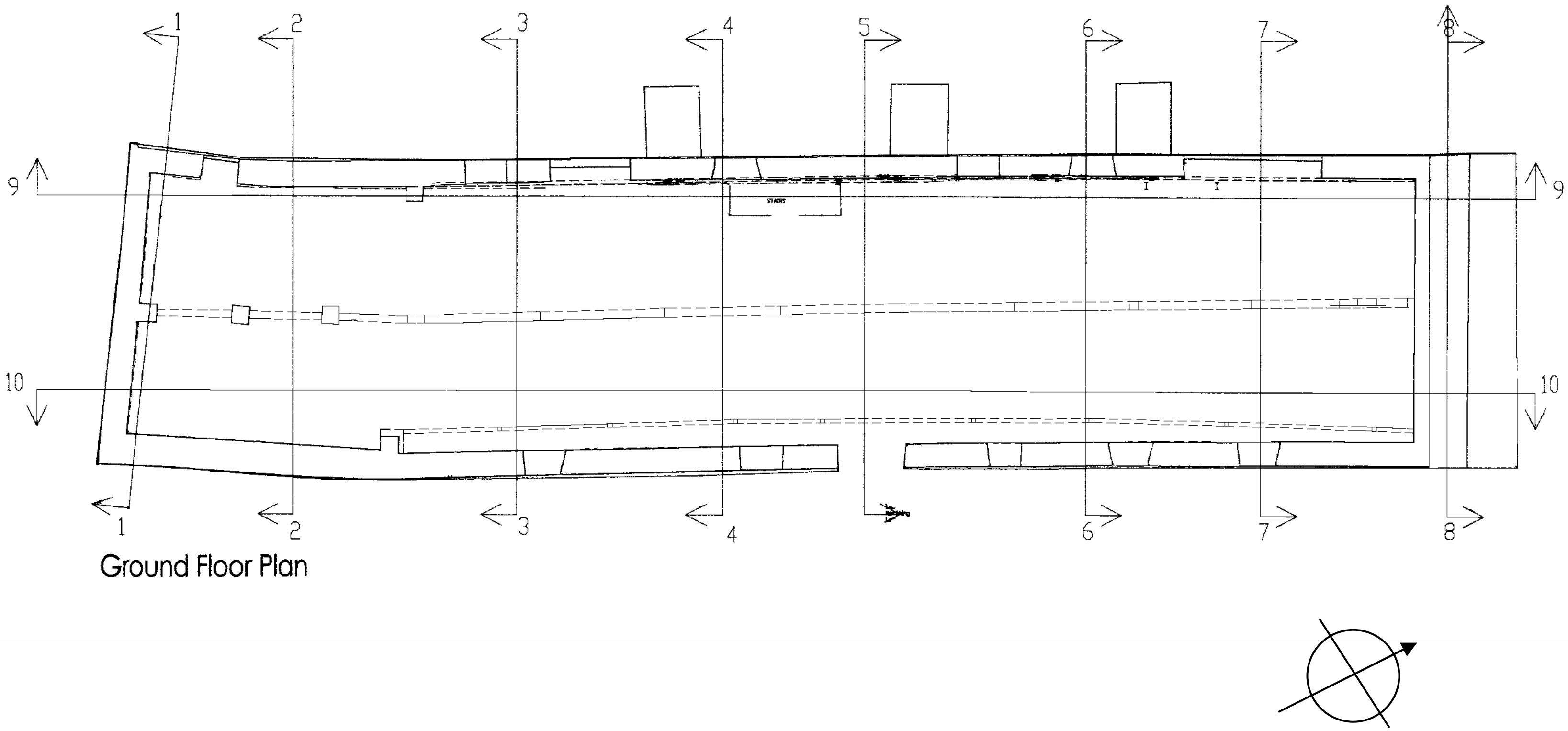

Figure 3: Ground-floor plan (Bain, Swan Architects)

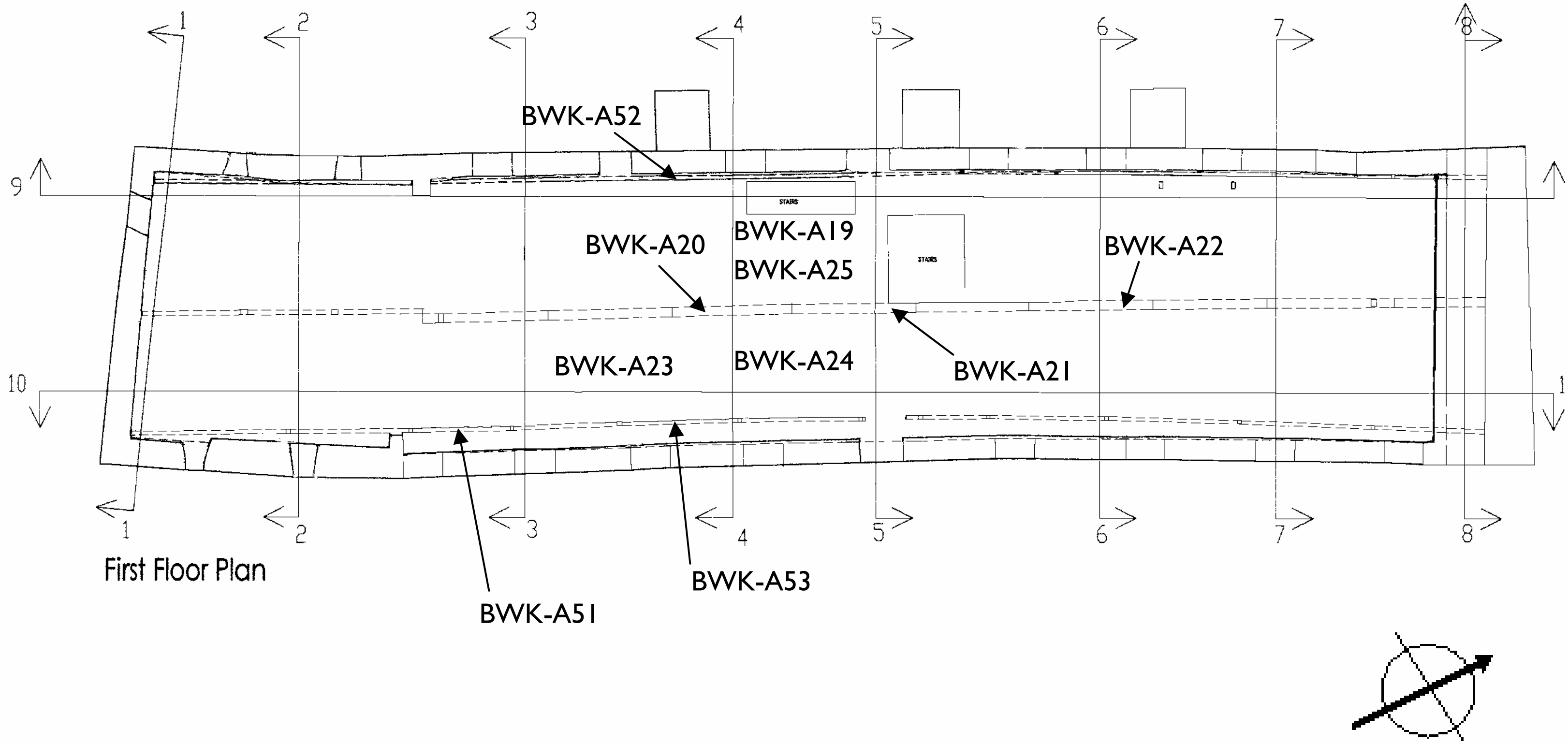

Figure 4: First-floor plan showing the location of samples BWK-A19–25 and BWK-A51–3 (Bain, Swan Architects)

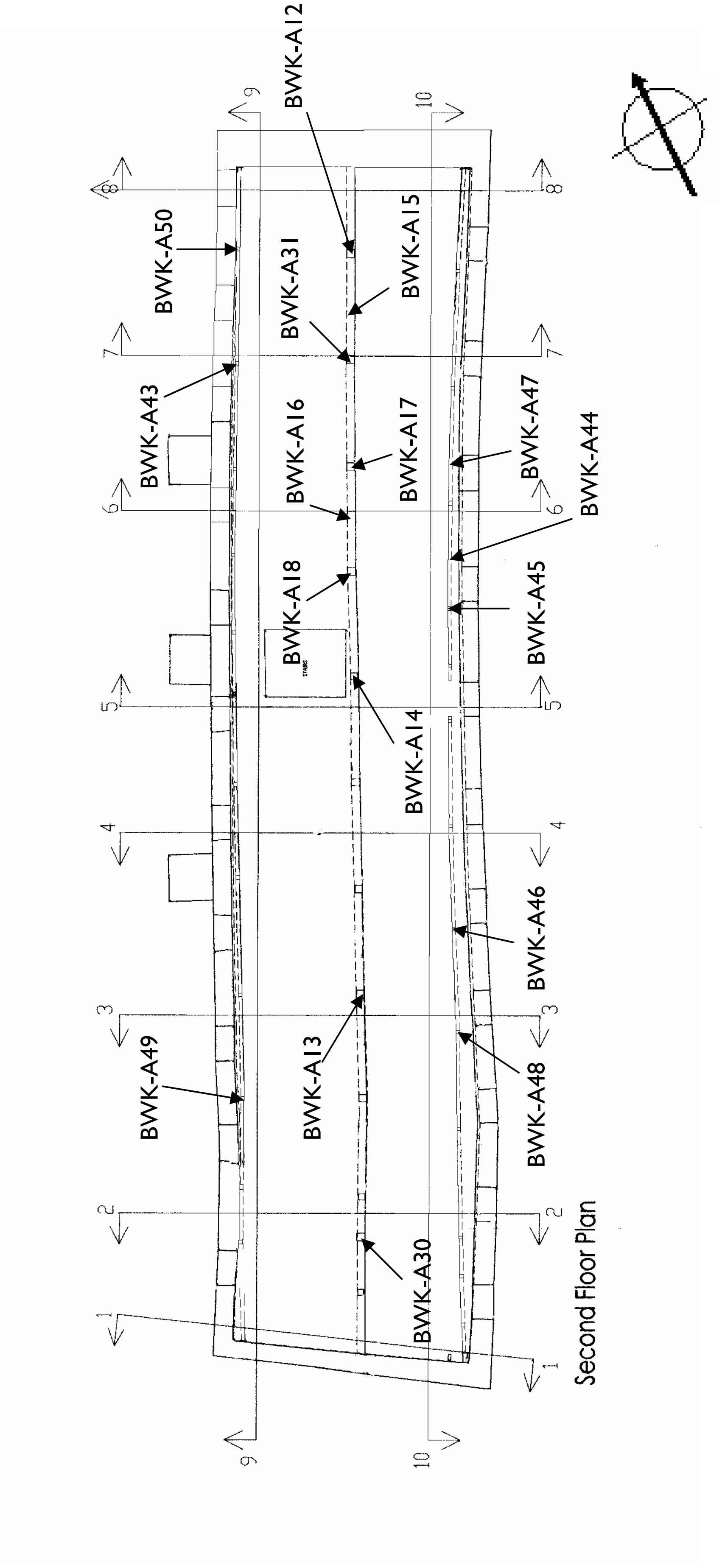

Figure 5: Second-floor plan showing the location of samples BWK-A12–18, BWK-A30–1, and BWK-A43–9 (Bain, Swan Architects)

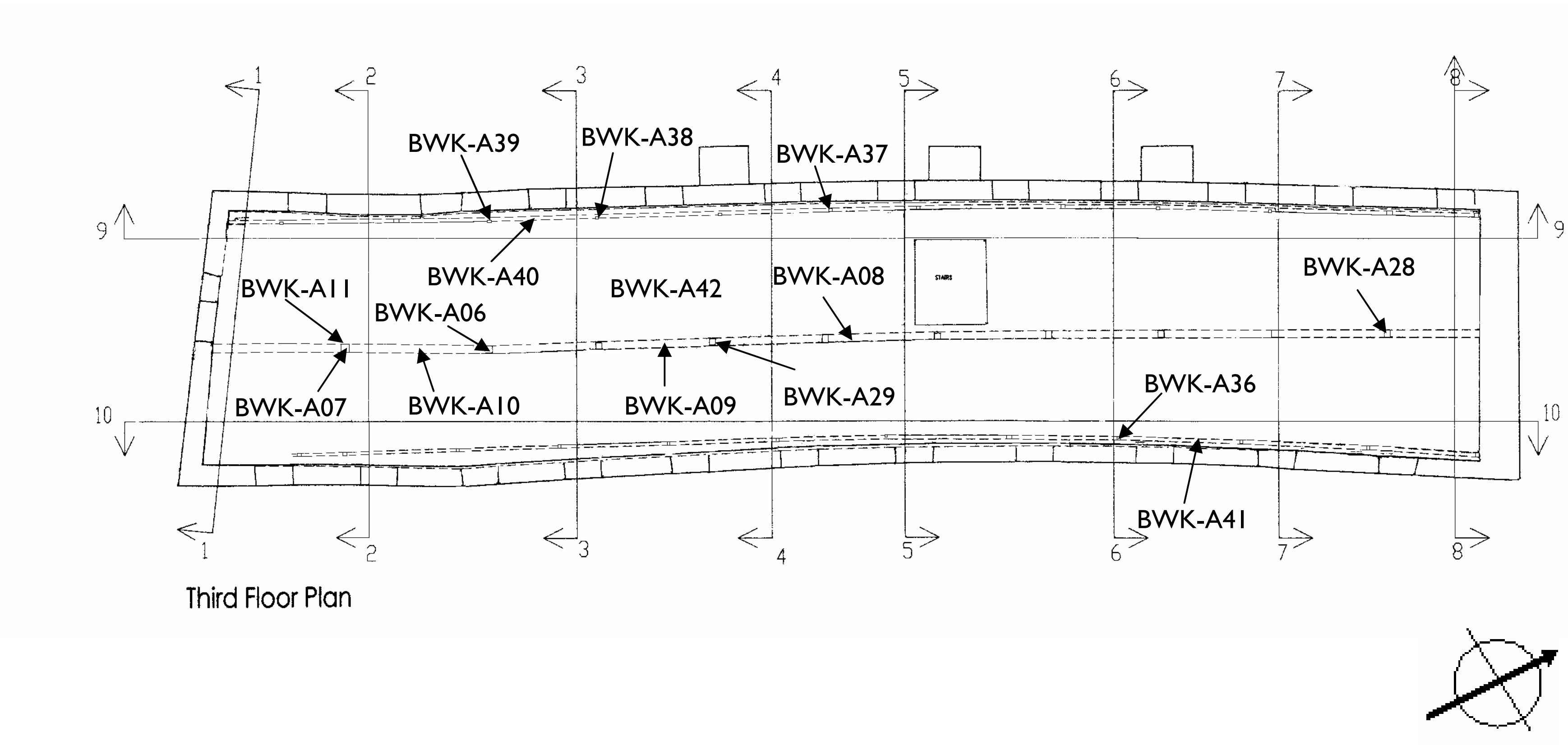

Figure 6: Third-floor plan showing the location of samples BWK-A06–11, BWK-A28–9, and BWK-A36–42 (Bain, Swan Architects)

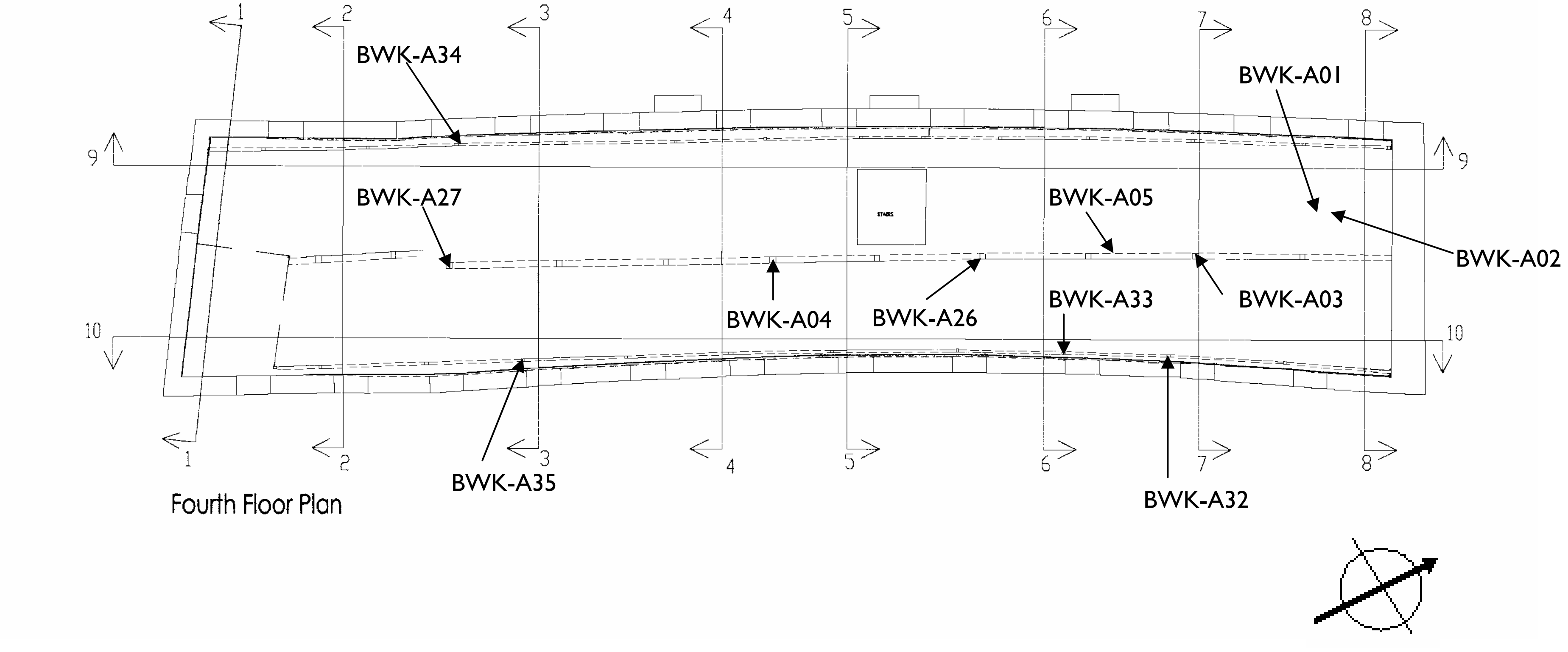

Figure 7: Fourth-floor plan showing the location of samples BWK-A01–05, BWK-A26–7, and BWK-A32–5 (Bain, Swan Architects)

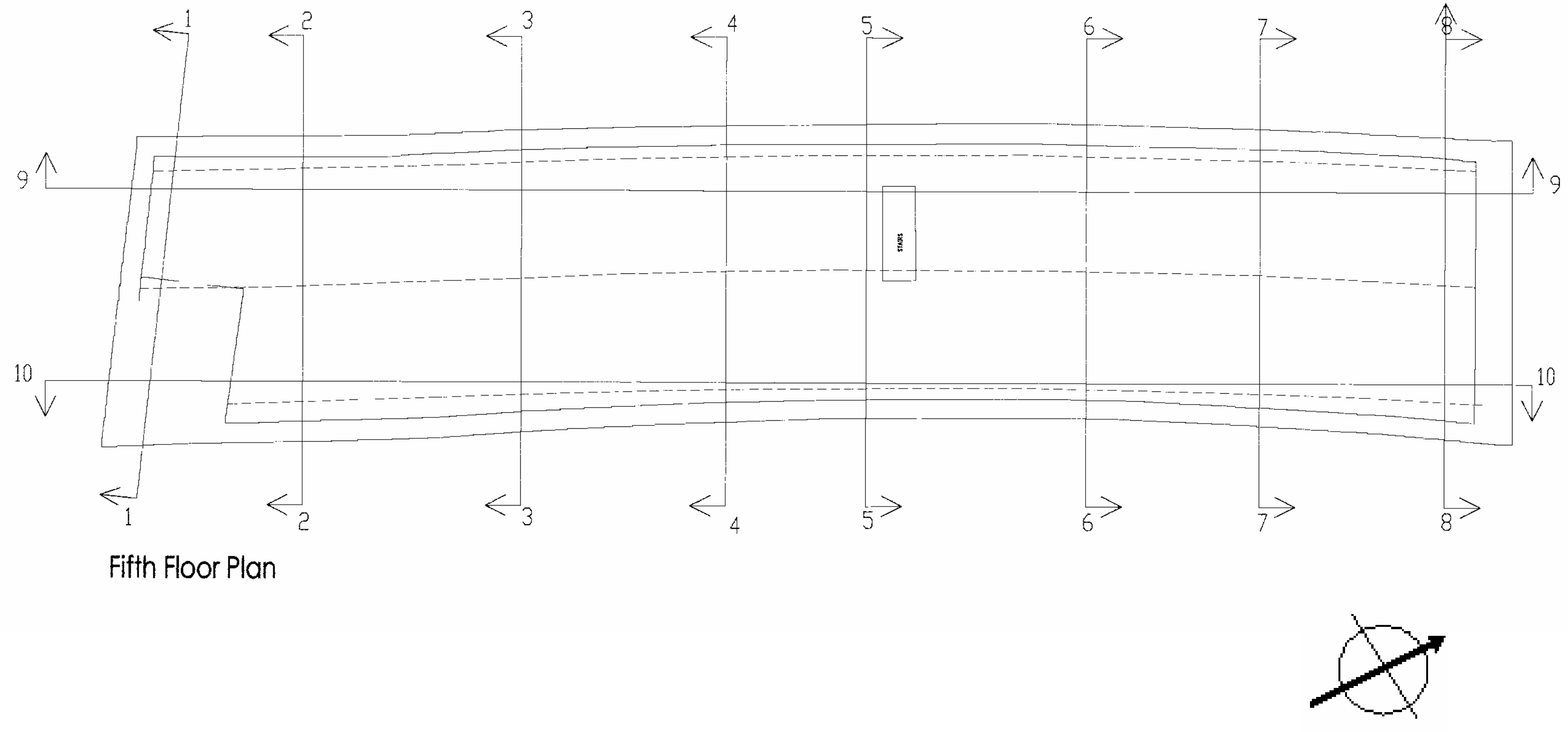

Figure 8: Fifth-floor plan (Bain, Swan Architects)

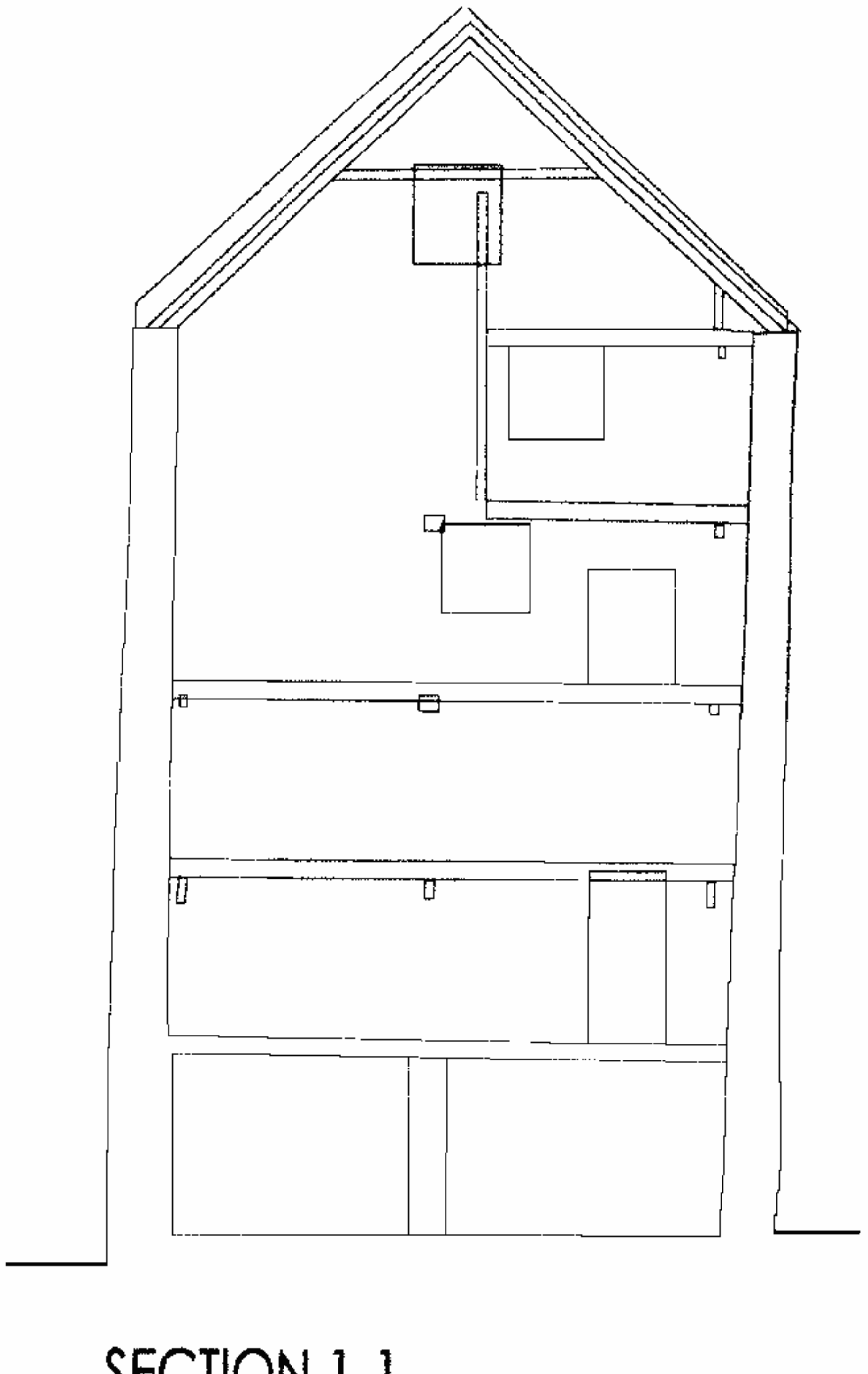

Figure 9: Section 1–1 (Bain, Swan Architects)

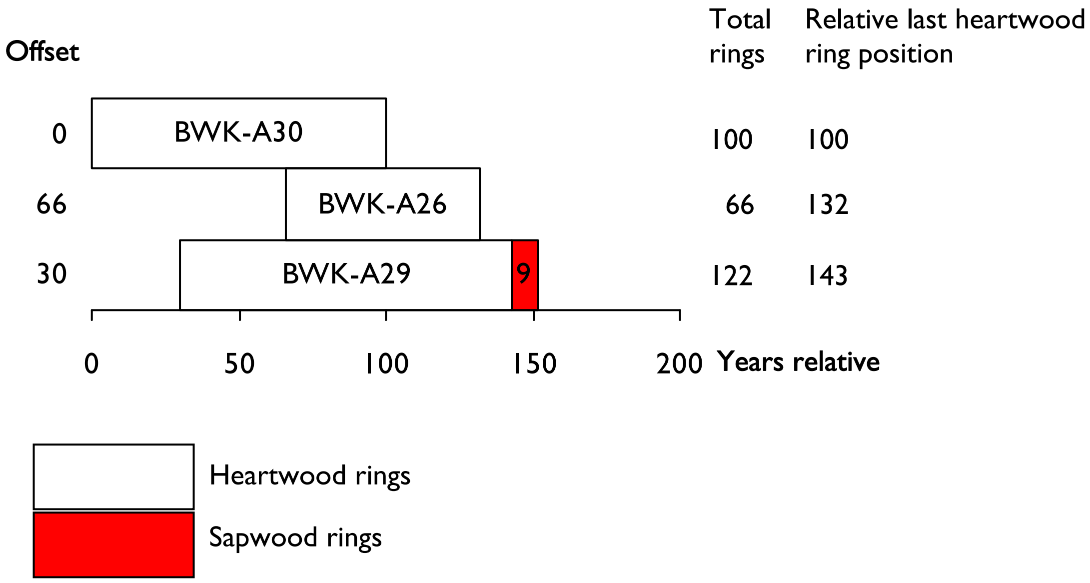

Figure 10: Bar diagram of samples in undated site sequence BWKASQ01

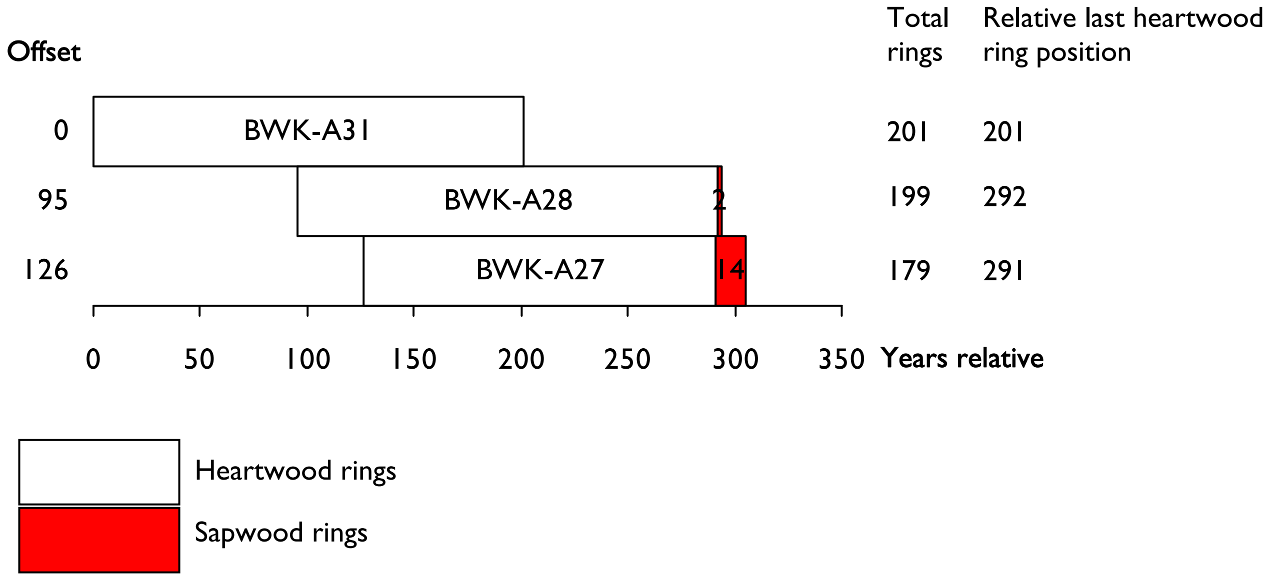

Figure 11: Bar diagram of samples in undated site sequence BWKASQ02

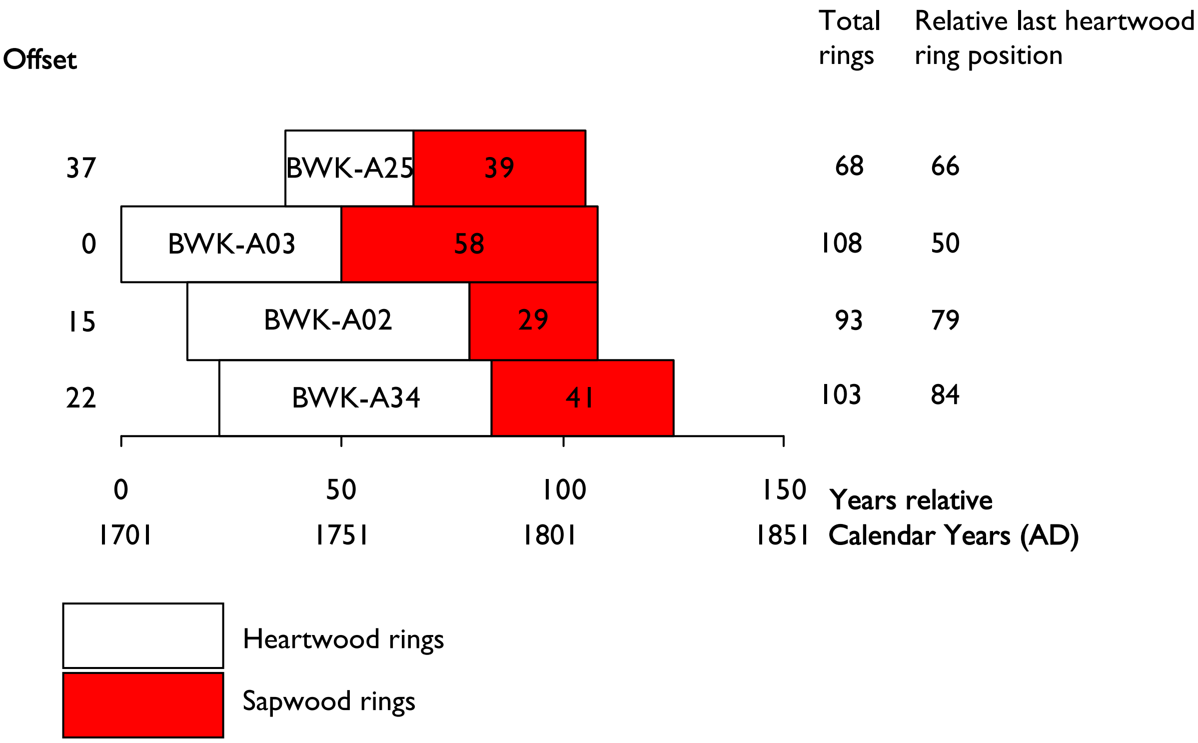

Figure 12: Bar diagram of samples in site sequence BWKASQ03

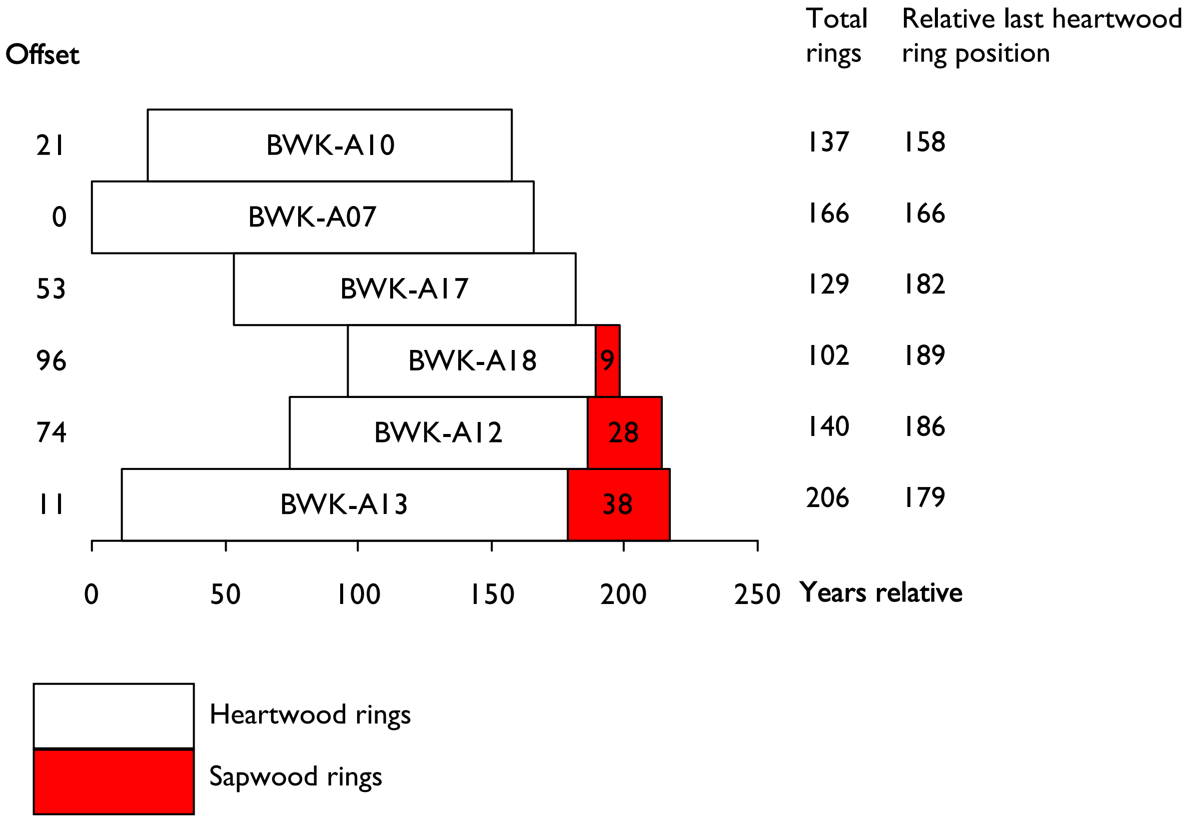

Figure 13: Bar diagram of samples in undated site sequence BWKASQ04

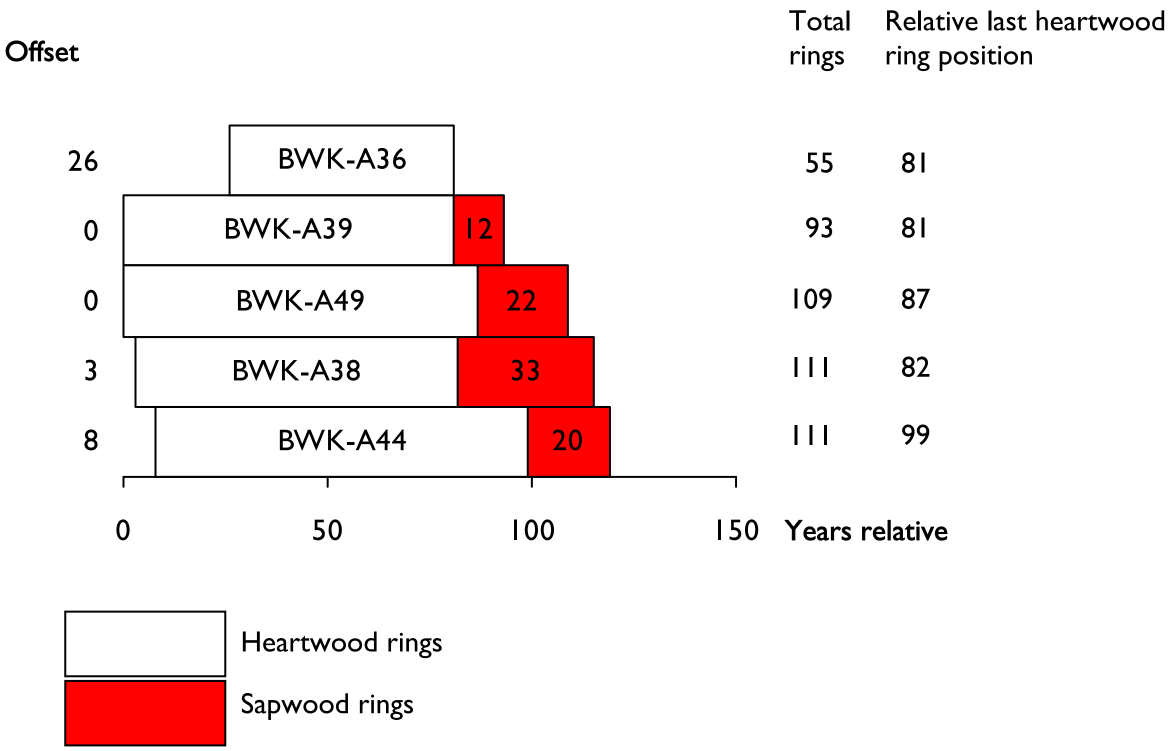

Figure 14: Bar diagram of samples in undated site sequence BWKASQ05

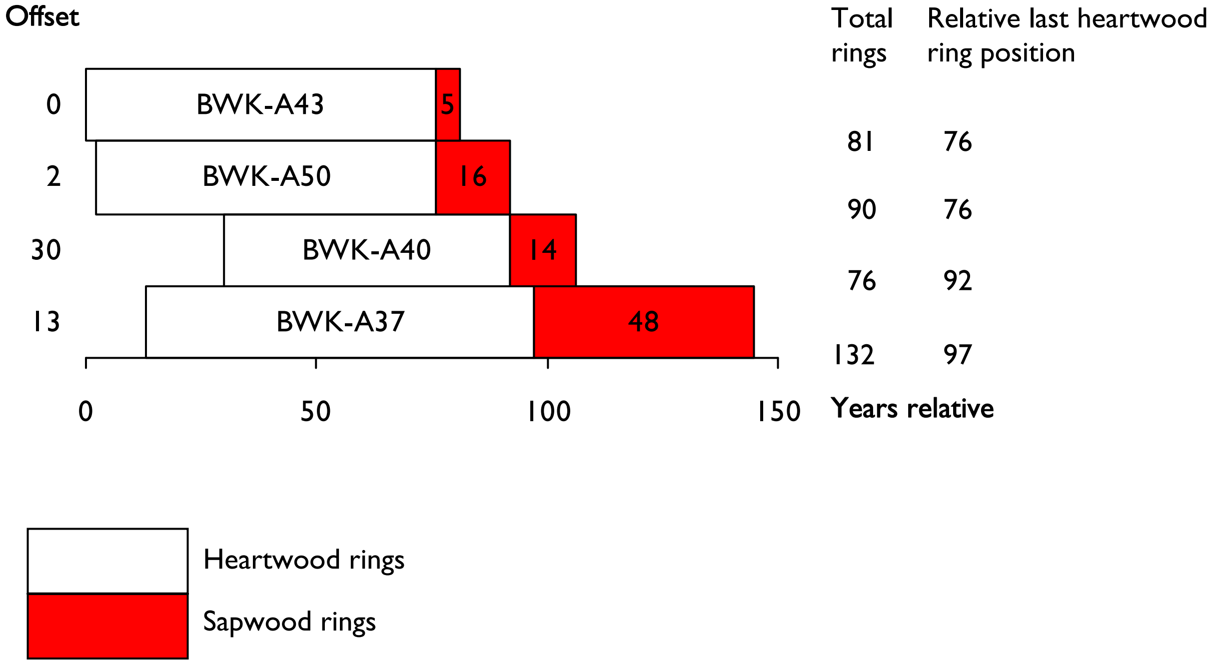

Figure 15: Bar diagram of samples in undated site sequence BWKASQ06

Figure 16: Bar diagram of samples in undated site sequence BWKASQ07

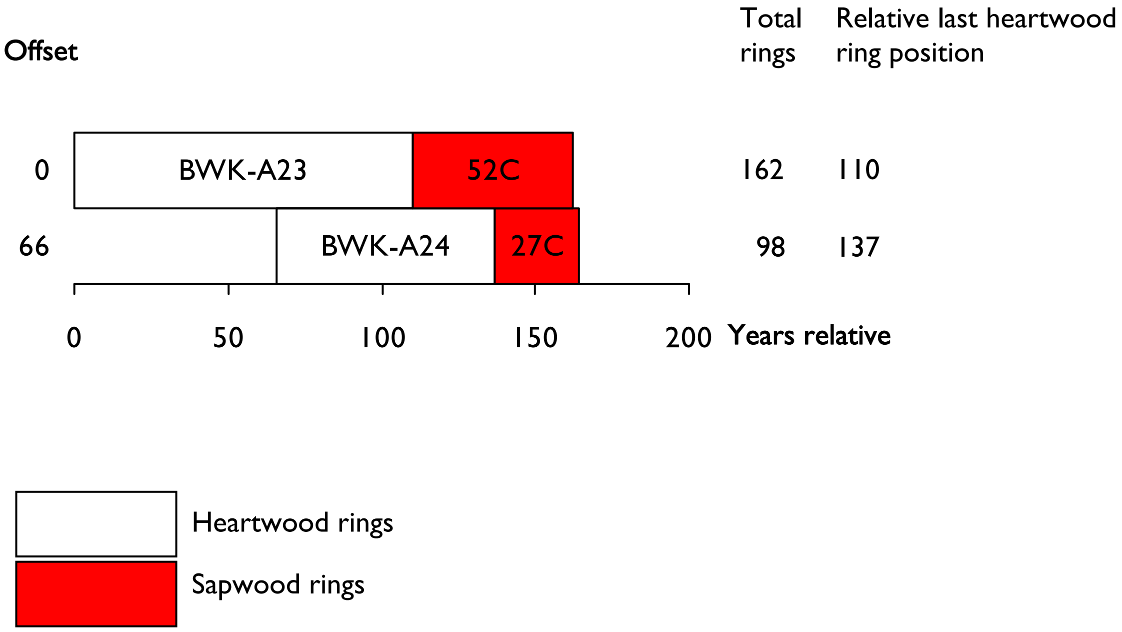

Figure 17: Bar diagram of samples in undated site sequence BWKASQ08

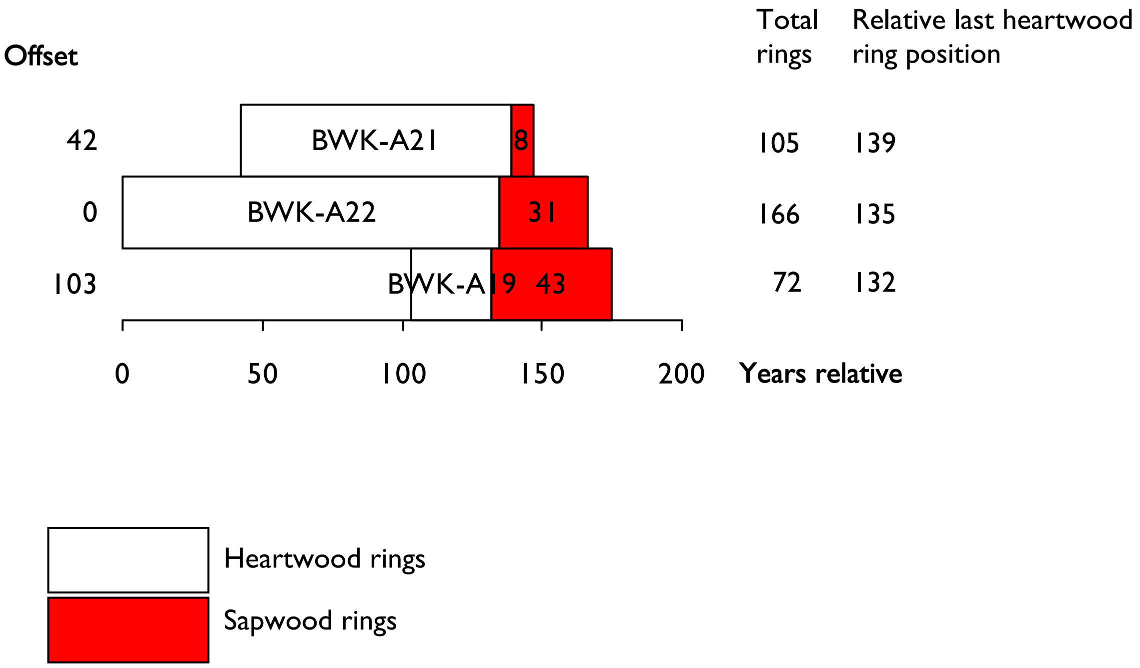

Figure 18: Bar diagram of samples in undated site sequence BWKASQ09

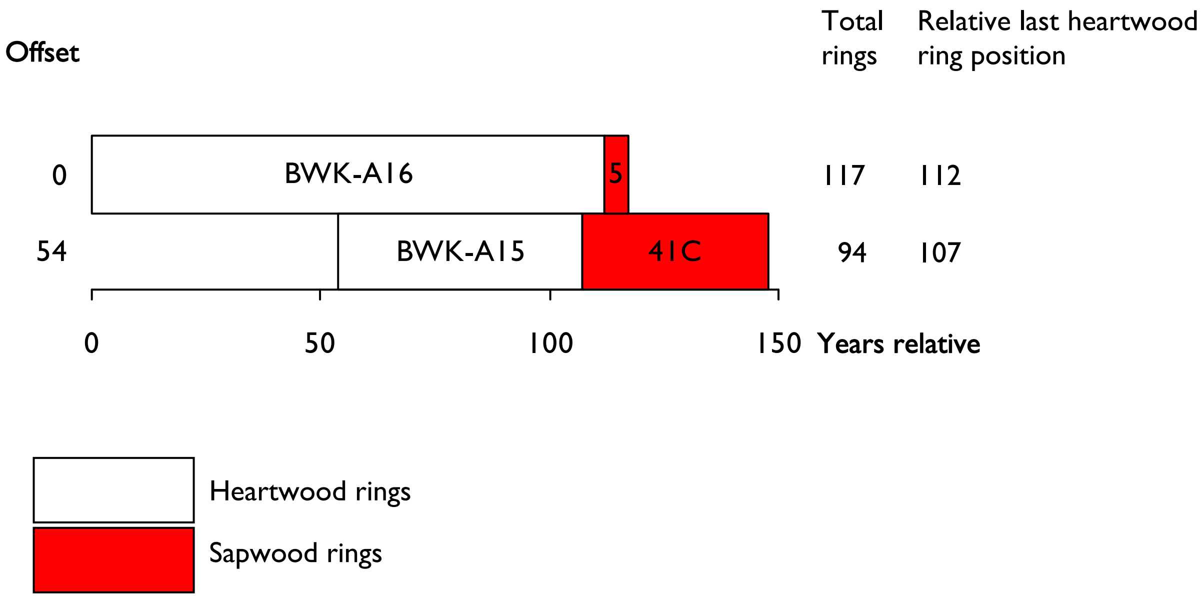

Figure 19: Bar diagram of samples in undated site sequence BWKASQ10

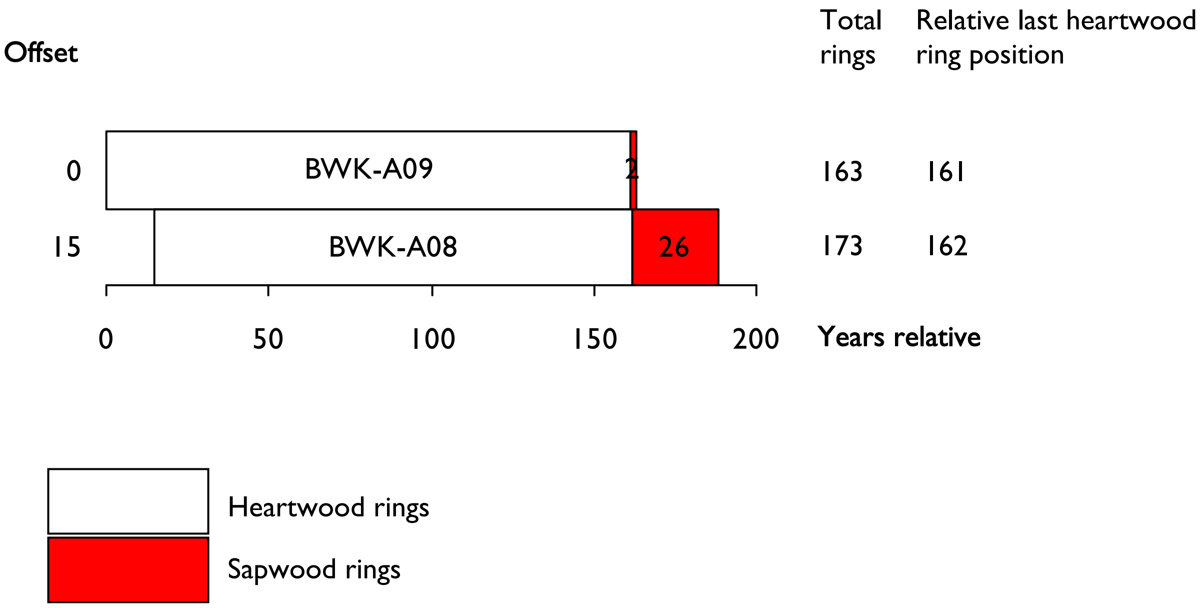

Figure 20: Bar diagram of samples in undated site sequence BWKASQ11

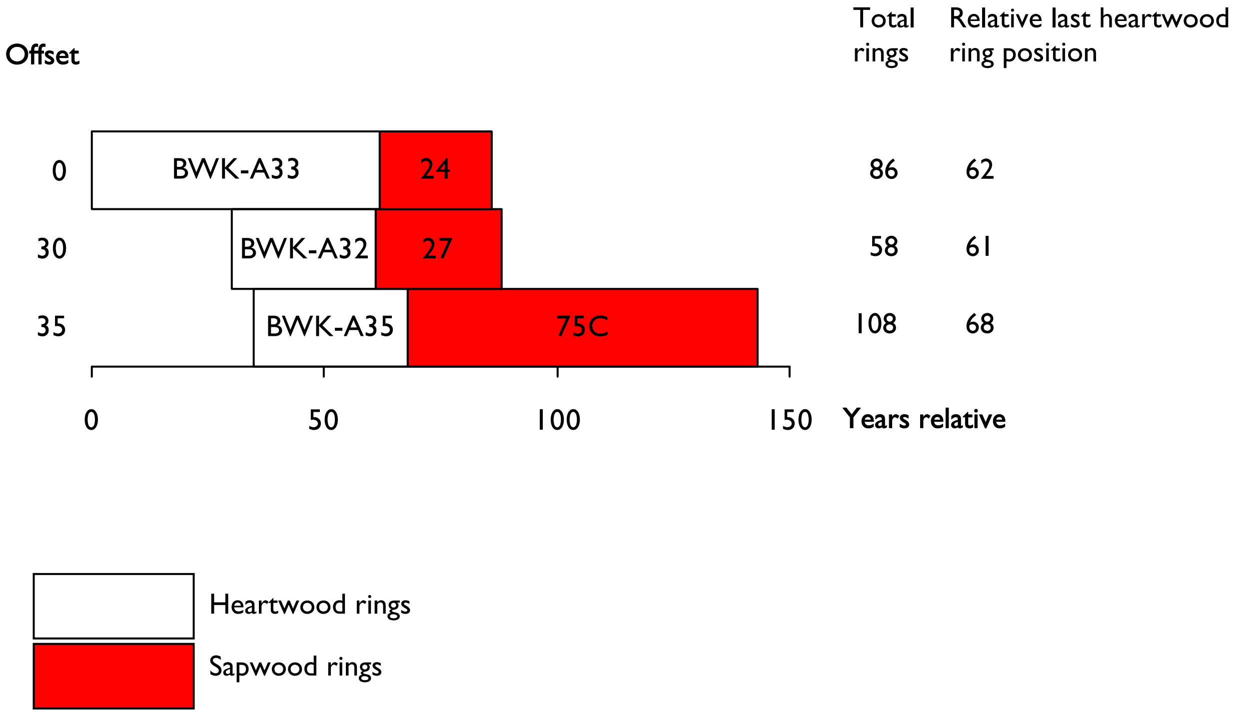

Figure 21: Bar diagram of samples in undated site sequence BWKASQ12

DATA OF MEASURED OAK SAMPLES

Measurements in 0.01mm units

```
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 133  78  89  73  79  69  55  64  70 105  93  91 120  94  70  76  89  69  99  81
  81  73  78  64  63  66  56  57  54  57  42  51  45  37  31  34  36  53  44  55
  38  32  38  49  53  69  81  56  66  45  56  57  70  70  58  65  58  47  66  67
  48  58  59  48  50  81
BWK-A26B 66
 120 105 101 100  90  80  41  59  76  96  82  94 126  96  71  81  95  74  92  81
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  36  30  35  50  52  60  85  51  67  53  50  61  69  62  45  75  48  56  68  61
  51  56  57  45  57  87
BWK-A27A 179
  73  90  73  94  60  69  70  60  62  52  53  37  57  47  59  62  64  46  66  55
  60  53  47  57  50  62  69  73  64  77  60  64  81  89  50  59  69  67  68  81
  69  47  53  58  57  50  67  67  69  80  79  87  78  73  66  72  67  78  78  67
  91 103 105  99  96  94  74  76  82  71  77  82  85  63  91 102  96  87  98  77
  73  72  71  73  79  86  76  76  63  83  90 117  89  87  79 102  89 119 156 173
 107 118 140 143 134  93 103 142 100 125 122 112 102  65  91  82  86  74  80  88
  95  77  86  99  92  86  85  76  87  65  55  80  72  52  93  84  82  80  89  69
  94 103  99  76  85  78  70  86  93  82  80  86  90  95 101  89  76  60  74  90
  77  88  95  84  72  94  82  98  85 121 102 105 117  93  87  96  76  92  69
BWK-A27B 179
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  71  43  55  54  53  44  75  65  67  75  71  91  75  81  63  63  72  67  83  62
  83  91 107  87 104  85  79  70  85  71  81  86  69  66  97 109  94  88  94  82
  72  77  59  81  72  95  74  73  75  74 101 105  88  84  97  97  87 122 162 180
 103 113 120 140 121 108  94 157 115 138 122 114 114  75  94  89  92  69  96  82
  98  73 100  86  97  83  85  73  96  67  60  72  73  68  82  80  89  71  85  75
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BWK-A28A 199
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 131 107  68 118  72 108  71  86 103 119  63 138  74  81  89  85  81  96  73  96
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BWK-A28B 199
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  59  83
BWK-A29B 122
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  57  86
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 108 101 117 115  95 113 131  97 115 106  99 118  82  89  98 123 114  85  98  83
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  99 120  98  92 111  77 105 101 102  97 104 124  82 144 108 113 104  90  90  63
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 112  99 115 111  99 109 128  98 114  98 111 115  83  83 101 123 102  86  90  80
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 111 138 150 136 133 111 118  96 102  88 114  64 130  91  91  73  98  89  98 107
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  83
BWK-A31B 201
 112 102  73 118 101  87  39  43  41  46  43  31  40  50  26  30  47  36  38  24
  20  28  37  34  47  53  61  51  68  81  63  69  72  64  98  43  64  79 100 104
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 120  57  78 105 119  70 116  91 107 113 107 117  99 110 114  95 130  98 115 125
 137 111 108  79 112 114 103  99 104 101 116 102 113  89 104 122  92  96  92 120
 100 125 155 148 133  91 124  95  99  99 107  68 127  97  81  84  87  91 100  92
 106 107 102 110 121  88 109  90  80  97  83  85  77  75  76  82  72  66  96  79
  98
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APPENDIX: TREE-RING DATING

The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1988). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure 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.

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	

Bar Diagram

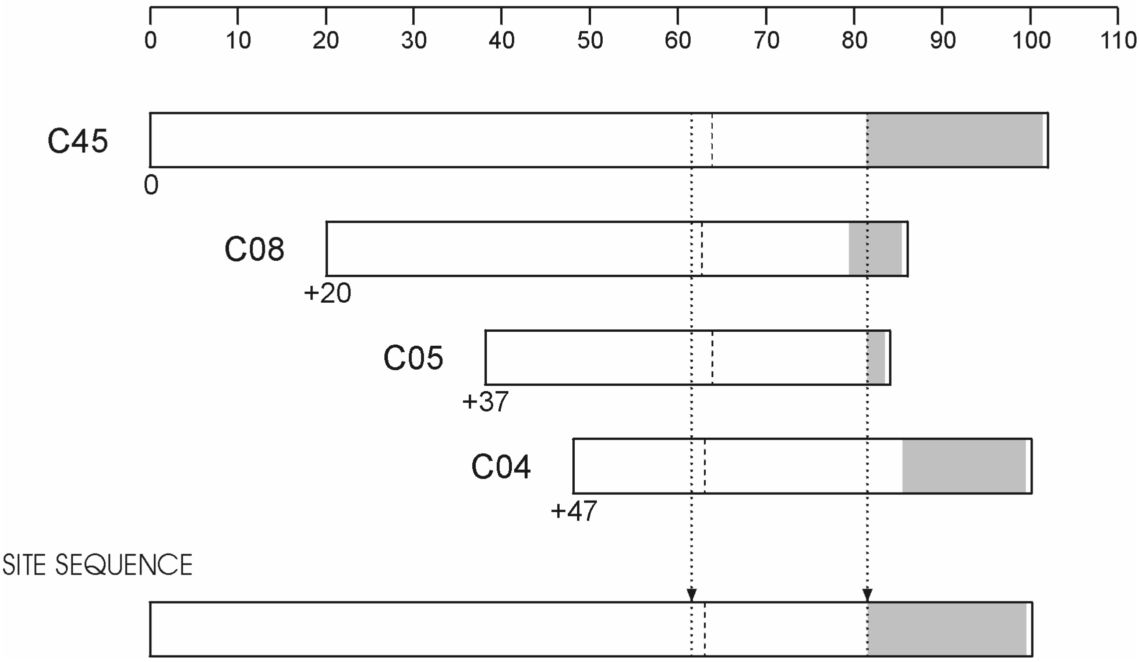


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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

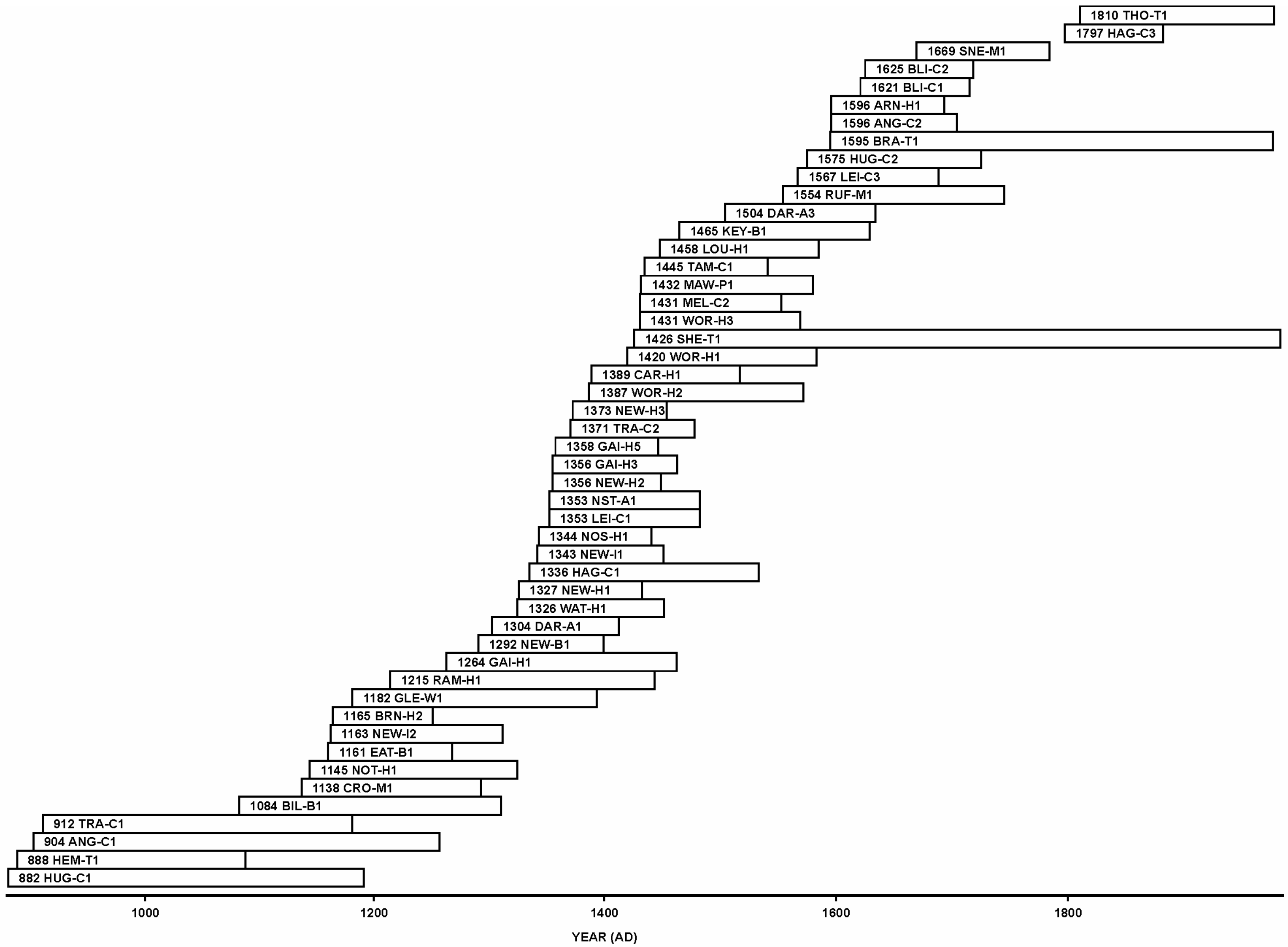
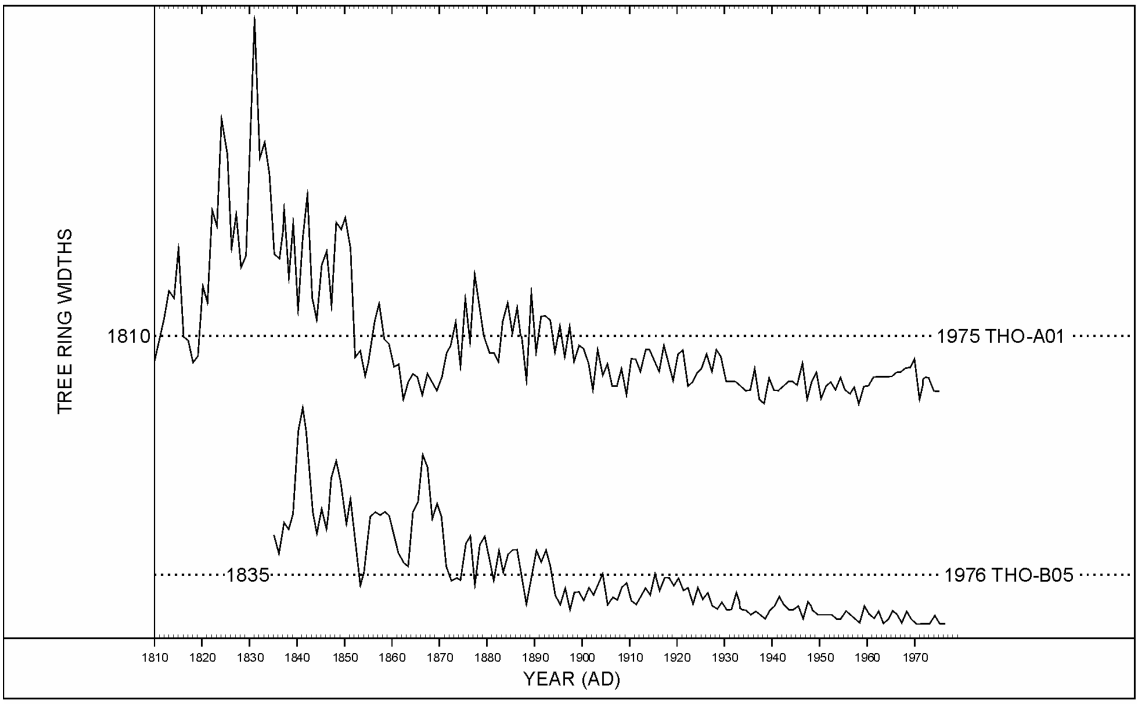


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

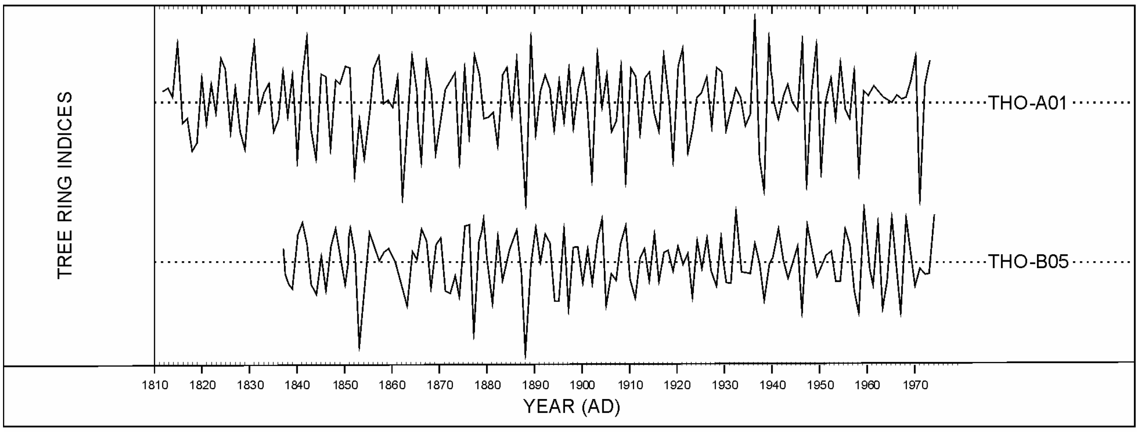


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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