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69 Newgate Street, Bishop Auckland, Co. Durham

Tree-ring Analysis and Radiocarbon Wiggle-matching of Pine Timbers

Alison Arnold, Robert Howard, Cathy Tyers, Dana Challinor, Bisserka Gaydarska and Michael Dee

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Summary

Tree-ring analysis was undertaken on 10 of the 12 samples obtained from the pine timbers to this roof. This analysis produced two site chronologies. The first site chronology (BSAASQ01) comprises seven samples and is 74 rings long overall, the second site chronology (BSAASQ02) comprises two samples and is 96 rings long overall. Although compared to an extensive body of reference data for pine, neither site chronology was considered conclusively dated by dendrochronology. The single remaining measured but ungrouped sample was also compared to the reference chronologies for pine, but again no secure dating was identified.

Radiocarbon dating was undertaken on nine single-ring samples from two timbers represented in the tentatively dated site master chronologies. Wiggle-matching of these results suggests that the final ring of site master sequence BSAASQ01, formed in *cal AD 1739–1753 (58% probability*) or *cal AD 1926–1942 (37% probability),* while the final ring of site master sequence BSAASQ02 formed in *cal AD 1742–1760 (59% probability*), or *cal AD 1855–1891 (30% probability)*, or *cal AD 1930–1946 (6% probability)*.

The tentative cross-matching identified for the site master chronologies by ring-width dendrochronology is thus supported independently by the radiocarbon wiggle-matching, allowing dating of BSAASQ01 to be accepted when it spans AD 1676–1749_{DR} and dating of BSAASQ02 to be accepted when it spans AD 1655–1750_{DR}.

The nine dated timbers are clearly coeval, but the wide variation in numbers of sapwood rings across Scandinavia means that it is not possible to estimate a felling date range for these timbers. Allowing for the missing sapwood, however, it is possible to suggest that the timbers used in the roof were felled in the latter half of the eighteenth century or possibly in the early nineteenth century.

Contributors

Alison Arnold, Robert Howard, Cathy Tyers, Dana Challinor, Bisserka Gaydarska and Michael Dee

Acknowledgements

Firstly, we would like to thank the owner of 69 Newgate Street, Mr Graham Thomas, for his enthusiasm and interest in this programme of tree-ring analysis, and for his unstinting help in arranging access for sampling. We would also like to thank the on-site contacting staff for their help on the day of sampling. Various dendrochronological colleagues from the British Isles and elsewhere in Europe, particularly Anne Crone, Aoife Daly, Marta

Dominquez-Delmas, and Coralie Mills, are thanked for allowing access to their data, We are grateful to Clare Howard (Historic England Architectural Investigator North East and Yorkshire Region) for commissioning this work. Finally, we would like to thank Shahina Farid (Historic England Scientific Dating Team) for facilitating this programme of tree-ring analysis.

Front cover image

69 Newgate Street in 2023 (photograph provided by Clare Howard)

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Introduction

The unlisted building at 69 Newgate Street, Bishop Auckland (Fig. 1), stands to the east side of the street, very close to the centre of the town. The low front elevation and steeply pitched roof of the main front range of this building suggests that it is an early survivor, potentially pre-eighteenth century. The roof (Figs 2–6), running from north to south in this front range, comprises two principal-rafter with tiebeam trusses, set between the north and south gable walls of brick, the trusses supporting two rows of purlins to each pitch of the roof. The purlins in turn supported (modern) common rafters. The principal rafters protrude through a panelled ceiling and are embedded into the wall.

Dendrochronology was commissioned as one of the supporting elements to the Bishop Auckland's Heritage Action Zone (HAZ), an initiative created to improve the town's historic centre and bring it back to being a vibrant market town for both locals and visitors.

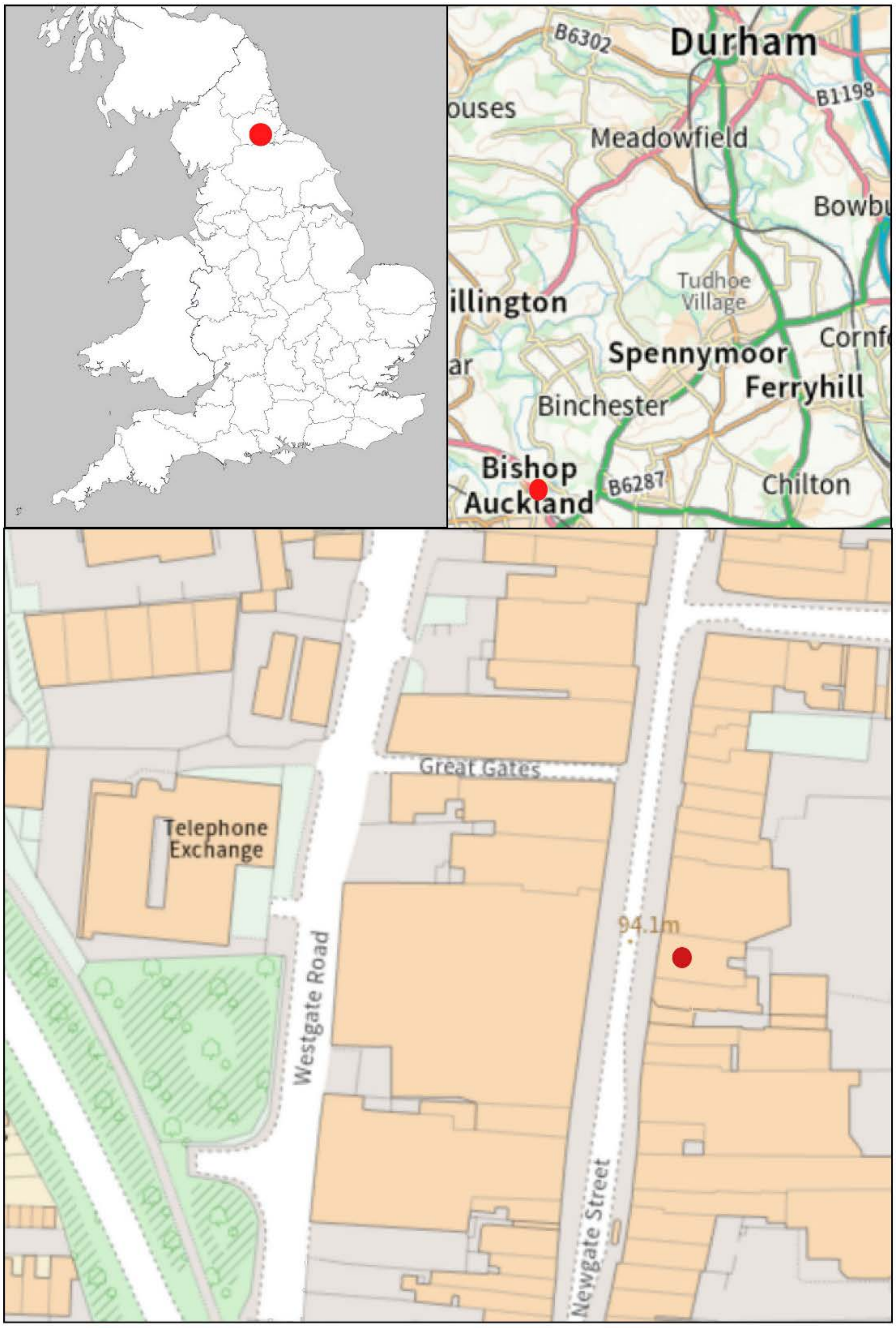

Figure 1 Maps to show the location of 69 Newgate Street, Bishop Auckland, in red. Scale: top right 1:200,000; bottom 1:1,600. © Crown Copyright and database right 2024. All rights reserved. Ordnance Survey Licence number 100024900

Sampling

Dendrochronological analysis was requested by Clare Howard, Historic England Architectural Investigator North East and Yorkshire Region, to provide independent dating evidence of this potentially early surviving building.

An initial assessment of the timbers in the various parts of the building revealed that all the extant timbers appeared to be conifer and, although the majority of these appeared to be part of modern, twentieth-century, works, there were some, particularly in the roof of the room on the street frontage, which appeared to be possibly older. These potentially older timbers comprised the two principal-rafter with tiebeam trusses and the double row of purlins to each pitch of the roof.

Thus, from the potentially suitable roof timbers available, a total of 12 samples was obtained by coring. Each sample was given the code BSA-A (for Bishop Auckland, site ‘A’) and numbered 01–12. These sampled timbers have been located on a series of annotated photographs (Figs 2-6), the trusses being numbered from north to south. Details of the samples are given in Table 1.

Table 1: Details of tree-ring samples from 69 Newgate Street, Bishop Auckland, Co. Durham

Sample number	Sample location	Total rings	Sapwood rings	First measured ring relative date	Last heartwood ring relative date	Last measured ring relative date
BSA-A01	East upper purlin, north wall – truss 1 (bay 1)	62	9	------	------	------
BSA-A02	West lower purlin, north wall – truss 1 (bay 1)	60	18	1682_{DR}	1723_{DR}	1741_{DR}
BSA-A03	East principal rafter, truss 1	nm (38)	---	------	------	------
BSA-A04	West principal rafter, truss 1	93	30	1658_{DR}	------	1750_{DR}
BSA-A05	Tiebeam (cut through), truss 1	62	32	1684_{DR}	1713_{DR}	1745_{DR}
BSA-A06	East upper purlin, truss 1 – 2 (bay 2)	60	21	1690_{DR}	1728_{DR}	1749_{DR}
BSA-A07	West upper purlin, truss 1 – 2 (bay 2)	56	14	1689_{DR}	1744_{DR}	1744_{DR}
BSA-A08	East lower purlin, truss 1 – 2 (bay 2)	(+6nm) 45	4	1676_{DR}	------	1720_{DR}
BSA-A09	West lower purlin, truss 1 – 2 (bay 2)	62	25	1686_{DR}	1747_{DR}	1747_{DR}
BSA-A10	East principal rafter, truss 2	52	15	1698_{DR}	------	1749_{DR}
BSA-A11	West principal rafter, truss 2	88	30	1655_{DR}	1717_{DR}	1742_{DR}
BSA-A12	East upper purlin, truss 2 – south wall (bay 3)	nm (22)	---	------	------	------

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

Figure 2 Annotated photograph of truss 1/bay 1, viewed looking south (photograph Robert Howard)

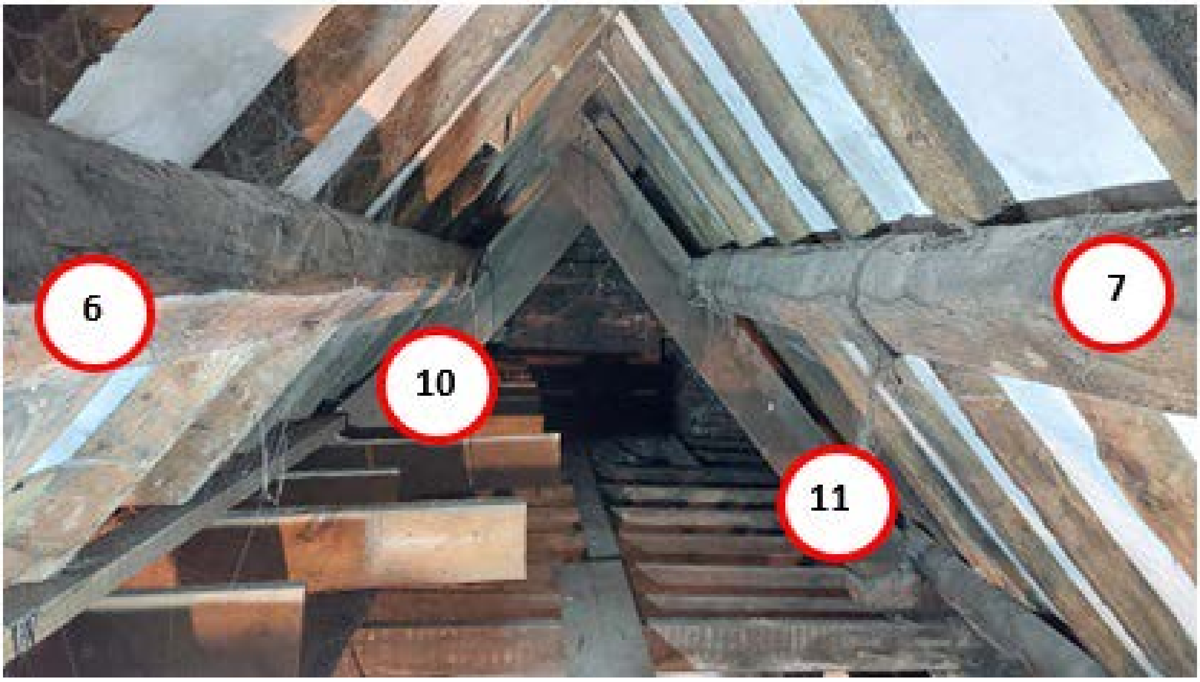

Figure 3 Annotated photograph of truss 2/bay 2, viewed looking south (photograph Robert Howard)

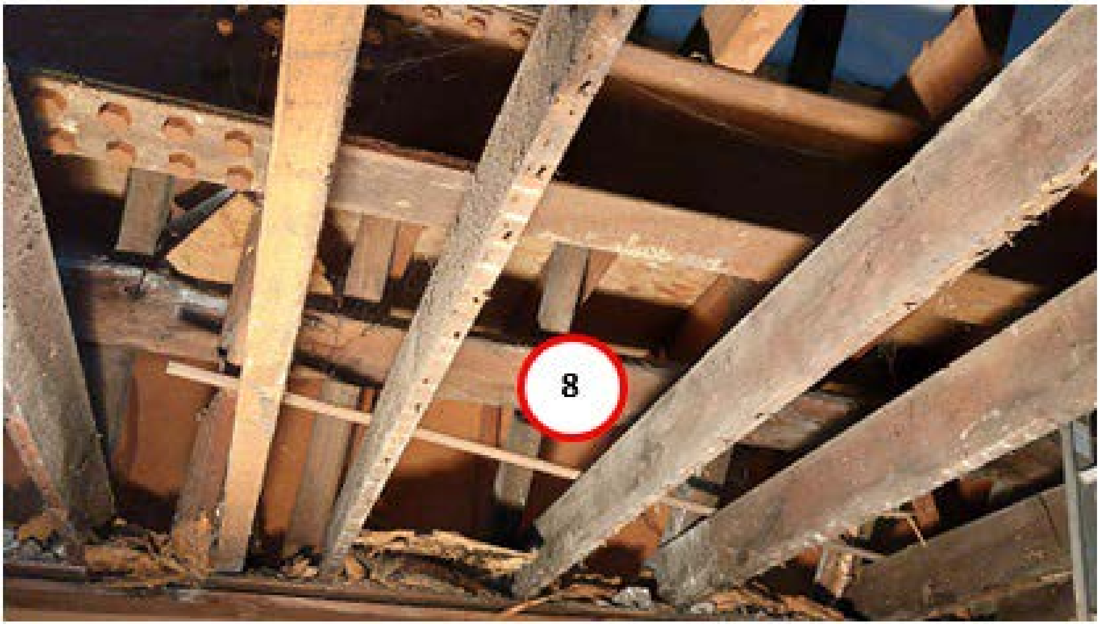

Figure 4 Annotated photograph of bay 2, viewed looking east (photograph Robert Howard)

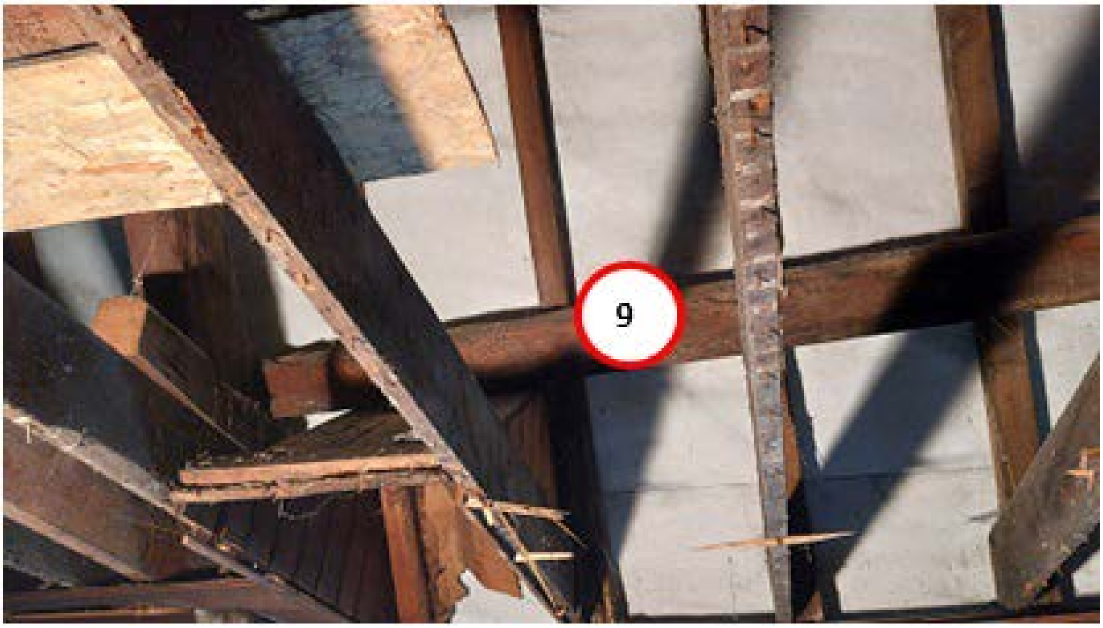

Figure 5 Annotated photograph of bay 2, viewed looking west (photograph Robert Howard)

Figure 6 Annotated photograph of bay 3, viewed looking south-east (photograph Robert Howard)

Wood identification

All of the core samples, bar BSA-A12, were submitted for microscopic identification to confirm the conifer species present. Thin sections of wood were taken by hand using a double-edged razor blade and mounted on a microscope slide for examination under high-powered transmitted light using a Meiji EMZ-2 microscope (x40–x400). Where necessary, all the three planes for identification were thin-sections: transverse section (TS), radial section (RS), and transverse longitudinal section (TLS). Allocation to genus was made with reference to identification keys (Gale and Cutler 2000; InsideWood 2014 onwards) and modern reference slides from Kew Gardens.

All of the cores were confirmed as *Pinus* sp. (Table 2), with the following observed characteristics: abrupt early/latewood transition, presence of resin canals, uniseriate bordered pits, fenestriform cross-field pitting and dentate ray tracheids. This is typical of the European *Pinus sylvestris* or the North American species *Pinus resinosa*. Insect damage was commonly noted in the later rings.

Table 2: Wood identifications of tree-ring samples from 69 Newgate Street, Bishop Auckland, Co. Durham

Sample number	Species	Notes
BSA-A01	*Pinus* sp.	some damage in later wood
BSA-A02	*Pinus* sp.	lots of insect damage in later wood
BSA-A03	*Pinus* sp.	lots of insect damage in later wood
BSA-A04	*Pinus* sp.	early wood only - small piece
BSA-A05	*Pinus* sp.	occasional insect damage in later wood
BSA-A06	*Pinus* sp.	lots of insect damage in later wood
BSA-A07	*Pinus* sp.	some damage in later wood
BSA-A08	*Pinus* sp.	lots of insect damage in later wood
BSA-A09	*Pinus* sp.	early wood only - small piece
BSA-A10	*Pinus* sp.	lots of insect damage in later wood
BSA-A11	*Pinus* sp.	lots of insect damage in later wood

Tree-ring analysis and results

Each of the 12 samples obtained from 69 Newgate Street was prepared by sanding and polishing. It was seen at this time that two samples, BSA-A03 and BSA-A12, had too few rings for the reliable dating of pine (less than 40 each) and they were rejected from this programme of analysis.

The annual growth ring widths of the remaining 10 samples were, however, measured, these data being given at the end of this report. The 10 measured data series were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix). This comparative process indicated that two groups of cross-matching samples could be formed. At a minimum *t*-value of 5.1, seven samples formed the first group, and at a minimum *t*-value of 5.8, two samples formed the second group.

The first group of seven samples cross-match with each other as shown in the bar diagram, Figure 7 and in Table 3. The seven samples were combined at their indicated off-set positions to form BSAASQ01, a site chronology with an overall length 74 rings. Site chronology BSAASQ01 was then compared to an extensive corpus of reference data for pine, which identified some consistent cross-matching when this site sequence spans AD 1676–1749 (Table 4). This evidence is not, however, considered sufficient to consider this site chronology securely dated by ring-width dendrochronology due to the relatively limited number of reference chronologies with which BSAASQ01 matches.

The second site chronology comprises two samples, BSA-A04 and BSA-A11, cross-match each other at a *t*-value of 5.8 (Baillie and Pilcher 1973) as shown in the bar diagram, Figure 7. These two samples were also combined at the indicated off-set positions to form BSAASQ02, a site chronology with an overall length 96 rings. Site chronology BSAASQ02 was also compared to the same extensive corpus of reference data for pine, which identified some very tenuous cross-matching when this site sequence spans AD 1655–1750 (Table 5). This evidence is clearly not sufficient to consider this site chronology securely dated by ring-width dendrochronology.

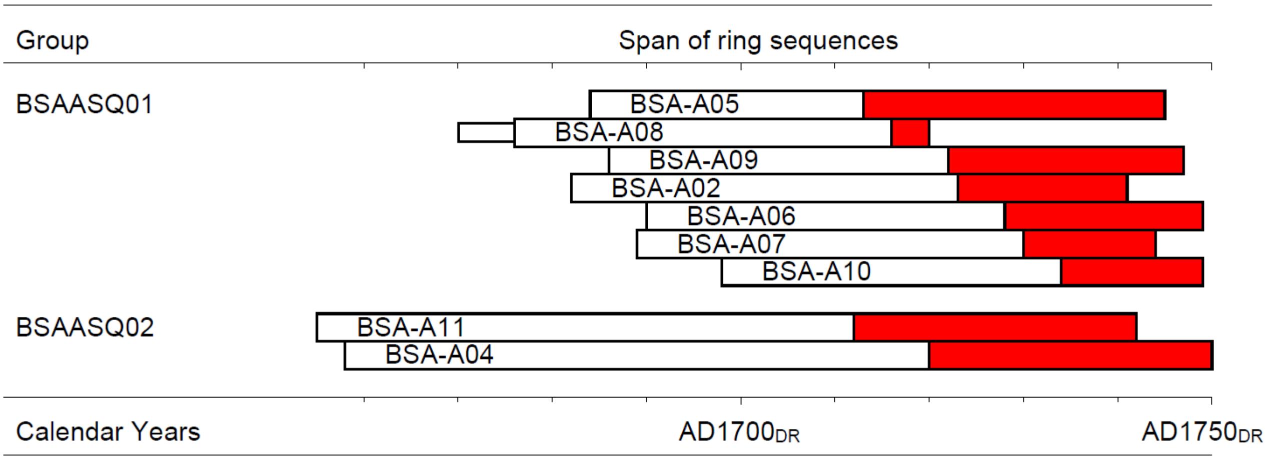

Figure 7 Bar diagram showing the relative positions of the ring series in site chronologies BSAASQ01 and BSAASQ02. The calendar dates are determined by a combination of dendrochronology and radiocarbon dating. White bars = heartwood rings; red bars = sapwood rings

These two site chronologies were then compared with the single remaining measured but ungrouped sample. There was, however, no further cross-matching. The ungrouped sample was, therefore, compared individually with the same extensive corpus of reference data for pine, but there was again no consistent cross-matching and this sample must, therefore, remain undated by ring-width dendrochronology.

Table 3: *t*-values (Baillie and Pilcher 1973) obtained between cross-matched timbers forming site master chronology BSAASQ01. - = *t*-value less than 3.0; \ = overlap less than 30 rings

	t-values					
Sample	BSA-A05	BSA-A06	BSA-A07	BSA-A08	BSA-A09	BSA-A10
BSA-A02	5.7	4.1	6.1	3.7	5.9	-
BSA-A05	*	3.2	8.1	5.5	6.2	5.3
BSA-A06		*	4.8	3.9	6.9	-
BSA-A07			*	4.1	6.5	4.0
BSA-A08				*	5.1	\
BSA-A09					*	4.3

Table 4: *t*-values (Baillie and Pilcher 1973) obtained between site master chronology BSAASQ01 (when spanning AD 1676–1749) and relevant reference chronologies

Reference chronology	Date span	*t*-values	Reference
Poland: north central region	AD 1168–1994	4.2	Zielski pers comm
Sweden: Gotaland	AD 1636–1855	4.2	Bartholin pers comm
Northumberland: Berwick upon Tweed (imported)	AD 1607–1770	7.1	Arnold et al. 2015
London: Millers House, Three Mills Lane (imported)	AD 1607–1762	6.8	Tyers forthcoming (a)
South Yorkshire: Crucible Works, Wicker Lane, Sheffield (imported)	AD 1650–1804	4.9	Tyers and Groves 2003
North Yorkshire: Saltwick foreshore, Whitby (imported)	AD 1668–1755	4.8	C Tyers unpubl
London: Hertford House (imported)	AD 1604–1773	4.5	Tyers forthcoming (b)
Berkshire: Windsor Castle (imported)	AD 1641–1798	4.2	Arnold et al. forthcoming
Devon: Warleigh House, Tamerton Foliot (imported)	AD 1543–1759	4.0	Arnold et al. 2006
London: House Mill, Three Mills Lane (imported)	AD 1608–1801	4.0	Tyers forthcoming (a)

Table 5: *t*-values (Baillie and Pilcher 1973) obtained between site master chronology BSAASQ02 (when spanning AD 1655–1750), a truncated version of BSAASQ02 (when spanning AD 1655–1732; outer rings containing bands of very narrow rings removed) and relevant reference chronologies. - = *t*-value of less than 3.0

		t-values	*t*-values	
Reference chronology	Date span	BSAASQ02	BSSASQ02t	Reference
Sweden: Gravsten	AD 1469–1840	3.3	-	Bartholin pers comm
Sweden: Gotaland	AD 1636–1855	3.2	-	Bartholin pers comm
Northumberland: Berwick upon Tweed (imported)	AD 1607–1770	3.8	5.2	Arnold et al. 2015
London: Millers House, Three Mills Lane (imported)	AD 1607–1762	3.2	3.4	Tyers forthcoming (a)
London: Hertford House (imported)	AD 1604–1773	3.2	4.5	Tyers forthcoming (b)
Cornwall: Godolphin House, Godolphin Cross (imported)	AD 1528–1769	3.0	-	Tyers and Tyers forthcoming
Cambridgeshire: Grand Arcade, Cambridge (imported)	AD 1636–1820	3.2	-	Tyers 2007
County Durham: 69 Newgate Street, BSA-A08 (imported)	AD 1676–1720	4.1	4.1	this report

Radiocarbon dating

Following the failure of the ring-width dendrochronology to provide secure calendar dating for the timberwork from the building, samples from the two master chronologies were selected for radiocarbon dating and wiggle-matching. Timber BSA-A09 was selected from site master chronology BSAASQ01. This core has 62 growth rings that span relative rings 11–72 of this tree-ring chronology (Fig 8). Timber BSA-A04 was selected from site master chronology BSAASQ02. This core has 93 growth rings that span relative rings 3–96 of this tree-ring chronology (Fig 9).

Radiocarbon dating is based on the radioactive decay of ^{14}C, which trees absorb from the atmosphere during photosynthesis and store in their growth-rings. The radiocarbon from each year is stored in a separate annual ring. Once a ring has formed, no more ^{14}C is added to it, and so the proportion of ^{14}C versus other carbon isotopes reduces in the ring through time as the radiocarbon decays. Radiocarbon ages, like those in Table 6, measure the proportion of ^{14}C in a sample and are expressed in radiocarbon years BP (before present, 'present' being a constant, conventional date of AD 1950).

Table 6: Radiocarbon measurements from pine samples from 69 Newgate Street, Bishop Auckland, Co. Durham

Laboratory Number	Sample	Radiocarbon Age (BP)	$\delta^{13}C$ (‰)
GrM-35474	BSA-A09, ring 5 (pine, heartwood)	138±16	−22.37±0.15
GrM-35475	BSA-A09, ring 30 (pine, heartwood)	76±17	−24.18±0.15
GrM-35476	BSA-A09, ring 42 (pine, heartwood)	96±17	−22.44±0.15
GrM-35478	BSA-A09, ring 49 (pine, heartwood)	155±20	−23.86±0.15
GrM-35481	BSA-A09, ring 62 (pine, heartwood)	195±20	−22.19±0.15
GrM-35482	BSA-A04, ring 10 (pine, heartwood)	182±20	−22.61±0.15
GrM-35483	BSA-A04, ring 39 (pine, heartwood)	112±18	−23.66±0.15
GrM-35484	BSA-A04, ring 64 (pine, heartwood)	95±18	−22.72±0.15
GrM-35485	BSA-A04, ring 83 (pine, heartwood)	160±21	−23.10±0.15

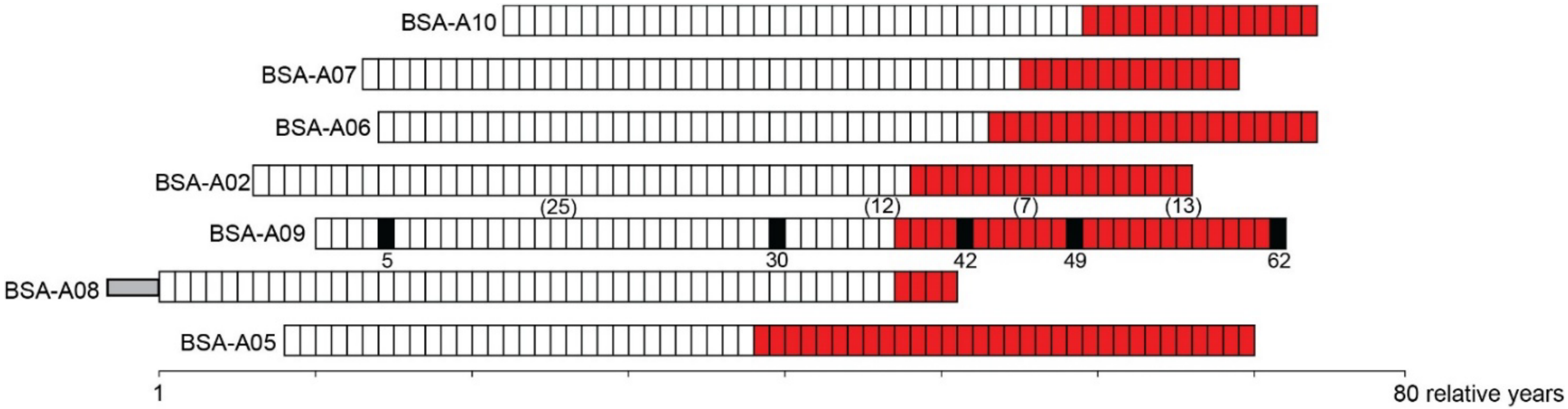

Figure 8 Schematic illustration of BSAASQ01 to locate the single ring sub-samples submitted for radiocarbon dating, numbers – dated rings, numbers in brackets – gaps between dated rings, red – sapwood rings, narrow grey bar – unmeasured heartwood rings

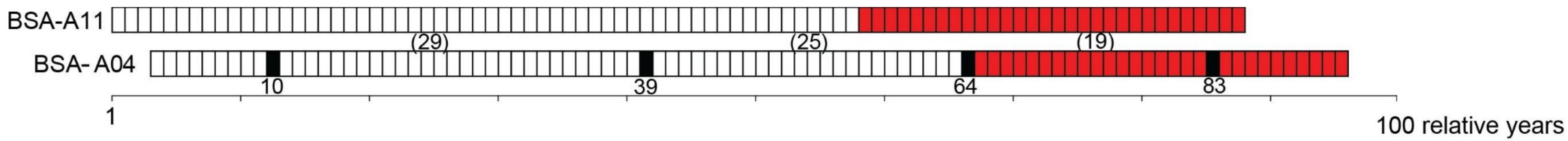

Figure 9 Schematic illustration of BSAASQ02 to locate the single ring sub-samples submitted for radiocarbon dating, numbers – dated rings, numbers in brackets – gaps between dated rings, red – sapwood rings

Nine radiocarbon measurements have been obtained from single annual tree-rings from timbers BSA-A04 and BSA-A09 (Table 6; Figs 8–9). Dissection was undertaken by Alison Arnold and Robert Howard at the Nottingham Tree-Ring Dating Laboratory. Prior to sub-sampling, the core was checked against the tree-ring width data. Then each annual growth ring was split from the rest of the tree-ring sample using a chisel or scalpel blade. Each radiocarbon sample consisted of a complete annual growth ring, including both earlywood and latewood. Each annual ring was then weighed and placed in a labelled bag. Rings not selected for radiocarbon dating as part of this study have been archived by Historic England.

Radiocarbon dating was undertaken by the Centre for Isotope Research, University of Groningen (GrM-), the Netherlands in 2024. Each ring was converted to α-cellulose using an intensified aqueous pretreatment (Dee et al. 2020) and combusted in an elemental analyser (IsotopeCube NCS), coupled to an Isotope Ratio Mass Spectrometer (Isoprime 100). The resultant CO_2 was graphitised by hydrogen reduction in the presence of an iron catalyst (Wijma et al. 1996; Aerts-Bijma et al. 1997). The graphite was then pressed into aluminium cathodes and dated by Accelerator Mass Spectrometry (AMS) (Synal et al. 2007; Salehpour et al. 2016).

Data reduction was undertaken as described by Wacker et al. (2010), and the facility maintains a continual programme of quality assurance procedures (Aerts-Bijma et al. 2021), in addition to participation in international inter-comparison exercises (Scott et al. 2017; Wacker et al. 2020). These tests demonstrate the reproducibility and accuracy of these measurements.

The results are conventional radiocarbon ages, corrected for fractionation using $\delta^{13}C$ values measured by Accelerator Mass Spectrometry (Stuiver and Polach 1977; Table 6). The quoted $\delta^{13}C$ values were measured by Isotope Ratio Mass Spectrometry, and more accurately reflect the natural isotopic composition of the sampled wood.

Wiggle-matching

Radiocarbon ages are not the same as calendar dates because the concentration of ^{14}C in the atmosphere has fluctuated over time. A radiocarbon measurement has thus to be calibrated against an independent scale to arrive at the corresponding calendar date. That independent scale is the IntCal20 calibration curve (Reimer et al. 2020). For the period covered by this study, this is constructed from radiocarbon measurements on tree-ring samples dated absolutely by dendrochronology. The probability distributions of the calibrated radiocarbon dates from BSA-A09, derived from the probability method (Stuiver and Reimer 1993), are shown in outline in Figures 10 and 11, and for BSA-A04 in Figures 12 and 13.

Wiggle-matching is the process of matching a series of calibrated radiocarbon dates which are separated by a known number of years to the shape of the radiocarbon calibration curve. At its simplest, this can be done visually, although statistical methods are usually employed. Floating tree-ring sequences are particularly suited to this approach as the calendar age separation of tree-rings submitted for dating is known precisely by counting the rings in the timber. A review of the method is presented by Galimberti et al. (2004).

The approach to wiggle-matching adopted here employs Bayesian chronological modelling to combine the relative dating information provided by the tree-ring analysis with the calibrated radiocarbon dates (Christen and Litton 1995). It has been implemented using the program OxCal v4.4 (http://c14.arch.ox.ac.uk/oxcal.html; Bronk Ramsey et al. 2001; Bronk Ramsey 2009). The modelled dates are shown in black in Figures 10–13 and quoted in italics in the text. The Acomb statistic shows how closely the assemblage of calibrated radiocarbon dates as a whole agree with the relative dating provided by the tree-ring analysis that has been incorporated in the model; an acceptable threshold is reached when it is equal to or greater than An (a value based on the number of dates in the model). The A statistic shows how closely an individual calibrated radiocarbon date agrees with its position in the sequence (most values in a model should be equal to or greater than 60).

Figure 10 illustrates the chronological model for BSAASQ01. This model incorporates the gaps between each dated annual ring known from tree-ring counting in core BSA-A09 (e.g. that the carbon in ring 5 of the measured tree-ring series (GrM-35474) was laid down 25 years before the carbon in ring 30 of the series (GrM-35474; Fig 8), with the radiocarbon measurements (Table 6) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer et al. 2020).

The model has good overall agreement (Acomb: 96.8, An: 31.6, n: 5; Fig 10), with all radiocarbon dates having good individual agreement (A > 60). It suggests that the final ring of the site master sequence BSAASQ01, formed in *cal AD 1739–1753 (58% probability; BSAASQ01 last ring*; Fig 10) or *cal AD 1926–1942 (37% probability)*, probably in *cal AD 1742–1751 (48% probability)* or *cal AD 1932–1938 (21% probability)*.

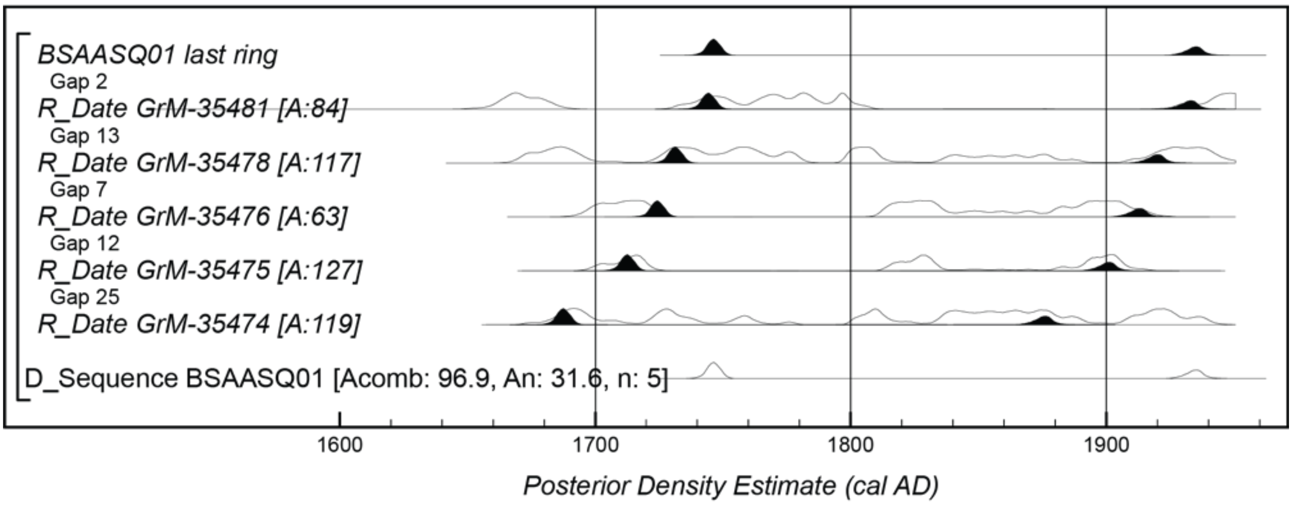

Figure 10 Probability distributions of dates from BSAASQ01. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. Distributions other than those relating to particular samples correspond to aspects of the model. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly

When the last surviving ring of this master sequence is constrained to have formed in AD 1749, as suggested tentatively by the ring-width dendrochronology, the model again has good overall agreement (Acomb: 89.3, An: 28.9, n: 6; Fig 11), although *GrM-35476* has poor individual agreement (A: 19). This is within statistical expectation.

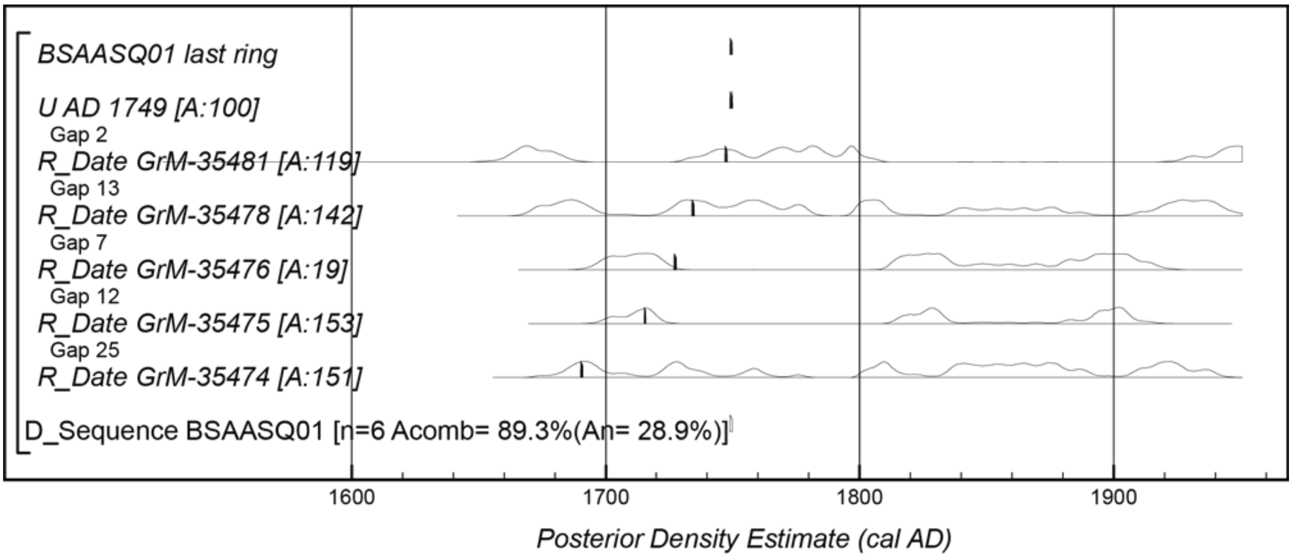

Figure 11 Probability distributions of dates from BSAASQ01, including the tentative date produced by ring-width dendrochronology for the formation of its last surviving ring in AD 1749. The format is identical to that of Fig 10. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly

Figure 12 illustrates the chronological model for BSAASQ02. The model has good overall agreement (Acomb: 80.4, An: 35.4, n: 5; Fig 12), with all radiocarbon dates having good individual agreement (A > 60). It suggests that the final ring of the site master sequence BSAASQ01, formed in *cal AD 1742–1761 (59% probability;* BSAASQ02 *last ring*; Fig 12) or *cal AD 1855–1892 (30% probability)*, or *cal AD 1929–1946 (6% probability)*, probably in *cal AD 1744–1758 (53% probability*) or *cal AD 1862–1867 (6% probability)*, or *cal AD 1879–1888 (9% probability)*.

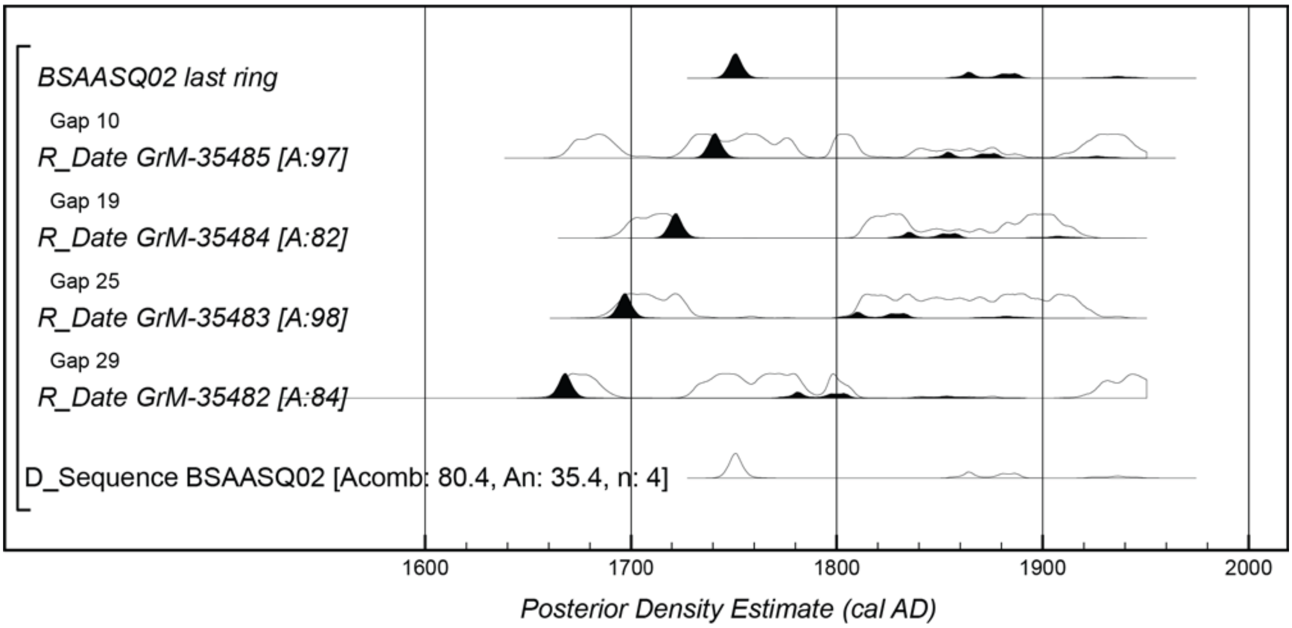

Figure 12 Probability distributions of dates from BSAASQ02. Each distribution represents the relative probability that an event occurs at a particular time. The format is identical to that of Fig 10. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly

When the last surviving ring of this master sequence is constrained to have formed in AD 1750, as suggested tentatively by the ring-width dendrochronology, the model again has good overall agreement (Acomb: 110.9, An: 31.6, n: 5; Fig 13), with all the radiocarbon dates again having good individual agreement (A > 60).

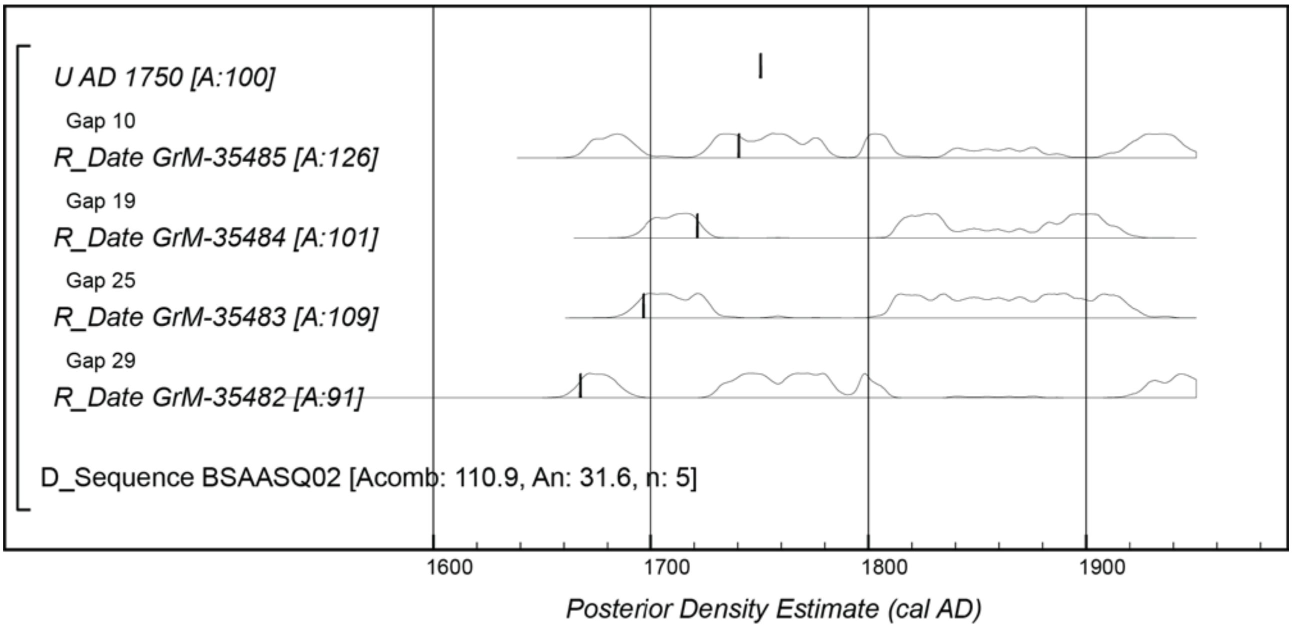

Figure 13 Probability distributions of dates from BSAASQ02, including the tentative date produced by ring-width dendrochronology for the formation of its last surviving ring in AD 1750. The format is identical to that of Fig 10. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly

Interpretation

The two site master chronologies of pine timbers from 69 Newgate Street, BSAASQ01 and BSAASQ02, could not be dated securely by ring-width dendrochronology, although both sequences produced some consistent cross-matching with the available reference chronologies (Tables 4 and 5).

Radiocarbon wiggle-matching provided independent evidence for the date of the site master chronologies (Figs 10 and 12), which is consistent with the tentative dates suggested by the tree-ring analysis. When the last ring of the wiggle-match sequence of BSAASQ01 is constrained to fall in AD 1749, the model has good overall agreement Acomb: 89.3, An: 28.9, n: 6; Fig 11), and all the individual dates have good individual agreement (A > 60) except for *GrM-35476* (A: 19). This is within statistical expectation. Equally, when the last ring of the wiggle-match sequence of BSAASQ02 is constrained to fall in AD 1750, the model has good overall agreement (Acomb: 110.9, An: 31.6, n: 5; Fig 13), and all the individual dates have good individual agreement (A > 60).

This allows the tentative dating provided by the ring-width dendrochronology to be accepted, and the chronologies to be dated as spanning AD 1676–1749$_{DR}$ (BSAASQ01) and AD 1655–1750$_{DR}$ (BSAASQ02). The subscript $_{DR}$ indicates that these are not dates determined independently by ring-width dendrochronology, and that the two master chronologies should not be utilised as a ring-width master sequences for dating other sites.

The dating evidence given in Tables 4 and 5 suggests that the timbers used in the building were likely to have been imported from Scandinavia, this being based on the previous dendro-provenancing of the timbers represented by the various English site chronologies to likely source areas across Scandinavia. Clearly the evidence with respect to source of the two timbers forming BSAASQ02 is far from conclusive but the low levels of matching with other Scandinavian sourced timbers are not replicated with timbers from other sources.

The nine dated timbers are clearly coeval but the wide variation in numbers of sapwood rings across Scandinavia (e.g. Groves and Locatelli 2005) means that it is not possible to provide a felling date range for these timbers. However, bearing in mind the extant sapwood rings on the samples, it is possible to suggest that the timbers used in the roof were felled in the latter half of the eighteenth century or possibly in the early nineteenth century.

Conclusion

The successful dating of nine of the timbers from the roof has indicated that, if the timbers are associated with the primary construction of the front range, that it is later than the pre-eighteenth century date that had been tentatively suggested. However, the late eighteenth- to early nineteenth-century date obtained through this analysis needs to be placed in a wider context with other research before being assumed to be the date of construction of the front range. The probable use of timbers imported from Scandinavia adds to the growing body of dendrochronologically identified imported conifers and hence enhances our knowledge of timber trade at this time.

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Data of Measured Samples

Measurement in 0.01 mm unit

BSA-A01A 62
69 82 78 20 87 132 108 91 108 111 79 75 92 129 119 156 131 168 75 230
219 50 105 178 197 128 153 161 175 234 129 135 125 128 110 123 110 80 128 117
139 145 207 175 164 121 114 98 116 96 136 100 133 160 172 276 178 99 104 90
118 150

BSA-A01B 62
83 90 79 20 85 128 101 84 112 97 87 70 88 117 126 175 181 165 75 233
221 41 105 182 197 137 142 144 172 213 135 137 116 128 114 124 107 87 115 155
152 142 207 171 171 121 114 100 117 100 121 100 114 148 182 283 180 107 100 87
118 135

BSA-A02A 60
278 328 249 267 196 237 261 230 299 282 237 251 340 253 251 186 234 291 254 232
177 239 182 189 160 139 153 184 154 107 120 167 190 165 143 178 140 98 139 223
215 179 182 159 143 173 92 139 128 151 112 112 162 128 95 82 147 102 64 93

BSA-A02B 60
259 323 242 274 209 239 265 226 304 309 234 236 351 253 217 174 242 289 264 234
189 239 185 192 163 139 139 181 162 115 117 154 190 173 149 170 142 95 131 235
214 178 185 164 143 161 94 130 135 159 143 114 154 126 92 90 142 103 70 110

BSA-A04A 93
223 290 206 166 212 218 163 238 257 230 321 392 331 284 246 232 179 214 276 285
203 185 176 153 158 175 160 214 170 173 139 134 117 135 134 114 150 110 137 148
157 139 142 107 156 137 128 139 147 165 131 150 143 117 95 95 123 153 165 134
107 153 222 198 201 97 107 161 128 132 143 89 115 93 109 48 92 94 131 134
203 217 191 119 160 153 83 95 68 42 68 43 90

BSA-A04B 93
231 274 184 165 222 225 169 226 258 212 328 393 334 288 251 232 175 217 271 279
211 175 194 152 166 165 160 212 160 174 145 123 116 143 137 98 162 115 126 146
139 160 135 114 153 137 125 162 143 168 139 148 145 119 92 96 118 161 144 139
109 145 225 189 197 114 110 156 122 121 135 98 110 100 106 48 83 102 125 128
211 221 182 122 162 146 105 92 55 57 56 48 81

BSA-A05A 62
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196 135 113 91 132 148 163 139 138 175 183 226 196 189 140 139 131 196 236 210
168 159 153 117 128 120 128 110 108 106 140 111 41 71 92 67 50 82 82 98
168 189

BSA-A05B 62
279 351 318 351 343 267 284 360 296 285 327 298 205 169 283 256 222 217 210 217
192 135 118 90 129 142 167 140 137 176 192 226 198 187 135 139 121 192 259 201
173 151 143 117 100 146 129 104 114 104 140 109 45 64 98 62 60 73 87 106

161 201

BSA-A06A 60
284 411 305 286 392 303 321 246 294 303 305 233 272 260 185 135 119 78 117 156
211 121 86 121 214 186 172 187 164 83 104 115 129 193 228 242 188 100 100 107
118 171 175 160 175 123 86 93 118 43 100 76 123 126 109 112 131 138 75 134

BSA-A06B 60
314 378 306 279 392 296 321 255 291 303 282 227 287 250 189 132 114 79 123 146
217 132 85 110 224 182 163 200 171 87 99 110 134 180 240 243 181 92 95 101
121 165 171 165 176 132 78 93 70 96 93 81 118 139 110 114 137 139 95 162

BSA-A07A 56
272 289 323 309 304 352 196 210 150 278 266 223 198 236 167 160 120 92 72 77
145 131 110 100 147 153 147 125 156 133 100 104 136 178 207 211 184 145 132 137
166 170 173 126 151 239 152 84 96 132 112 85 84 95 110 151

BSA-A07B 56
254 293 322 316 293 357 206 192 164 267 261 221 196 249 171 158 126 94 70 82
115 150 114 115 159 144 139 131 137 153 92 107 132 180 205 213 179 142 136 142
167 170 171 135 140 245 143 87 95 150 110 73 92 93 104 145

BSA-A08A 45
104 108 139 143 171 159 234 310 251 257 295 335 328 260 292 322 271 221 351 268
217 192 234 225 229 159 265 206 163 135 118 79 76 94 114 82 99 128 154 170
165 156 107 101 148

BSA-A08B 45
107 117 137 151 169 157 232 309 259 259 287 328 339 264 278 325 282 224 326 257
230 188 222 229 231 164 268 217 148 134 117 76 84 96 118 96 100 134 129 168
142 148 117 107 181

BSA-A09A 62
326 343 359 320 292 421 368 259 409 266 282 209 261 253 247 147 268 241 182 125
142 135 154 145 171 114 106 142 224 215 193 212 184 105 104 167 187 221 221 214
167 124 106 140 123 181 175 139 168 92 49 50 73 56 46 37 79 115 153 157
145 142

BSA-A09B 62
316 359 364 276 293 416 360 264 395 253 278 200 264 249 242 150 257 242 193 120
136 132 165 139 167 101 110 150 229 209 173 210 175 103 114 155 192 235 200 239
155 124 107 142 121 190 182 140 170 103 51 48 75 54 42 48 70 115 156 167
143 134

BSA-A10A 52
191 204 234 194 198 162 175 154 166 173 242 195 203 164 198 159 195 165 178 143
136 115 80 119 157 163 150 128 175 142 154 153 181 218 200 195 281 251 154 192
271 262 221 223 221 260 231 286 207 181 175 262

BSA-A10B 52

196 215 243 184 209 149 176 144 162 189 242 199 201 164 198 151 198 166 182 139
132 103 92 117 160 169 144 132 180 139 153 152 189 225 192 201 276 248 158 184
279 251 231 225 210 264 218 275 215 178 175 251

BSA-A11A 88
291 249 167 219 204 162 152 255 232 150 173 225 219 293 269 148 151 169 202 147
144 235 269 265 253 194 150 196 203 193 180 97 106 128 128 126 132 100 80 112
92 87 94 106 107 100 88 114 108 95 89 90 87 104 68 92 109 104 73 101
89 73 81 73 83 132 134 128 73 82 95 68 84 100 96 84 75 84 42 28
56 65 73 63 78 109 85 98

BSA-A11B 88
304 242 158 221 209 161 155 251 223 157 171 239 221 294 228 149 139 162 192 164
137 237 272 257 255 197 150 189 200 203 175 86 110 126 121 131 131 103 75 120
87 84 98 106 109 95 87 111 121 79 101 85 92 100 73 95 103 96 84 98
84 74 79 56 78 154 126 120 78 91 76 79 104 74 90 78 76 90 34 34
62 60 57 69 77 103 85 109

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

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 (i.e. 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).

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; e.g. 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 (e.g. 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 AD 1810 is very apparent as is the smaller later growth from about AD 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in AD 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

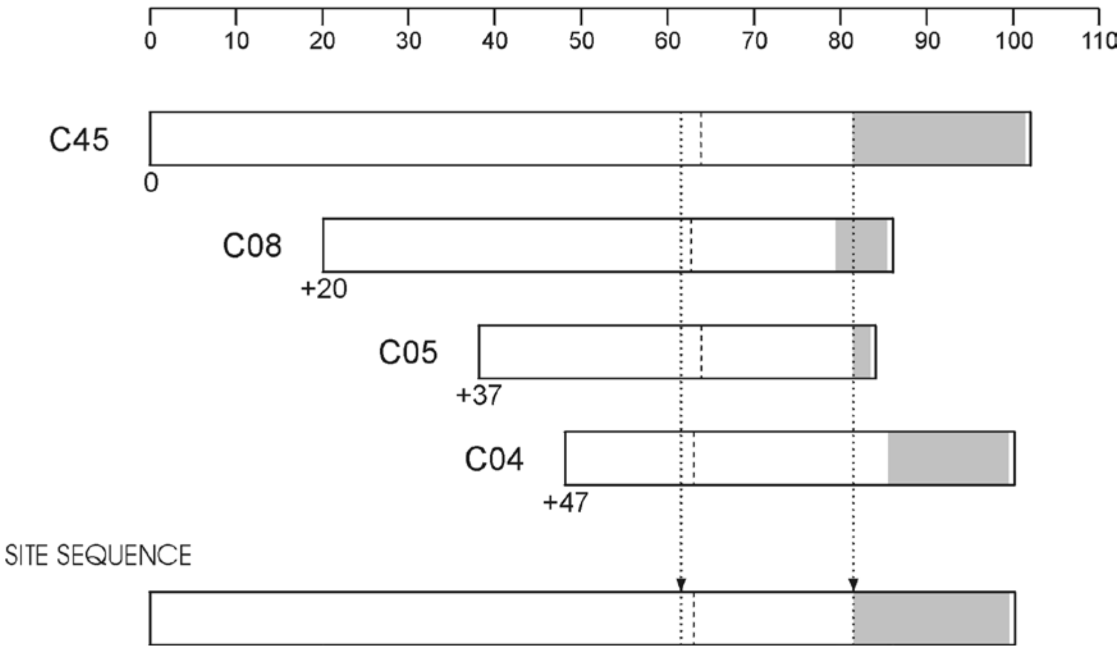

Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them. The bar diagram represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are 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.

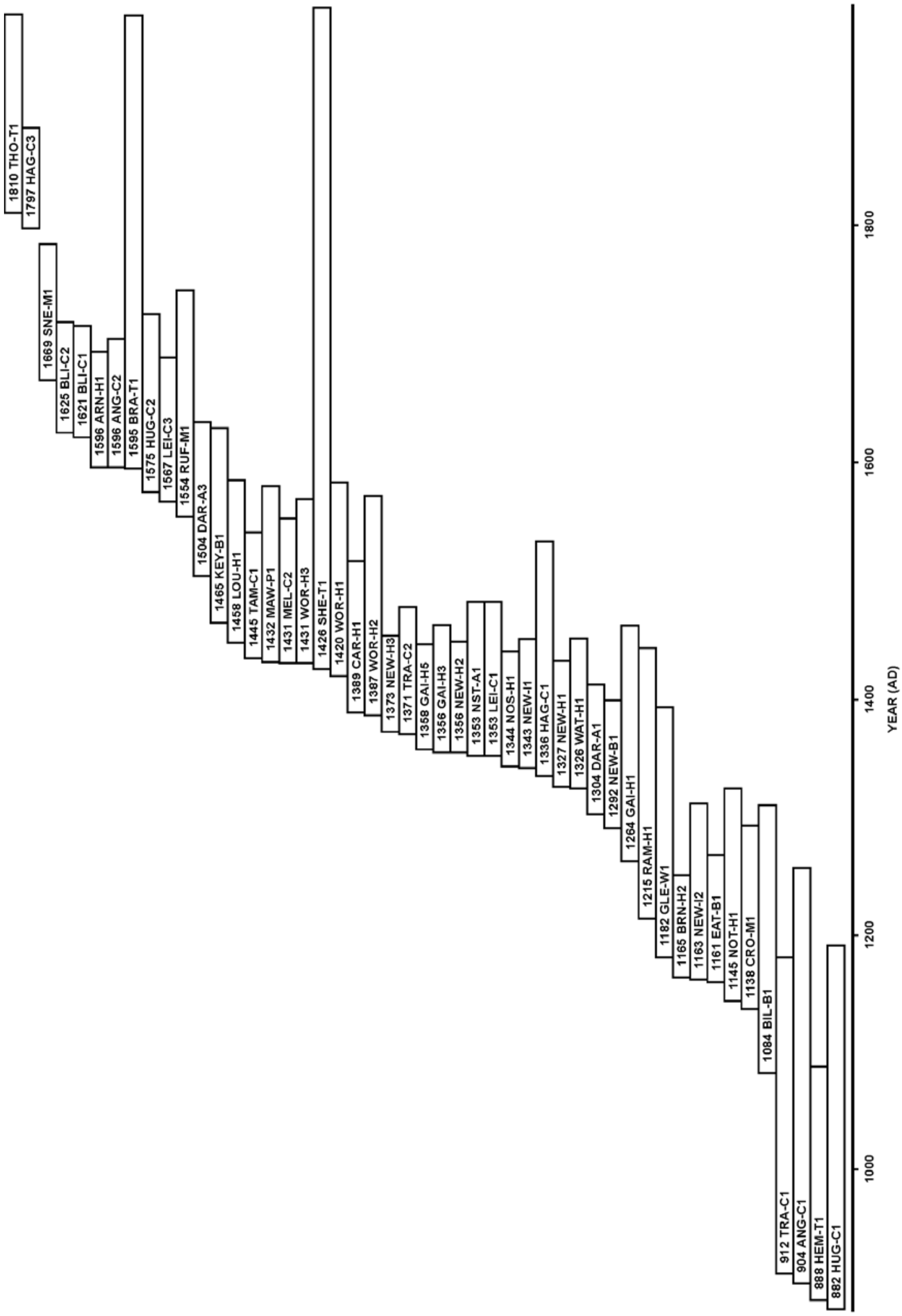

Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

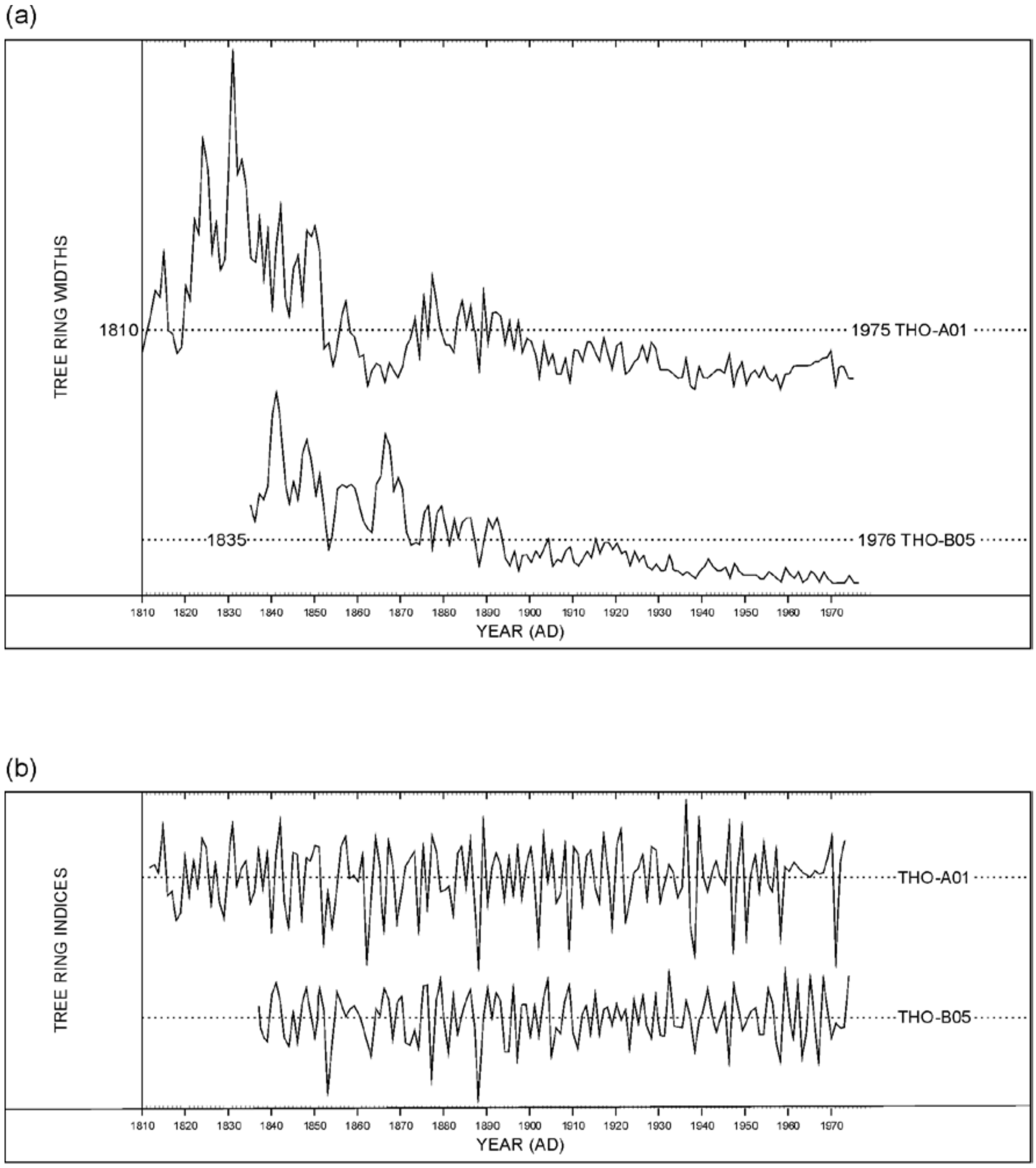

Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known. Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young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