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Deal Castle, Victoria Road, Deal, Kent

Tree-ring Analysis of Oak and Pine Timbers

Alison Arnold and Robert Howard

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SUMMARY

Dendrochronological analysis was undertaken on 51 of the 54 core samples obtained from Deal Castle, as well as the measurements, carried out *in situ*, of three boards from a door. This analysis produced six oak site chronologies, accounting for 21 samples, and one pine chronology comprising six samples. The first dated oak site chronology, comprising all six consoles to the ground floor of the Central Tower, is 137 rings long, these spanning AD 1465–1601. Interpretation of the sapwood gives these oak timbers an estimated felling date range of AD 1604–29. The second dated oak chronology comprises two door boards. One board is derived from a timber likely to have been felled after AD 1452, while the timber for the second board is likely to have been felled after AD 1535. The single pine chronology, comprising six samples from the timbers of the Gatehouse roof also dates, its 170 rings spanning the years AD 1520–1689. Interpretation of the sapwood on these samples would give these timbers, probably imported from Scandinavia, an estimated felling date in the late-seventeenth century. Twenty six measured oak samples, one measured pine sample, and one of the boards measured *in situ* remain ungrouped and undated.

CONTRIBUTORS

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INTRODUCTION

Deal Castle (Figs 1a–b), a Scheduled Monument, was the middle of three such fortifications built by Henry VIII *c* AD 1539–42 within three miles of each other and designed to cover shipping in The Downs within Goodwin Sands, and to protect the south-east coast from seaward attack. The other castles are at Walmer, to the south and Sandown to the north, the latter now almost totally destroyed by sea action. All three sites were linked to each other by massive earthworks, these now also obliterated.

Deal is the largest and most elaborate of the castles having a six-lobed keep and a central three-storeyed circular citadel, or tower. These rise only a little way above the six-lobed curtain wall to present up to 145 gunports or embrasures on five tiers, the whole structure set low within a deep moat. Entry is from the west over a stone bridge across the moat, through a stout and heavily studded arched door, and via a narrow vaulted passage into an entrance hall with large-beamed roof. The living quarters of the garrison were within the Central Tower, the various interconnecting segmented rooms on different levels, divided up by timber-framed partition walls, being accessed via a central spiral stairs.

Dendrochronological analysis at Deal Castle was requested by Roy Porter in an attempt to determine, with more precision, the dates of certain areas of the castle and any possible subsequent alterations. The castle has been subject to substantial alteration and repairs over the centuries, the most recent work being in the 1950s, and whilst some of this work has been documented, the dating of other earlier changes to the monument is primarily based on assumption and stylistic evidence. It was hoped that tree-ring analysis would determine the date of various elements of the castle and hence enhance the overall understanding of the historical development of the castle, but in addition the information gained would also feed into a new scheme of presentation.

Gatehouse

The Gatehouse has two roof trusses (Fig 2a). These trusses each comprise a pine tiebeam carrying an oak king-post and two pine principal rafters. These timbers in turn support a single inclined pine roof beam, the roof covering being pitched at an angle. Buried in the walls at the end of each tiebeam is a short vertical oak post. The main gates are composed of stiles, muntins, and rails, with panels between, and having arched/curved top pieces/door heads.

Central Tower

In the Central Tower the ground-floor ceiling is formed by a series of main ceiling beams radiating, like the spokes of a wheel, from the middle of the tower to the outer walls (Fig 2b). It is possible that some of these may represent repairs of the 1950s, though others would appear to be originals. Both the inner and outer ends of a number of these main ceiling beams (but not all) are supported by console posts, some of which again might be later repairs. The ground floor of the Central Tower is divided by four timber-framed partition walls of posts, rails and studs. These walls do not appear to be integral to the original construction work of the tower, and may represent either a change of design or a later alteration, though how much later is unknown. A central spiral stair provides access to the first floor and it is possible that the newel post and some of the stair treads may be original.

The first floor of the Central Tower is also divided by partition walls. Three doorways in these walls appear to be framed openings, unlike those to the ground floor which simply comprise gaps in the timbers of the partitions. As such, these first-floor doorways could possibly be separate inserts and potentially of a different date. A door, made up of five vertical oak boards, is in one of these first-floor doorways. Its date is also uncertain and whilst it may be original, it is also possible that it is of a later date.

SAMPLING

A comprehensive assessment of timbers throughout the castle as to their suitability for tree-ring analysis led to sampling being focused on a number of specific areas that appeared to contain sufficient numbers of suitable timbers (Figs 3a–b). Specifically, these areas comprise the roof and main gates of the Gatehouse, and the ground-floor ceiling, ground- and first-floor partition walls, the stairs, the first-floor doorways, and a first-floor door in the Central Tower. Sampling of the main gates of the Gatehouse was limited to the curved top pieces, all other elements were too small or too thin to sample, and in any case were derived from fast-grown trees and thus unsuitable for tree-ring analysis.

Thus from the areas selected for analysis a total of 54 samples was obtained by coring and a further three timbers were measured *in situ*. Each sample was given the code DEL-C (for Deal Castle) and numbered 01–57 (Table 1). Four samples (DEL-C01 – DEL-C04) were obtained from the curved architrave or edging pieces to the main gates of the castle, with a further 13 samples (DEL-C05 – DEL-C17) being obtained from the timbers of the two roof trusses to the Gatehouse. In the Central Tower 12 samples (DEL-C18 – DEL-C29) were taken from the ceiling beams and their supporting consoles to the ground floor, with 10 samples (DEL-C30 – DEL-C39) being obtained from the timbers of the ground-floor partition walls. Five samples (DEL-C40 – DEL-C44) were taken from a series of treads to the central spiral staircase of the Central Tower. Also in the Central Tower, at first-floor level, six samples (DEL-C45 – DEL-C50) were obtained from two doorframes, five samples (DEL-C51 – DEL-C54) were obtained from one of the partition walls, and finally samples DEL-C55 – DEL-57 were obtained as *in situ* measurements from the exposed top edges of three of the five boards of a door, the other two boards being unsuitable for analysis.

The locations of these samples were recorded at the time of sampling either on sketch drawings, annotated photographs, or simple schematic plans (Figs 4a–k). The trusses, frames, and other timbers have either been located on a north-south or east-west basis as appropriate, or in the case of the ceiling beams and consoles of the Central Tower, by counting clockwise from the northernmost timber. The treads of the stairs have been numbered from bottom to top.

ANALYSIS AND RESULTS

Each of the 54 core samples obtained were prepared by sanding and polishing. It was seen at this time that three samples had less than the 40 rings here deemed necessary for reliable dating and they were rejected from this programme of analysis. The annual growth-ring widths of the remaining 51 samples were measured; the data of these measurements, along with the three *in situ* measurements, is given at the end of this report. The data of all 54 measured series were then compared with each other by the Litton/Zainodin grouping procedure (see Appendix).

This comparative process resulted in the production of six oak site chronologies, DELCSQ01 – DELCSQ06, accounting for a total of 21 samples (Figs 5–10), and one pine site chronology, DELCSQ07, this comprising six samples (Fig 11). Each of the seven site chronologies thus created was then compared, as appropriate, to an extensive corpus of either oak or pine reference material. This process indicated a consistent and repeated match for only two of the six oak site chronologies, DELCSQ01 and DELCSQ06, as well as for the single pine site chronology, DELCSQ07. Site chronology DELCSQ01 with 137 rings spans the years AD 1465–1601 (Table 2), while site chronology DELCSQ06 with 153 rings spans AD 1368–1520 (Table 3). The pine site chronology DELCSQ07, with 170 rings, spans the years AD 1520–1689 (Table 4).

Each site chronology was also compared to the remaining measured but ungrouped oak or pine samples, but there was no further cross-matching. Each of the measured but ungrouped oak and pine samples were then compared individually with the full corpus of its respective reference material, but there was no further satisfactory cross-matching and all such samples must, therefore, remain undated.

INTERPRETATION AND DISCUSSION

Analysis by dendrochronology of the timbers of Deal Castle has produced six oak site chronologies, two of which can be dated, plus one dated pine site chronology.

Oak site chronology DELCSQ01 (dated)

This site chronology comprises exclusively samples from the consoles of the ground-floor ceiling in the Central Tower, its 137 rings spanning the years AD 1465–1601 (Fig 5). None of the samples retain complete sapwood (the last growth ring produced by the tree before it was felled), and it is thus not possible to provide a precise felling date for any timber. All the samples do, though, retain some sapwood or at least the heartwood/sapwood boundary.

The heartwood/sapwood boundary on the six samples is at a similar relative position/date, varying by only five years, and hence it is very likely that the timbers represented were all felled at the same time as each other. The average heartwood/sapwood boundary on these six samples is dated AD 1589 which, allowing for the minimum and maximum numbers of sapwood rings the trees are likely to have had (the 95% confidence interval being 15–40 sapwood rings), would give all of the timbers an estimated likely felling date range of AD 1604–29.

The interpretation as a single phase of felling is further supported by the overall level of cross-matching between these six samples, with values in excess of t=10.0 seen between samples DEL-C24 and C25, in excess of t=11.0 between samples DEL-C27 and C29, and even in excess of t=15.0 between DEL-C26 and C28. Such high levels of cross-matching suggest that some consoles have been derived from the same tree, with all the source trees probably growing in a single woodland area. In respect of the location of this woodland, site chronology DELCSQ01 matches quite widely across the southern and central parts of England and hence, whilst the timber could readily have been derived relatively locally, it is also possible that it was obtained from a more distant woodland.

The consoles associated with the ground-floor ceiling in the Central Tower therefore indicate a programme of building works in the early-seventeenth century.

Oak site chronology DELCSQ02 (undated)

DELCSQ02, also comprises six samples, all of them exclusively from the ground-floor ceiling beams of the Central Tower (Fig 6). This site chronology is 118 rings long, but it cannot be conclusively dated. Although undated, the relative position of the heartwood/sapwood boundary on the constituent samples varies by only seven years suggesting that these timbers were also cut as part of a single programme of felling. The cross-matching between these samples is somewhat more variable and suggests that the trees may have been derived from relatively widespread, although potentially closely related, woodland areas.

Oak site chronology DELCSQ03 (undated)

Samples DEL-C09 and DEL-C10 (Fig 7) are both from short posts buried in the walls of the Gatehouse and, whilst neither retain the heartwood/sapwood boundary, given that they cross-match with a value of t=7.9, it is likely that the source trees were growing close to each other. This, combined with the fact that both timbers are associated with the same truss, indicates that it is likely that they do actually represent a single phase of felling.

Oak site chronology DELCSQ04 (undated)

Samples DEL-C39 and DEL-C42 (Fig 8), respectively from a ground-floor partition wall post and a stair tread to the Central Tower, are clearly broadly coeval. However the heartwood/sapwood boundary is present on one, but not the other, and thus it is not possible to ascertain whether they represent a single phase of felling or two separate phases of felling. Whilst they do cross-match with a value of t=5.1 this does not conclusively demonstrate that they were felled at the same time.

Oak site chronology DELCSQ05 (undated)

Two of the three samples, DEL-C51 and DEL-C53 (Fig 9), both from rails of the first-floor partition wall in the Central Tower, were likely to have been felled at the same time as each other. Such an interpretation is based on the fact that their heartwood/sapwood boundaries are at similar positions, that they cross-match with a value of t=6.5, and that both timbers are part of the same partition wall.

Sample DEL-C33 from a door-post in the ground-floor partition wall timber in the Central Tower, on the other hand, is without the heartwood/sapwood boundary and thus its relative felling date cannot be determined. In this instance, although the cross-matching with samples DEL-C51 and DEL-C53 is good (t=4.7 and t=7.8 respectively), the outermost measured heartwood ring on sample DEL-C33 is several decades earlier than on DEL-C51 and DEL-C53 (Fig 9). While this timber could be earlier than those from the first-floor partition wall, the case is not proven as it could simply have been more heavily trimmed during conversion into a post.

Oak site chronology DELCSQ06 (dated)

Neither of the two dated series from boards of the first-floor door retains any sapwood or the heartwood/sapwood boundary (Fig 10), and it thus not possible to provide a felling date range. However, with a last heartwood ring date of AD 1520, and allowing for a minimum of 15 sapwood rings (the lower 95% confidence level) it is likely that the board represented by DEL-C56 was felled after AD 1535, whilst with a last heartwood ring date of AD 1437 it is likely that the board represented by DEL-C57 was felled after AD 1452. It is possible that the trees utilised for the two boards were felled at the same as each other and that they are coeval, but this is not certain. If they are of the same date, it is clear that the timber for sample DEL-C57 has been more heavily trimmed during conversion than has the timber represented by sample DEL-C56.

This site chronology matches well with a whole series of other reference chronologies derived from boards used in panelling, triptych's, and panel paintings, all thought to have been derived from sources elsewhere in Europe, predominantly the Baltic region. Thus the dated door boards are also derived from imported timber.

Oak sample DEL-C55 (undated)

Although sample DEL-C55, also from the first-floor door, has 112 rings, quite sufficient for reliable analysis, it remains undated. The sample shows no sign of distortion or stress which might make cross-matching and dating difficult, and the reason for the lack of dating is unknown. It is possible that the source tree grew in an area, and/or at a time, for which as yet there is no available reference material, although this seems relatively unlikely. It is, however, common in most programmes of tree-ring analysis that some samples remain undated, often for no apparent reason.

Pine site chronology DELCSQ07 (dated)

This site chronology comprises exclusively samples from the roof of the Gatehouse (Fig 11), its 170 rings spanning the years AD 1520–1689. It is possible that one, or possibly two, of the pine samples from the Gatehouse roof retain complete sapwood, although this is somewhat more difficult to determine on softwood timbers than on oak. One rafter (DEL-C16) has a last potential complete sapwood ring end-date, and hence a possible felling date, of AD 1689, while another rafter (DEL-C12) has a last possible complete sapwood ring end-date, and hence a possible felling date, of AD 1687. The amount of sapwood present on pines is very variable, far more so than oak, however the last measured ring dates on the other pine samples would also be suggestive of felling dates towards the very end of the seventeenth century. Thus it appears that the Gatehouse roof underwent a period of rebuilding or significant repair at the end of the seventeenth century.

The overall cross-matching between the samples in this site chronology suggests the likelihood that the trees may have grown in an extensive area of forest. This site chronology itself matches consistently with reference chronologies from Norway and Sweden, as well as those from other imported assemblages in the UK thought to be of potentially Scandinavian origin. Hence it appears possible that these timbers from the roof of the Gatehouse also have a Scandinavian origin.

CONCLUSION

In this instance, tree-ring analysis has dated relatively few timbers, an unusually high number of samples (75%) remaining undated. This may be due to the character of the timbers available here, there now appearing to be a distinct possibility not only that some of them are reused pieces of different felling dates inserted as part of later periods of repair, including that undertaken in the 1950s, but that more timbers have been replaced than was previously thought. Small groups of timbers of different dates are often more difficult to date than larger collections where the data is well replicated. It is also possible that many timbers are of dates and/or from areas for which, at present, there is little or no reference material available. This may be particularly applicable to the later 1950s timbers. In this respect it is possible that when further regional data are collected, the unmatched samples from Deal Castle may ultimately be dated.

The dating that has been obtained, however, is no doubt of some use, this demonstrating that one hitherto unknown programme of work appears to have been undertaken in the Central Tower in the early seventeenth century, and that the Gatehouse roof underwent an undocumented period of rebuilding or significant repair at the end of the seventeenth century. Analysis also shows that the boarded first-floor door to the Central Tower may be an early survival. The work undertaken here, furthermore, will add oak and pine chronologies to both the regional and wider European database, these helping to date other timbers in future.

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TABLES

Table 1: Details of tree-ring samples from Deal Castle, Kent

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Gatehouse main gate					
DEL-C01	North door, upper architrave piece	45	h/s	------	------	------
DEL-C02	North door, lower architrave piece	91	no h/s	------	------	------
DEL-C03	South door, upper architrave piece	42	no h/s	------	------	------
DEL-C04	South door, lower architrave piece	nm	---	------	------	------
	Gatehouse roof					
DEL-C05	King post, northern truss	71	h/s	------	------	------
DEL-C06	East wall post, northern truss	nm	---	------	------	------
DEL-C07	West wall post, northern truss	57	h/s	------	------	------
DEL-C08	King post, southern truss	71	6	------	------	------
DEL-C09	East wall post, southern truss	50	no h/s	------	------	------
DEL-C10	West wall post, southern truss	68	no h/s	------	------	------
DEL-C11	Tiebeam, northern truss (pine)	112	25	1526	1612	1637
DEL-C12	East rafter, northern truss (pine)	168	56C?	1520	1631	1687
DEL-C13	West rafter, northern truss (pine)	130	40	1549	1638	1678
DEL-C14	Roof beam, northern truss (pine)	150	70	1532	1611	1681
DEL-C15	Tiebeam, southern truss (pine)	337	66	------	------	------
DEL-C16	East rafter, southern truss (pine)	163	74C?	1527	1615	1689
DEL-C17	Roof beam, southern truss (pine)	101	21	1523	1602	1623

Table 1: (continued)

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Central Tower, ground-floor ceiling					
DEL-C18	Ceiling beam 10	96	h/s	------	------	------
DEL-C19	Ceiling beam 12	73	h/s	------	------	------
DEL-C20	Ceiling beam 3	89	h/s	------	------	------
DEL-C21	Ceiling beam 4	76	h/s	------	------	------
DEL-C22	Ceiling beam 8	116	h/s	------	------	------
DEL-C23	Ceiling beam 9	88	no h/s	------	------	------
DEL-C24	Console 1	90	h/s	1500	1589	1589
DEL-C25	Console 4	127	h/s	1465	1591	1591
DEL-C26	Console 5	90	h/s	1497	1586	1586
DEL-C27	Console 6	130	11	1472	1590	1601
DEL-C28	Console 7	115	h/s	1476	1590	1590
DEL-C29	Console 8	95	5	1499	1588	1593
	Central Tower, ground-floor partition walls					
DEL-C30	North-east partition, south-west rail	100	h/s	------	------	------
DEL-C31	North-east partition, mid-post	106	no h/s	------	------	------
DEL-C32	North-east partition, north-east post	86	no h/s	------	------	------
DEL-C33	North-west partition, lower post	66	no h/s	------	------	------
DEL-C34	North-west partition, mid-post	125	h/s	------	------	------
DEL-C35	North-west partition, north-west rail	60	no h/s	------	------	------
DEL-C36	North-west partition, north-west-post	111	no h/s	------	------	------
DEL-C37	South-west partition, south-west rail	57	h/s	------	------	------
DEL-C38	South-west partition, mid-post	46	no h/s	------	------	------
DEL-C39	South-west partition, south-west post	55	h/s	------	------	------

Table 1: (continued)

Sample number	Sample location	Total rings	Sapwood rings*	First measured ring date AD	Last heartwood ring date AD	Last measured ring date AD
	Central Tower, stairs					
DEL-C40	Newel post	94	no h/s	------	------	------
DEL-C41	Tread 1 (from bottom)	60	no h/s	------	------	------
DEL-C42	Tread 2	81	no h/s	------	------	------
DEL-C43	Tread 13	75	no h/s	------	------	------
DEL-C44	Tread 15	48	no h/s	------	------	------
	Central Tower, first-floor door frames					
DEL-C45	Doorway 1, south jamb	56	h/s	------	------	------
DEL-C46	Doorway 2, north jamb	59	no h/s	------	------	------
DEL-C47	Doorway 2, south jamb	69	no h/s	------	------	------
DEL-C48	Doorway 2, lintel	74	h/s	------	------	------
DEL-C49	Doorway 3, east jamb	65	no h/s	------	------	------
DEL-C50	Doorway 3, west jamb	120	h/s	------	------	------
	Central Tower, first-floor partition walls					
DEL-C51	West partition wall, east top rail	99	h/s	------	------	------
DEL-C52	West partition wall, main central post	nm	---	------	------	------
DEL-C53	West partition wall, west mid-rail	94	h/s	------	------	------
DEL-C54	West partition wall, west stud post	97	h/s	------	------	------
	Door 1 boards					
DEL-C55	Board 1 (outer/closing board)	112	no h/s	------	------	------
DEL-C56	Board 2	145	no h/s	1376	------	1520
DEL-C57	Board 4	70	no h/s	1368	------	1437

nm = sample not measured

h/s = the heartwood/sapwood ring is the last ring on the sample

C? = possible complete sapwood retained on sample, last measured ring is possibly the felling date of the timber represented

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Table 2: Results of the cross-matching of oak site sequence DELCSQ01 and relevant reference chronologies when the first-ring date is AD 1465 and the last-ring date is AD 1601

Reference chronology	Span of chronology	*t*-value	Reference
Chiddingly Place, East Sussex	AD 1324–1576	8.0	(Arnold and Litton 2003)
Avebury Manor, Avebury, Wiltshire	AD 1393–1596	7.8	(Arnold and Howard 2011 unpubl)
Long House, 62 Strand Street, Sandwich, Kent	AD 1466–1561	7.2	(Arnold *et al* 2001)
Cobham Hall, Cobham, Kent	AD 1317–1662	7.1	(Arnold *et al* 2003)
Church of St Andrew, Welham, Leicestershire	AD 1443–1633	6.7	(Arnold *et al* 2005)
Upwich, Droitwich, Worcestershire	AD 1454–1651	6.7	(Groves and Hillam1997)
Church of St Peter, Aston Flamville, Leicestershire	AD 1475–1620	6.4	(Arnold *et al* 2005)
Ightham Mote, Ivy Hatch, Kent	AD 1276–1648	6.2	(Howard 2002 unpubl)

Table 3: Results of the cross-matching of oak site sequence DELCSQ06 and relevant reference chronologies when the first-ring date is AD 1368 and the last-ring date is AD 1520

Reference chronology	Span of chronology	*t*-value	Reference
Baltic (area 1) panel paintings - imported	AD 1156 – 1597	8.2	(Hillam and Tyers 1995)
Flemish masters panel paintings – imported	AD 1169 – 1518	7.3	(Lavier and Lambert 1996)
Fulham Palace gate boards, London - imported	AD 1319 – 1484	7.0	(Bridge and Miles 2004)
Bowhill ceiling boards, Exeter, Devon - imported	AD 1161 – 1483	6.8	(Groves 2004)
Sutton House wall panelling (area 1), London - imported	AD 1259 – 1516	6.3	(Tyers 1991)
Otley Hall, wall panelling (area 2) Suffolk - imported	AD 1374 – 1584	6.0	(Tyers 2000)
Otley Hall, wall panelling (area 1) Suffolk - imported	AD 1259 – 1519	5.5	(Tyers 2000)
Albion Place barrel staves, Clerkenwell, London - imported	AD 1363 – 1478	5.5	(Tyers unpubl)

Table 4: Results of the cross-matching of pine site sequence DELCSQ07 and relevant reference chronologies when the first-ring date is AD 1520 and the last-ring date is AD 1689

Reference chronology	Span of chronology	*t*-value	Reference
Norway: 11-13 Oslo Bolvaerk	AD 1479–1622	7.7	(Daly *pers comm*)
Norway: Grunnskala Flesberg	AD 1383–1954	5.8	(Eidem 1959)
Sweden: Helsingland	AD 1001–1861	5.1	(Bartholin *pers comm*)
Sweden: Uppland	AD 1031–1638	5.0	(Bartholin *pers comm*)
Bromley Hall, London Borough of Tower Hamlets - imported	AD 1520–1689	7.0	(Bridge 2015)
107 Jermyn Street, City of Westminster, London (3) - imported	AD 1367–1710	6.8	(Groves and Locatelli 2005)
107 Jermyn Street, City of Westminster, London (4) - imported	AD 1507–1700	6.3	(Groves and Locatelli 2005)
Kirkleatham Hall Stables, Redcar, North Yorkshire (2) - imported	AD 1550–1701	5.7	(Arnold and Howard 2013)
73 Kew Green, Richmond, Surrey - imported	AD 1551–1699	5.5	(Tyers *pers comm*)

FIGURES

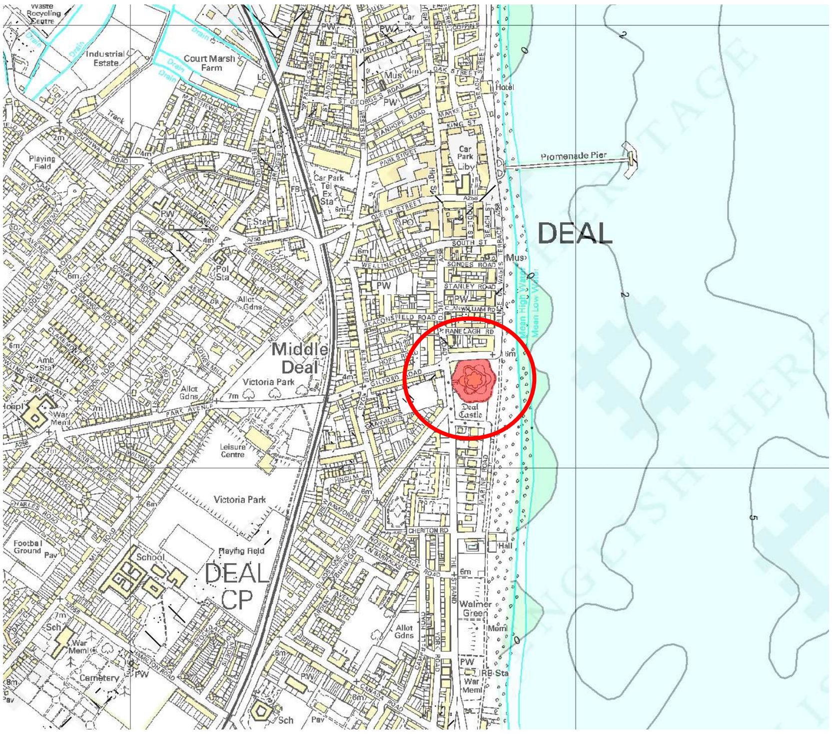


Figure 1a–b: Map to show the location of Deal (top) and Deal Castle (bottom) © Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900

Figure 2a–b: View of the timbers to the Gatehouse roof (top), and the ceiling beams, consoles, and partition wall timbers of the Central Tower (bottom) (photographs Robert Howard)

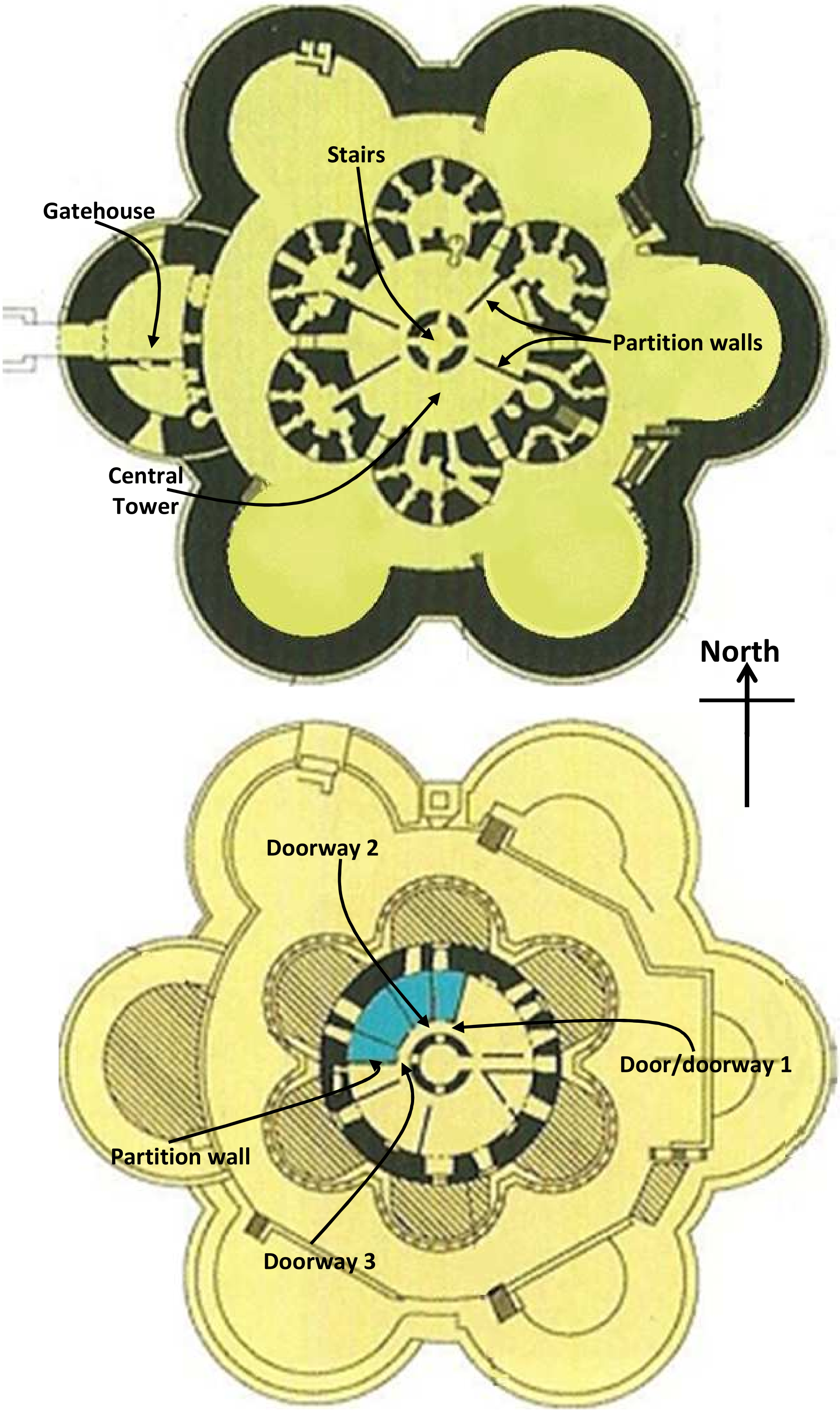


Figure 3a–b: Ground/first-floor plans (top/bottom) of Deal Castle to show sampled areas (after English Heritage Guidebook: Deal Castle)

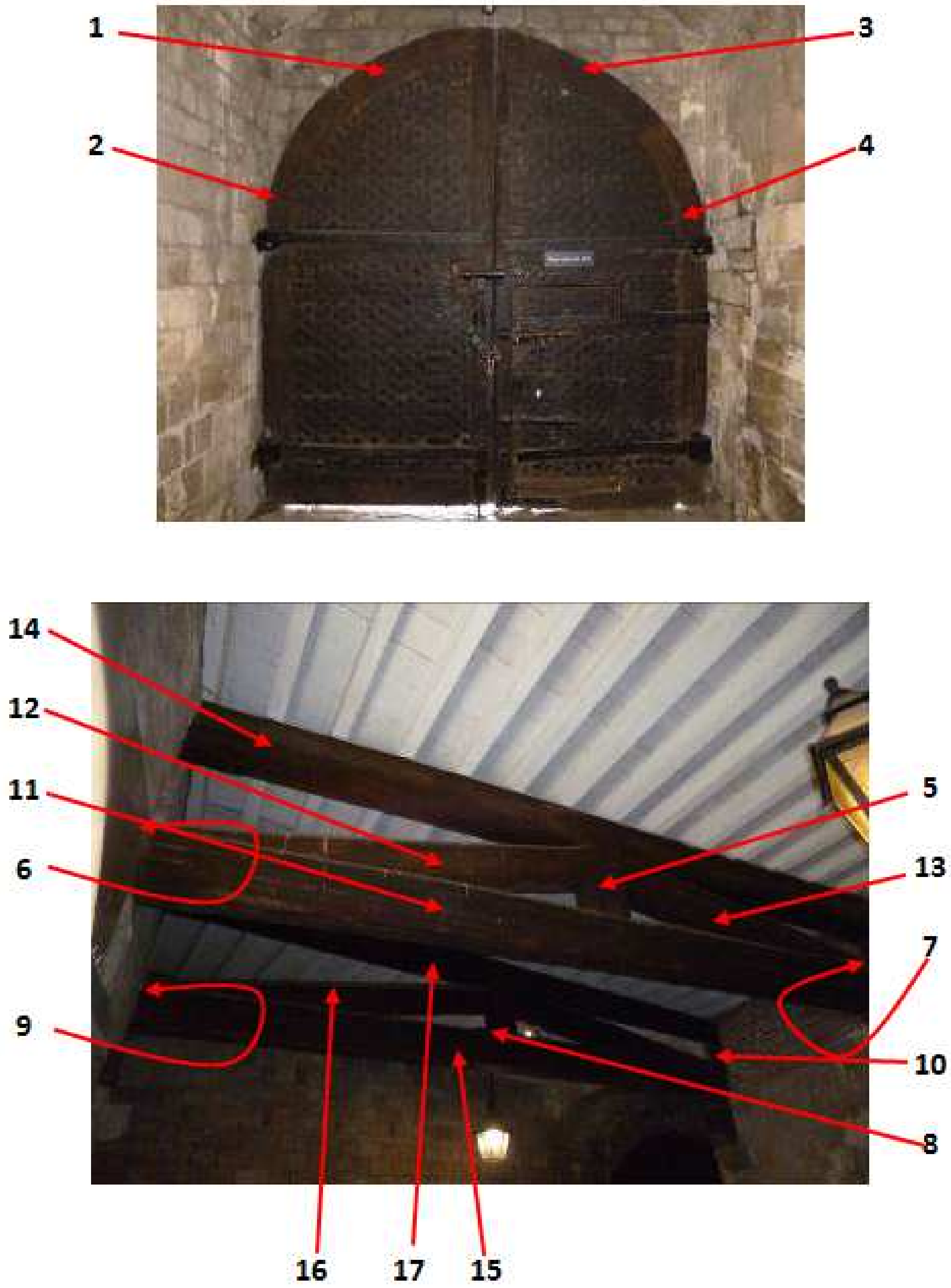


Figure 4a–b: Photographs to help locate sampled timbers of the main gates (top) and the Gatehouse roof (bottom) (photographs Robert Howard)

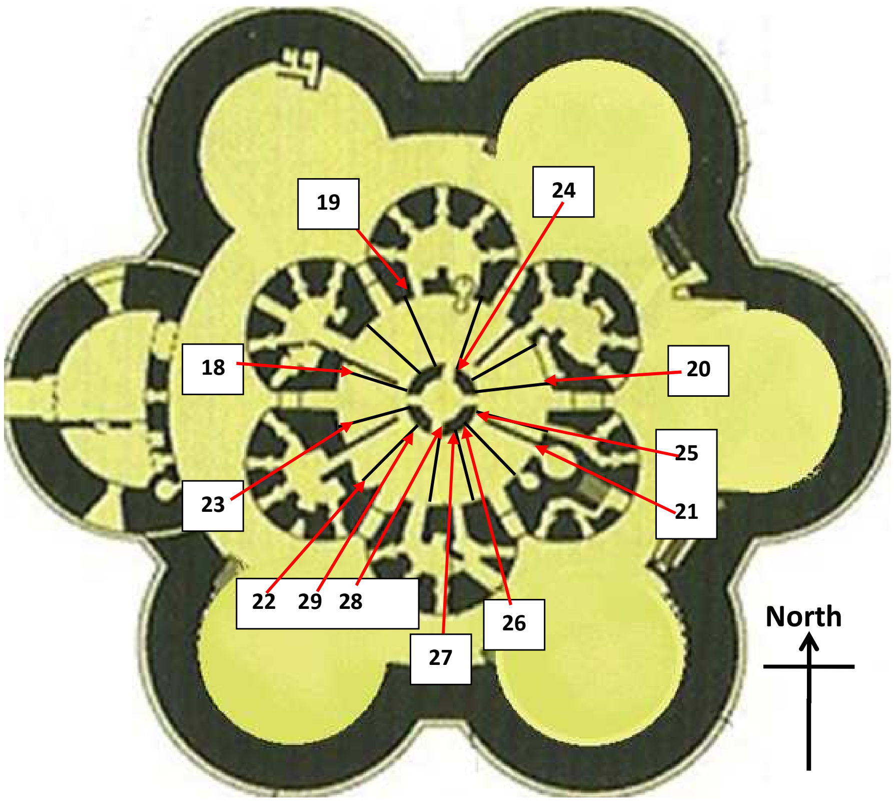


Figure 4c: Annotated plan at ground-floor level to help locate sampled timbers (after English Heritage Guidebook: Deal Castle)

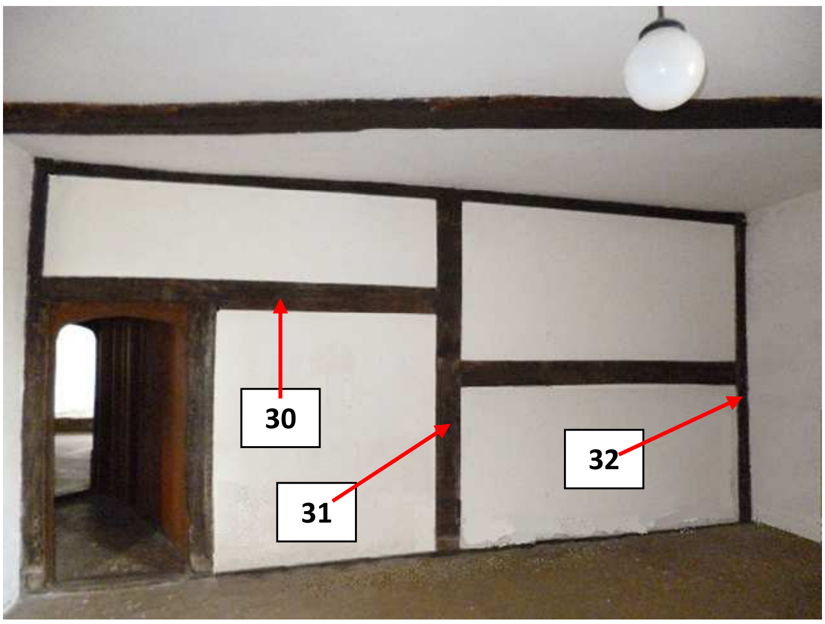
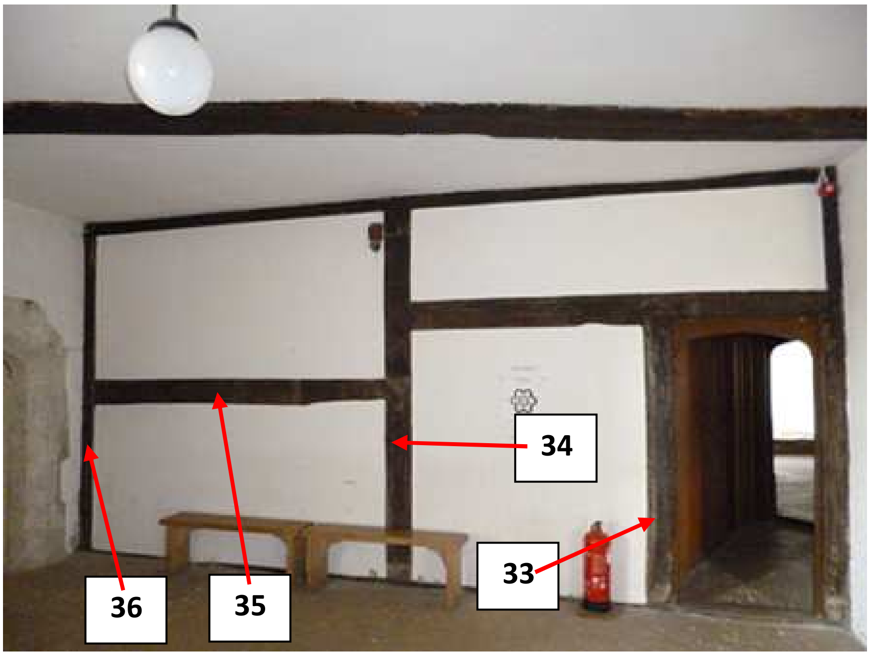


Figure 4d: Photograph to help locate sampled timbers from the north-east ground-floor partition wall (photographs Robert Howard



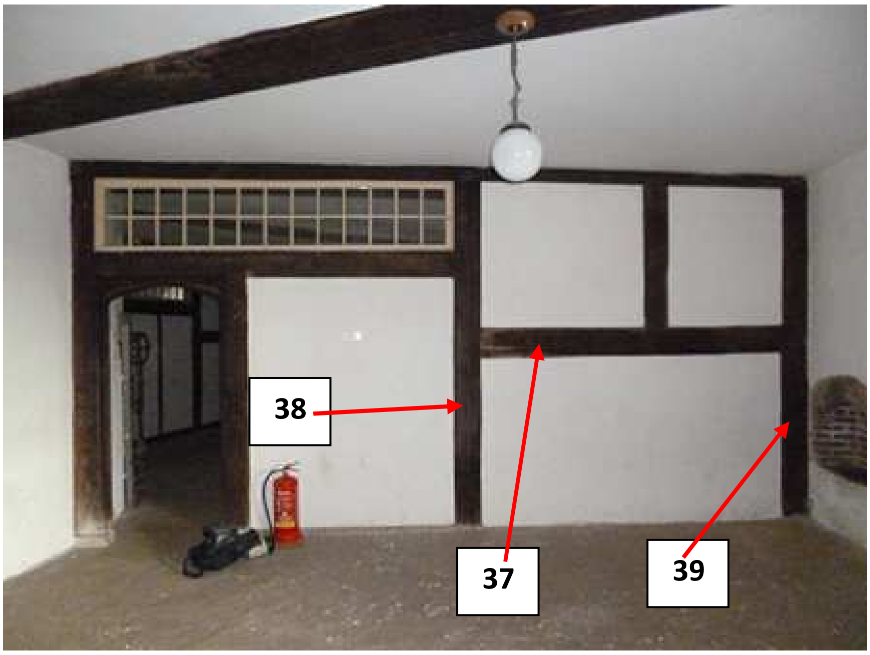


Figure 4e–f: Photographs to help locate sampled timbers from the south-west (top) and south-east (bottom) ground-floor partition walls (photographs Robert Howard)

Figure 4g: General view of the newel post and stairs (cored as samples DEL-C40–44) (photograph Robert Howard)

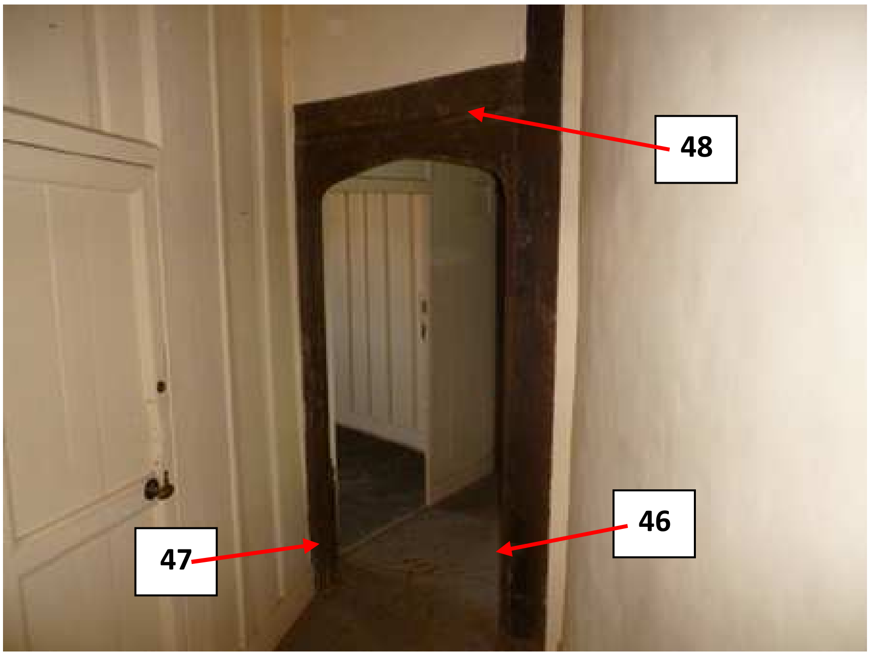


Figure 4h–i: Photographs to help locate sampled timbers of the first-floor doorway 1 (top) and 2 (bottom) (photographs Robert Howard)

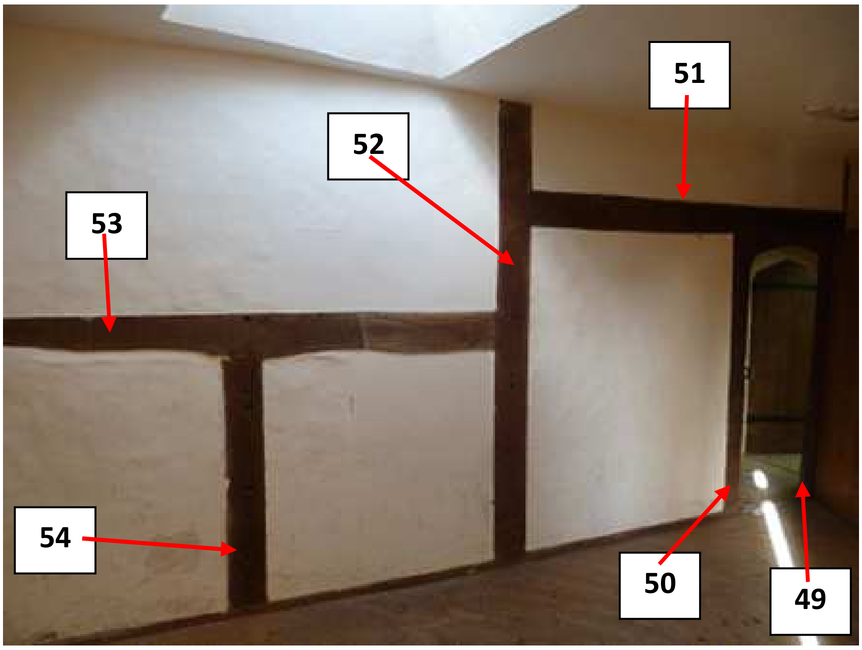
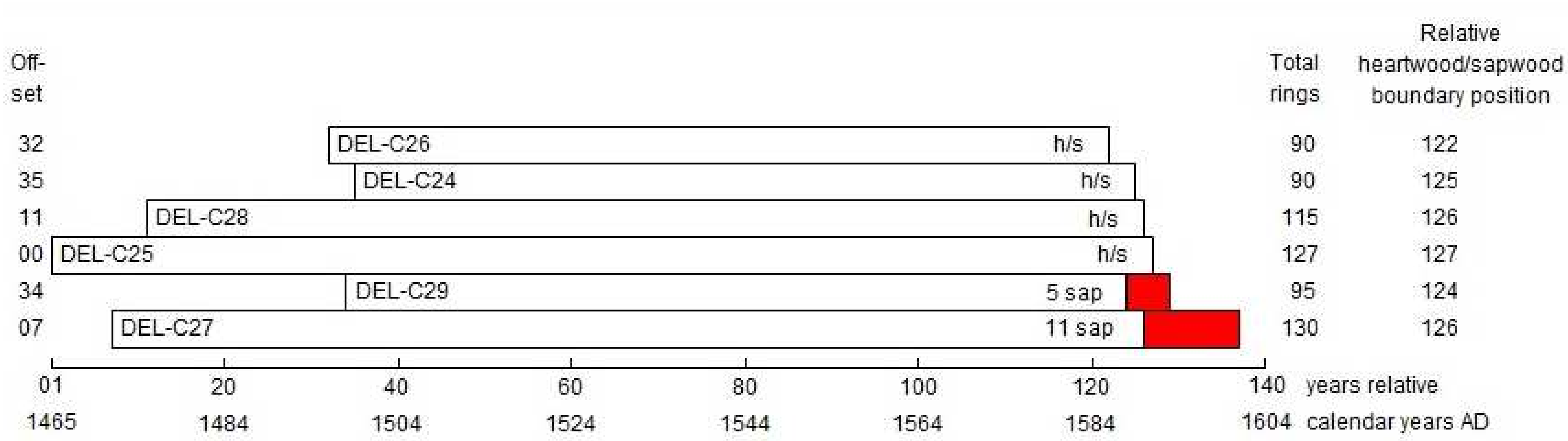
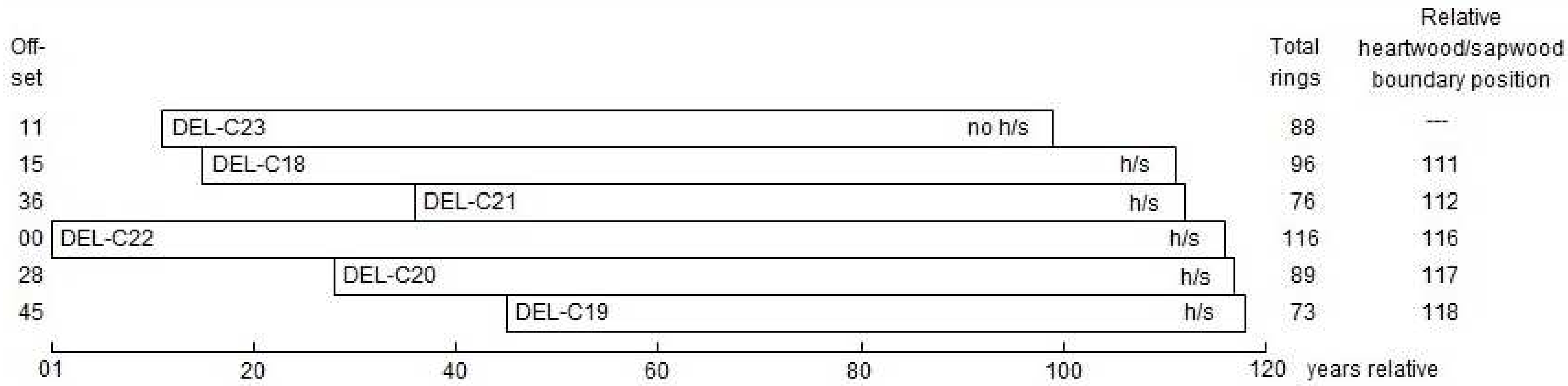


Figure 4j–k: Photograph to help locate sampled timbers of the first-floor partition wall and doorway 3 (top) and board-built door (bottom) (photographs Robert Howard)



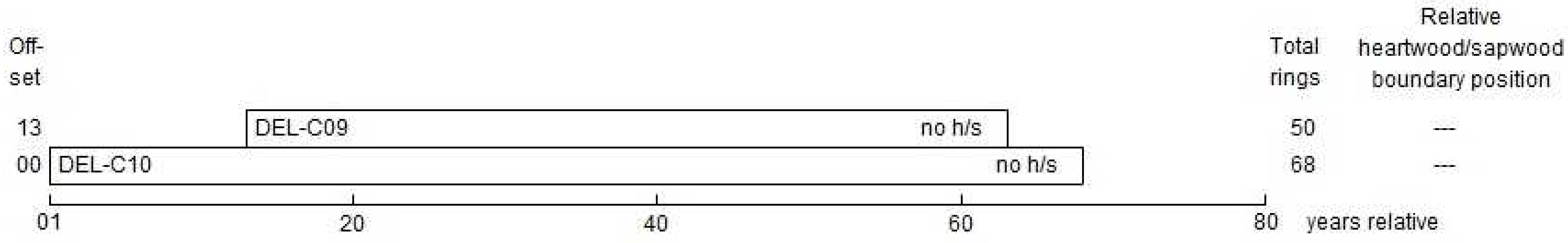
White bars = heartwood rings, red bars = sapwood rings; h/s = heartwood/sapwood boundary

Figure 5: Bar diagram of the oak samples, all from consoles of the ground-floor ceiling timbers in the Central Tower, in site chronology DELCSQ01



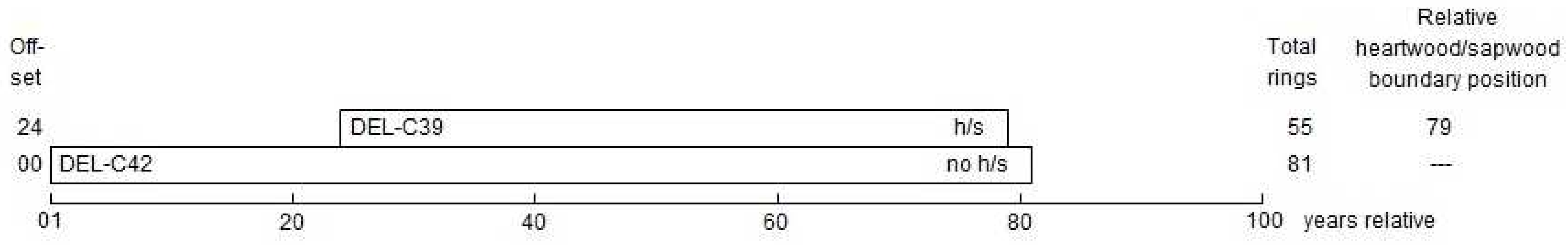
White bars = heartwood rings, h/s = heartwood/sapwood boundary

Figure 6: Bar diagram of the oak samples, all from ground-floor ceiling beams in the Central Tower, in site chronology DELCSQ02



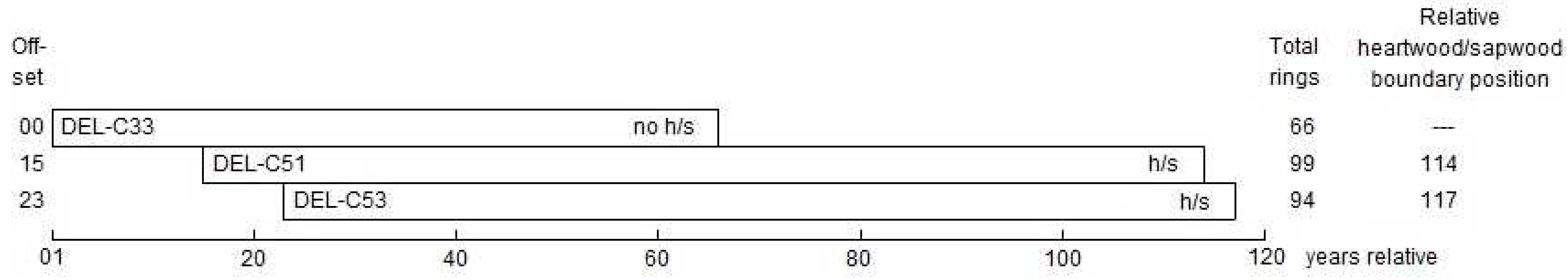
White bars = heartwood rings, h/s = heartwood/sapwood boundary

Figure 7: Bar diagram of the oak samples, both from short posts associated with the south truss in the Gatehouse, in site chronology DELCSQ03



White bars = heartwood rings, h/s = heartwood/sapwood boundary

Figure 8: Bar diagram of the oak samples, both from different elements of the Central Tower, in site chronology DELCSQ04



White bars = heartwood rings, h/s = heartwood/sapwood boundary

Figure 9: Bar diagram of the oak samples, all associated with partitions in the Central Tower, in site chronology DELCSQ05

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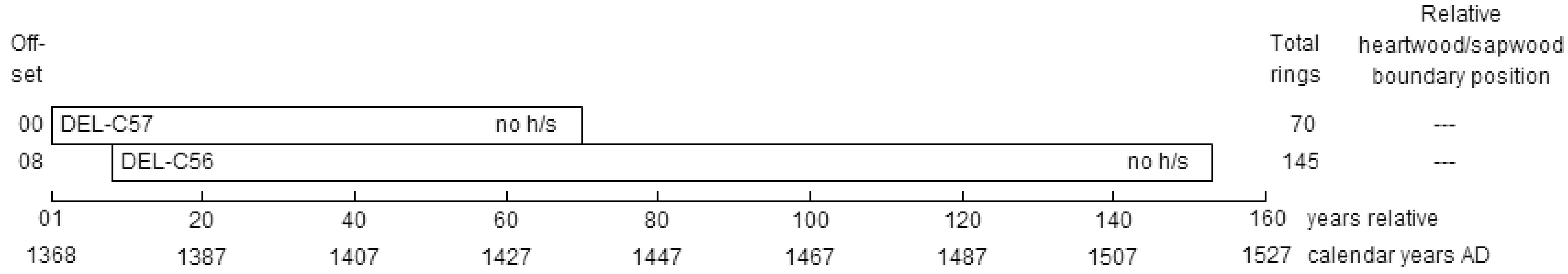

White bars = heartwood rings, h/s = heartwood/sapwood boundary

Figure 10: Bar diagram of the oak samples, both associated with boarded first floor door in the Central Tower, in site chronology DELCSQ06

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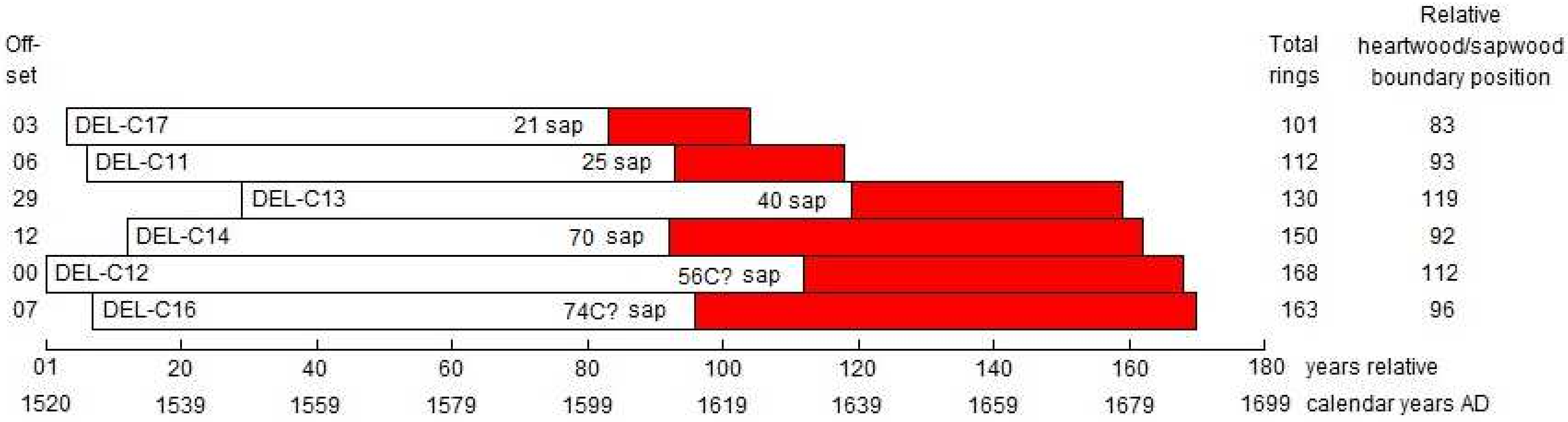

White bars = heartwood rings, red bars = sapwood rings

C? = possible complete sapwood retained on sample, last measured ring is possibly the felling date of the timber represented

Figure 11: Bar diagram of the pine samples, all from the roof of the Gatehouse, in site chronology DELCSQ07

DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

DEL-C01A 45
144 164 108 116 129 108 128 192 237 203 278 150 173 130 110 196 196 151 191 192
114 67 78 114 82 121 101 75 105 77 79 96 96 92 80 102 109 96 121 88
92 115 143 147 163
DEL-C01B 45
135 164 104 125 123 104 122 188 186 206 290 182 189 125 121 180 189 154 178 196
96 68 74 102 92 127 98 71 103 72 81 101 107 95 76 106 116 92 115 100
89 117 132 168 135
DEL-C02A 91
319 194 150 360 386 395 121 140 282 130 71 130 146 201 130 149 147 160 149 136
131 75 86 87 110 85 118 200 160 171 195 212 189 150 230 280 210 207 183 180
213 214 182 181 164 200 214 184 195 199 173 145 184 141 155 210 167 189 173 139
120 92 104 124 178 160 100 90 87 92 84 82 89 84 86 88 78 64 82 100
73 81 86 94 116 95 131 143 150 145 187
DEL-C02B 91
365 177 152 335 372 389 117 151 280 137 66 135 134 171 139 130 144 138 150 120
76 91 120 102 121 100 126 238 171 167 189 204 189 150 220 286 213 203 179 179
200 224 179 178 162 198 218 181 195 200 165 153 195 139 157 215 176 198 170 132
121 92 93 120 176 150 98 85 91 96 72 88 85 84 94 78 67 71 85 104
85 80 72 103 115 96 140 125 165 140 179
DEL-C03A 42
186 330 424 257 201 442 278 280 259 462 403 492 492 457 635 603 348 657 682 417
996 642 634 704 742 490 461 584 694 624 565 615 426 293 448 479 534 231 404 303
334 310
DEL-C03B 42
165 338 422 259 209 439 300 290 251 457 431 489 507 493 640 628 353 653 663 429
908 638 628 715 737 504 451 565 663 627 565 606 421 297 427 482 532 225 406 287
338 315
DEL-C05A 71
347 347 464 435 534 478 452 564 303 368 482 449 653 352 497 391 522 297 246 301
214 90 57 96 120 73 139 150 215 231 568 234 103 42 57 67 112 142 247 122
264 184 220 126 145 296 239 93 228 159 134 92 137 182 165 90 87 85 80 58
53 56 45 46 53 53 51 56 42 59 68
DEL-C05B 71
336 364 463 440 530 468 432 584 325 393 492 443 639 338 471 412 517 302 252 301
207 95 45 103 121 78 134 148 220 231 584 229 98 48 51 57 106 129 242 120
251 192 203 114 157 280 234 100 213 170 115 94 159 189 172 89 93 87 78 52
55 59 43 45 53 64 49 42 46 59 67
DEL-C07A 57
231 194 273 236 352 601 389 418 316 541 394 515 457 321 432 385 488 519 505 439
381 498 431 353 441 428 346 352 395 268 222 287 221 281 275 198 213 178 224 269
140 169 253 259 258 307 467 409 321 318 301 235 367 226 245 240 345
DEL-C07B 57
235 195 275 246 338 586 428 414 330 503 431 545 465 301 441 372 468 497 521 416
371 519 446 328 440 417 351 400 407 256 246 286 232 276 275 193 218 180 204 269
139 162 260 240 242 293 488 406 303 321 290 240 363 208 247 249 330
DEL-C08A 71
302 303 200 166 150 70 102 73 204 390 423 290 243 317 318 195 360 296 232 369

282 174 470 239 328 329 590 331 345 393 434 296 517 361 436 229 158 149 171 178
243 293 275 187 239 295 309 263 203 256 304 195 279 256 274 211 262 350 274 166
181 404 279 146 202 193 258 223 150 190 357
DEL-C08B 71
285 305 200 169 155 62 95 73 203 403 414 284 258 319 319 186 363 297 223 378
290 177 460 236 313 317 548 296 328 398 426 300 526 362 429 231 157 143 175 189
235 289 278 177 229 299 305 271 198 256 296 203 274 293 265 210 268 349 260 174
178 399 289 129 215 192 265 233 143 202 348
DEL-C09A 50
541 359 284 239 198 352 272 294 366 278 307 196 209 139 177 275 247 330 244 254
323 549 432 278 318 320 237 329 326 343 325 248 173 209 321 225 317 359 232 219
165 185 360 254 204 234 295 331 234 300
DEL-C09B 50
573 321 280 240 199 354 278 298 366 275 315 197 203 142 181 269 255 331 235 265
313 541 429 276 329 314 239 331 315 339 328 262 175 222 330 235 323 362 221 221
151 184 370 252 209 228 306 334 243 290
DEL-C10A 68
235 320 321 317 250 184 198 255 221 158 85 85 376 462 413 343 342 324 459 368
348 450 396 328 226 188 203 239 242 275 221 179 198 276 428 326 279 334 287 331
340 230 257 254 175 167 200 298 206 264 232 137 167 96 125 214 157 181 203 305
271 237 292 261 260 156 126 190
DEL-C10B 68
238 376 313 316 254 189 198 260 223 160 89 93 354 461 400 342 342 335 440 355
357 457 389 317 228 176 200 239 246 289 228 186 202 278 410 315 279 359 309 335
338 232 251 256 181 150 208 300 212 253 234 143 165 95 121 219 158 178 216 298
271 234 306 253 262 156 120 232
DEL-C11A 112
276 196 229 256 204 216 245 273 246 225 182 185 169 316 209 232 232 160 139 151
182 182 152 175 149 175 183 192 148 171 128 125 203 203 153 139 140 129 135 132
126 151 150 185 189 213 159 140 195 160 151 142 118 157 165 210 202 186 165 189
165 178 153 234 193 159 215 189 155 189 161 175 155 131 113 117 177 195 184 139
127 122 146 119 162 161 162 142 124 96 125 190 128 131 158 153 137 151 134 156
153 129 129 104 126 106 121 115 118 94 93 129
DEL-C11B 112
252 202 225 261 206 224 246 264 250 222 187 182 176 312 203 227 231 159 140 150
183 177 153 178 150 174 183 191 146 166 123 119 207 198 154 142 142 123 134 134
115 159 148 191 189 214 159 139 197 158 157 143 123 157 164 210 195 190 160 189
162 170 167 225 167 163 226 198 156 187 162 175 159 131 111 116 177 197 186 139
129 119 150 120 161 159 161 150 115 100 121 187 119 136 151 152 143 154 123 170
145 131 130 106 124 103 125 106 120 98 93 131
DEL-C12A 168
296 200 221 156 254 343 275 234 246 278 260 234 254 225 183 232 169 197 153 215
135 134 131 133 134 132 105 130 146 128 158 185 108 157 132 153 104 128 170 146
166 165 128 134 135 111 111 115 90 85 96 112 93 87 86 95 101 106 109 101
103 97 73 65 77 100 88 75 64 50 70 65 70 75 82 55 67 90 82 70
74 67 76 76 75 64 46 59 78 75 78 77 67 51 45 57 66 75 33 38
53 52 44 48 51 46 42 39 53 53 40 65 28 83 59 64 67 74 68 41
52 50 52 43 28 48 60 69 43 31 68 60 61 54 53 49 50 40 40 50
59 51 47 44 50 59 42 51 53 55 43 34 38 31 32 28 37 34 40 49
46 48 42 50 51 42 54 59
DEL-C12B 168
244 202 209 163 256 341 271 239 244 282 269 244 268 227 187 217 156 196 137 239
139 125 135 132 133 133 110 120 147 133 158 182 110 151 142 149 105 128 168 149

171 162 129 131 135 111 109 118 90 89 96 112 90 84 89 96 100 103 112 104
90 98 71 60 81 109 84 79 62 45 64 71 67 69 90 56 68 81 84 71
73 72 70 81 73 65 45 59 76 79 79 73 67 53 50 57 61 81 32 40
54 50 40 51 50 50 40 36 54 45 41 64 29 81 55 62 68 68 67 48
59 47 55 42 30 49 63 67 46 28 71 57 58 56 53 46 51 33 40 44
61 46 54 42 51 55 41 52 55 54 46 37 37 32 31 33 35 31 46 46
45 48 40 50 54 41 49 62
DEL-C13A 130
455 456 495 446 466 462 422 399 402 446 350 304 208 184 193 202 157 175 242 151
251 267 206 157 98 143 198 201 208 201 179 186 182 162 150 178 228 190 200 148
159 154 157 218 203 231 173 179 151 110 95 131 93 156 162 142 141 134 143 156
127 109 190 171 156 153 137 165 140 113 108 100 191 153 168 118 119 109 111 126
99 91 85 107 84 59 68 56 65 74 85 93 87 88 86 71 52 59 71 70
60 50 44 43 46 46 47 37 38 31 29 28 42 43 35 37 45 27 34 35
36 40 46 38 40 40 25 39 28 40
DEL-C13B 130
444 462 501 447 462 472 419 398 407 437 351 298 219 170 202 207 156 173 235 152
262 260 207 157 99 145 198 207 212 197 173 185 178 165 150 184 229 192 187 156
160 150 166 223 206 226 184 173 153 114 89 132 102 158 161 142 143 132 140 156
122 111 178 172 162 161 135 165 131 106 111 97 192 153 172 116 118 109 110 126
98 95 91 103 86 57 65 54 62 75 81 96 93 87 90 75 54 56 71 69
56 49 52 41 43 55 46 38 33 31 28 32 48 43 34 30 35 34 34 37
40 40 45 35 42 35 30 40 29 39
DEL-C14A 150
334 211 87 394 321 491 343 324 266 318 336 287 362 295 232 281 242 268 253 253
256 246 185 153 122 113 143 206 147 139 156 162 178 150 160 242 177 238 186 228
132 162 164 153 137 130 129 97 102 103 100 102 87 128 114 90 96 82 89 67
60 82 147 90 101 87 81 72 89 59 114 142 128 115 78 68 91 127 102 160
109 81 75 48 90 90 61 54 121 99 101 125 104 98 100 90 100 71 75 65
75 59 46 47 33 53 62 31 53 34 25 40 33 34 43 46 53 56 49 37
32 45 47 55 53 42 34 28 37 35 49 48 54 65 44 54 46 59 63 71
50 52 43 39 42 50 50 79 62 73
DEL-C14B 150
336 208 79 359 313 483 341 323 256 357 338 293 350 298 225 285 243 264 249 258
241 235 196 153 120 117 154 207 145 143 162 160 179 140 160 243 178 235 185 238
130 160 161 152 139 129 126 100 104 100 99 108 87 125 114 90 95 82 89 67
64 87 142 90 104 89 84 67 87 62 113 137 130 112 77 77 96 114 101 167
119 78 62 58 84 90 71 71 110 96 97 125 103 100 97 88 97 87 62 68
84 59 43 47 31 52 66 34 52 35 29 37 37 34 44 46 52 56 42 46
36 42 52 50 50 43 34 27 40 37 43 52 55 68 37 57 46 61 63 71
53 50 44 39 41 50 53 75 62 65
DEL-C15A 337
106 64 69 70 79 81 84 79 62 111 90 94 85 64 62 34 36 39 39 28
47 44 56 41 40 33 39 50 36 43 54 63 48 46 60 66 58 44 46 38
35 48 35 39 30 28 28 32 32 37 60 46 71 69 60 37 55 41 62 77
40 38 38 36 25 32 17 20 19 16 16 26 17 21 21 22 28 21 20 15
14 28 21 25 34 27 38 37 37 58 72 50 82 77 50 64 53 64 81 60
65 53 51 66 52 42 53 42 30 29 35 25 21 15 14 13 15 16 7 13
11 18 24 21 28 25 24 32 32 45 33 25 19 17 10 7 8 10 9 4
10 10 17 15 13 18 17 7 14 17 10 15 12 7 3 4 10 11 17 10
10 6 4 10 12 7 16 14 17 14 16 11 25 19 14 22 15 28 32 24
26 26 20 28 23 17 7 32 29 25 24 31 21 16 18 22 32 46 23 39
32 31 39 43 50 68 45 45 53 82 64 71 73 67 95 60 78 144 112 78

73 75 101 71 75 103 112 97 74 73 104 94 102 97 81 68 75 79 62 68
83 85 64 85 81 68 66 72 62 67 78 97 53 45 49 44 46 39 35 56
51 54 54 39 39 24 26 23 16 24 23 29 26 34 28 27 21 37 26 29
24 26 29 29 28 28 32 35 29 29 24 22 29 12 18 25 23 21 15 23
21 14 21 21 20 18 17 14 25 26 18 17 26 29 23 26 20 26 26 23
25 26 25 28 29 20 19 24 12 24 19 20 20 18 14 15 19
DEL-C15B 337
97 61 66 73 85 79 87 84 62 110 92 94 92 69 58 37 38 34 38 27
46 44 42 43 47 28 44 46 39 41 58 54 57 53 60 60 58 44 48 39
35 42 37 41 28 25 31 32 32 37 56 46 71 72 71 38 54 42 58 76
46 34 38 35 25 33 19 20 12 17 20 25 20 21 14 24 28 22 21 18
14 31 23 22 33 29 33 39 38 59 76 51 81 75 50 68 53 69 79 62
64 53 57 62 53 39 42 39 29 29 31 28 20 16 13 12 10 10 10 12
9 13 23 24 19 22 23 28 26 37 43 33 29 17 17 12 11 8 14 10
8 8 8 14 18 13 20 16 16 10 13 9 16 10 9 5 8 10 8 13
9 9 10 11 13 12 15 16 16 18 10 12 18 20 14 16 22 33 31 25
25 25 24 24 25 16 7 33 25 29 23 25 22 16 22 30 28 37 25 44
32 33 33 37 57 62 42 49 50 79 67 67 78 66 94 58 80 144 112 77
71 75 99 72 74 103 114 96 72 78 105 92 100 96 80 67 77 87 60 64
85 89 71 82 71 75 71 72 60 71 69 91 57 42 50 44 44 33 41 63
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21 14 25 19 16 24 16 14 26 24 17 15 27 34 24 26 18 25 26 22
23 28 28 26 25 17 26 19 15 18 21 19 23 17 12 16 23
DEL-C16A 163
167 160 149 190 169 212 228 186 196 162 173 175 208 180 173 192 178 190 195 170
141 150 145 154 162 71 96 117 131 103 109 160 174 151 109 110 128 142 101 112
119 104 109 112 92 103 96 92 84 103 93 107 103 107 99 95 93 104 141 107
86 78 60 85 75 67 50 85 67 79 76 73 78 82 53 75 71 66 68 39
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50 46 53 56 29 28 31 40 37 37 49 68 81 51 52 59 65 53 47 43
65 76 106
DEL-C16B 163
160 152 154 188 170 209 225 184 196 160 180 180 207 182 169 190 177 191 192 157
135 163 146 147 160 82 96 113 141 106 103 160 173 153 111 107 130 148 99 104
123 104 108 112 87 101 101 92 84 107 90 107 111 105 100 93 85 109 132 103
95 73 64 85 70 70 53 82 68 79 73 75 76 79 53 69 75 69 67 42
64 74 57 79 82 76 72 46 43 65 69 43 37 60 51 32 46 51 42 35
44 54 62 40 32 59 34 26 38 32 53 45 48 45 43 42 48 29 34 51
60 48 29 45 30 43 39 48 54 50 28 30 37 62 50 46 40 52 47 62
43 48 54 56 28 30 34 39 32 43 47 70 79 53 50 59 65 58 47 33
78 62 96
DEL-C17A 101
179 179 246 199 126 189 179 201 192 250 250 230 200 162 232 160 221 164 204 195
162 176 196 210 228 175 165 156 225 211 259 152 137 85 128 175 209 233 93 112
195 240 175 187 198 128 168 150 96 104 78 89 70 40 66 87 104 93 111 128
106 112 192 102 117 84 107 84 86 100 91 85 92 106 109 145 110 125 78 152
131 81 62 90 95 125 108 116 133 93 79 83 77 115 103 59 74 109 111 79
97
DEL-C17B 101
180 178 246 195 121 201 175 225 194 247 257 221 198 153 237 137 210 171 202 199

157 185 192 203 229 185 157 146 228 213 247 150 135 87 114 173 218 226 108 100
188 234 160 198 203 129 159 149 103 112 60 93 62 46 68 87 101 85 125 98
117 129 195 110 110 75 94 87 85 95 89 89 89 109 115 132 115 123 76 151
135 78 71 87 84 140 107 115 121 87 84 87 77 111 102 62 74 98 130 81
115
DEL-C18A 96
396 301 292 246 384 435 275 360 246 316 285 149 232 211 205 294 375 315 285 286
209 200 160 182 197 198 196 187 140 262 177 200 243 270 245 207 199 183 268 293
243 255 210 155 119 178 168 166 139 121 144 126 135 145 150 164 151 164 160 164
75 82 85 132 112 203 146 125 134 109 139 137 110 125 149 90 96 96 166 98
191 143 103 142 106 118 135 146 144 180 118 144 102 125 78 133
DEL-C18B 96
398 330 294 229 374 445 278 346 255 313 289 148 229 216 204 289 377 321 292 293
211 201 176 179 183 204 195 186 164 276 181 196 244 266 250 198 207 183 270 293
244 249 217 156 117 176 174 154 139 124 131 131 131 146 154 162 153 163 156 168
72 94 87 143 117 192 137 125 134 109 140 140 115 122 142 101 96 99 161 110
185 139 109 139 110 120 136 143 135 183 130 145 101 125 60 127
DEL-C19A 73
359 246 388 352 172 165 164 208 269 385 348 271 242 193 246 211 278 364 210 259
172 164 206 233 321 253 268 135 187 185 127 146 214 332 285 393 265 210 207 289
270 289 231 287 289 189 117 182 220 168 307 185 150 171 124 189 153 135 141 191
198 194 111 128 78 123 208 384 273 250 146 153 168
DEL-C19B 73
398 235 355 355 180 159 173 196 262 387 334 269 250 200 253 211 278 343 208 263
174 164 201 242 324 270 260 140 198 196 127 160 241 310 290 400 260 190 229 276
293 277 246 267 299 178 119 180 232 159 320 191 149 173 128 193 148 129 144 196
198 163 108 123 90 111 212 387 271 243 147 156 171
DEL-C20A 89
337 325 353 378 331 368 364 234 257 248 343 285 278 272 246 185 237 239 253 202
248 188 258 244 164 225 271 406 331 232 190 214 287 257 254 225 179 196 122 160
200 214 292 254 252 189 177 181 193 306 316 253 252 184 174 228 252 185 180 184
168 123 96 129 112 155 142 127 99 95 127 134 148 110 89 128 107 120 93 75
78 91 95 131 138 165 137 90 146
DEL-C20B 89
303 342 346 376 335 365 355 230 267 280 353 308 248 271 246 189 225 228 256 200
242 182 222 223 182 209 307 375 331 242 196 220 290 270 278 237 168 206 121 170
208 240 295 273 242 190 173 190 179 310 298 247 258 196 184 228 255 182 183 178
145 116 89 128 113 147 140 126 103 91 136 128 156 103 88 117 109 125 87 75
73 95 98 122 144 161 147 102 147
DEL-C21A 76
123 94 150 165 171 234 177 112 213 199 167 153 207 126 151 175 144 166 200 230
182 114 88 107 221 190 168 162 146 175 125 119 173 191 216 182 189 110 159 133
146 216 203 154 196 142 156 138 135 169 154 125 134 147 94 92 100 210 146 187
121 110 103 84 124 131 155 85 125 139 100 81 68 73 75 125
DEL-C21B 76
138 91 150 171 185 207 184 120 207 188 179 164 210 129 166 166 146 159 207 237
189 100 84 128 192 199 158 167 145 174 125 111 174 196 207 177 190 104 178 112
139 210 200 154 187 154 162 136 132 176 168 153 137 169 101 81 92 221 156 181
126 107 109 85 118 135 139 93 112 150 96 94 66 79 73 138
DEL-C22A 116
290 265 229 318 401 380 287 162 194 242 259 216 216 142 110 139 122 144 194 133
178 196 142 153 139 164 110 117 171 128 188 182 206 181 232 198 157 146 143 184
140 176 140 121 187 207 162 134 135 117 126 141 128 154 181 216 89 65 57 81

96 124 170 199 170 179 148 140 177 157 156 221 226 209 200 159 174 261 218 220
259 212 179 137 136 237 257 212 249 194 120 140 140 131 143 173 129 125 109 121
126 109 125 107 117 119 124 107 123 121 140 168 170 168 162 212
DEL-C22B 116
259 258 229 319 413 385 289 162 196 241 264 186 220 150 121 146 135 154 213 129
164 171 128 127 119 146 99 112 148 121 175 179 192 196 237 196 160 148 139 184
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96 121 173 195 171 185 150 140 174 159 154 217 225 216 201 162 184 244 213 219
275 212 168 129 132 242 271 209 231 200 115 146 133 128 139 171 117 123 121 118
121 97 134 114 118 125 113 114 115 123 146 167 167 162 168 228
DEL-C23A 88
449 258 265 169 210 350 470 385 278 284 310 317 351 371 421 184 231 327 176 305
271 238 170 235 126 189 192 176 212 132 220 210 145 187 203 155 162 181 123 154
145 125 114 142 126 155 120 110 125 154 125 143 117 126 120 110 128 189 146 148
132 134 140 160 112 100 165 128 120 186 150 111 100 109 128 149 113 146 168 100
142 129 152 135 154 104 127 134
DEL-C23B 88
445 266 252 152 217 359 451 350 280 296 300 292 360 396 453 189 226 330 178 307
271 237 163 234 134 188 184 182 203 140 210 221 140 187 203 170 162 193 120 144
147 127 120 143 131 162 115 106 128 142 126 138 117 117 126 106 127 179 142 148
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149 131 152 150 143 106 131 172
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183 194 269 176 234 148 170 181 132 110 84 164 139 139 104 160 145 154 109 139
126 118 64 84 82 88 78 57 79 114 85 65 81 59 60 59 62 62 57 56
42 45 50 53 45 46 39 40 54 64 76 90 81 81 68 68 48 54 60 84
82 76 75 68 76 84 82 66 68 90
DEL-C24B 90
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194 215 277 166 244 145 168 186 134 106 85 173 140 125 114 154 165 142 110 146
128 115 84 87 81 93 76 56 79 110 78 70 76 70 64 57 60 52 59 56
42 53 50 51 54 47 35 40 60 71 76 87 79 85 67 75 47 50 71 85
89 73 73 79 79 82 72 68 67 115
DEL-C25A 127
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151 173 107 124 137 101 138 120 132 144 114 127 120 135 120 82 70 128 100 139
99 119 129 117 73 56 142 112 120 115 147 162 153 146 136 122 128 56 98 90
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96 62 74 79 84 116 123 107 100 96 97 70 71 81 87 91 76 77 92 112
117 101 77 81 79 51 111
DEL-C25B 127
227 202 248 184 225 217 326 332 242 287 282 175 226 248 357 346 295 152 277 350
300 317 214 159 192 257 157 143 139 296 220 267 182 192 234 182 187 187 167 162
137 178 108 115 137 96 150 122 125 140 110 146 117 145 115 70 71 128 110 126
106 125 120 121 66 62 135 112 128 116 150 146 178 152 139 124 125 56 94 85
103 88 78 99 131 81 103 118 106 88 121 120 91 99 119 84 96 105 100 93
110 65 77 93 68 114 119 105 104 95 103 69 61 86 93 94 75 90 77 96
121 102 74 72 84 55 121
DEL-C26A 90
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248 330 201 156 189 271 217 327 229 202 173 173 120 96 175 183 219 139 231 200

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264 296 223 154 189 264 202 339 228 193 168 187 110 96 185 168 228 152 220 181
225 170 189 140 153 95 104 95 89 107 123 104 164 118 146 156 129 144 166 118
137 110 103 89 93 125 132 120 159 110 96 110 146 164 187 168 185 193 209 115
93 118 168 131 88 79 109 112 92 146
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112 110 93 181 135 126 84 81 82 106 60 75 67 82 81 52 89 112 85 82
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121 106 87 108 75 87 81 100 117 84 88 95 96 101 123 104 84 121 75 103
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245 127 134 158 187 175 172 162 158 135 149 85 123 157 115 170 196 162 178 229
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189 206 146 177 123 212 162 184 135 136 180 184 145 185 115 162 173 158 146 186
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210 198 207 162 151 154 242 207 295 146 146 158 169 130 107 187 193 235 169 207
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71 53 50 78 67 54 77 75 72 85 65 51 76 81 110
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149 133 153 225 139 174 158 136 124 146 85 59 182 124 114 104 203 139 126 90
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168 199 156 176 146 162 144 150 138 145 147 150 153 157 128 93 111 101 110 85
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97 74 93 128 112 168
DEL-C31B 106
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182 111 149 168 187 153 243 230 307 157 202 165 148 161 200 193 179 190 157 140
159 187 162 173 140 160 137 141 141 143 151 144 157 153 126 101 107 100 105 94
88 111 93 101 101 128 136 130 178 150 179 165 106 109 154 176 158 185 208 238
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99 88 95 123 118 186
DEL-C32A 86
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167 176 170 210 239 218 191 210 158 155 128 125 152 187 193 217 303 301 220 192
253 286 237 181 181 218 195 304 193 185 180 100 140 160 132 121 138 129 170 120
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232 220 214 135 143 150
DEL-C32B 86
231 307 297 278 321 258 259 242 195 180 137 203 200 167 175 203 242 221 223 160
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252 284 225 173 178 213 194 318 206 175 181 106 140 154 135 128 136 136 171 132
157 176 234 185 156 179 141 120 104 149 193 137 181 184 205 224 190 156 196 174
222 227 190 143 137 168
DEL-C33A 66
530 388 415 619 482 510 651 436 603 523 422 324 360 311 246 248 220 165 234 251
409 270 227 278 231 318 242 268 233 163 206 198 243 234 221 225 177 208 258 219
267 221 265 176 181 196 115 108 156 154 127 149 119 183 253 134 207 146 143 118
196 115 125 165 232 242
DEL-C33B 66
539 374 442 614 482 501 639 446 589 532 434 303 363 305 247 240 223 155 237 256
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96 91 83 102 71 75 56 57 89 87 95 92 58 62 56 54 82 104 84 75
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93 110 148 137 122 156 203 109 99 65 63 69 83 109 112 100 254 375 330 311

268 271 221 181 162
DEL-C34B 125
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250 205 246 149 93 103 111 160 153 149 118 150 99 90 52 41 41 60 84 114
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102 77 84 104 81 69 46 73 90 75 98 90 59 59 54 67 81 93 92 84
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319 256 193 177 153
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121 125 100 96 130 112 107 103 93 84 93
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152 218 212 234 153 138 151 169 153 152 130 154 177 150 162 177 117 209 186 150
203 113 72 81 107 146 148 173 225 206 145 156 123 135 185 233 169 155 123 118
96 124 121 132 117 100 162 171 140 160 156 188 236 183 135 125 110 153 146 129
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328 318 284 231 298 262 304 336 309 317 306 247 300 323 262 296 215 243 287 327
385 299 385 333 300 265 282 300 337 322 274 381 296 298 309 371 356
DEL-C37B 57
437 459 468 530 457 449 408 373 412 380 385 420 428 350 445 282 284 332 242 303
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378 309 337 375 293 266 298 303 331 334 256 396 297 283 316 402 399
DEL-C38A 46
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340 334 389 342 285 485 425 329 365 210 267 330 550 405 382 321 294 339 285 227
359 387 337 296 184 223
DEL-C38B 46
698 657 782 637 496 614 600 488 428 383 331 313 229 315 402 489 408 421 394 309
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349 391 349 303 174 240
DEL-C39A 55
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154 185 181 131 264 243 162 130 106 98 120 107 113 103 171
DEL-C39B 55
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DEL-C40B 94
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212 190 159 251 200 150 296 225 240 234 180 178 178 125 112 125 96 70 70 118
DEL-C41B 60
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317 325 296 279 239 221 219 220 226 284 312 231 162 187 221 208 238 253 202 200
212 181 171 225 216 186 278 221 209 225 184 181 168 131 112 105 106 75 87 121
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236 238 193 207 214 193 225 249 425 324 317 312 279 207 262 281 296 334 303 381
298
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447 307 311 278 309 251 262 244 252 148 262 200 242 318 307 200 228 384 283 303
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DEL-C44B 48
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175 245 225 220 315 323 298 326 355 189 193 300 180 235 194 225 199 135 200 111
136 99 157 118 143 167 153 175
DEL-C45A 56

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DEL-C45B 56
280 229 403 498 449 421 360 390 401 372 196 129 146 229 283 214 152 242 397 316
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159 215 303 214 212 306 414 253 390 209 228 240 324 278 265 368
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DEL-C46B 59
397 344 564 416 584 530 332 392 390 450 468 582 484 400 414 409 459 584 509 267
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DEL-C47A 69
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214 261 231 274 292 191 184 160 180 195 231 240 160 135 175 225 212 242 164 182
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199 193 165 344 281 227 247 362 369
DEL-C47B 69
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139 175 196 175 162 234 152 187 134 170 152 165 173 136 138 150 104 81 90 127
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DEL-C50B 120

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130 130 100 110 80
DEL-C56B 145
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140 130 100 90 70
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150 170 120 180 140 170 130 180 200 110 120 80 100 90 110 70 100 130 100 100
130 140 100 160 150 130 180 120 220 150
DEL-C57B 70
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270 300 250 260 200 200 220 170 230 120 201 200 250 190 230 110 220 170 220 160
170 170 130 201 140 160 130 180 201 120 120 90 100 100 110 80 130 120 100 100
100 120 110 150 150 120 220 120 200 120

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 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, which grew in 1976

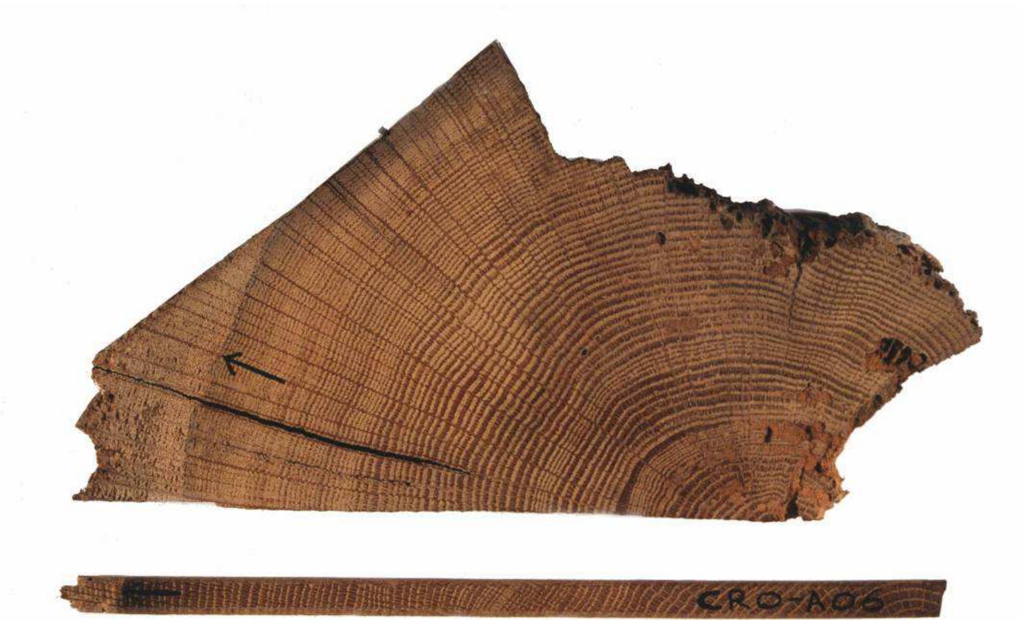


Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil

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

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

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

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

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

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

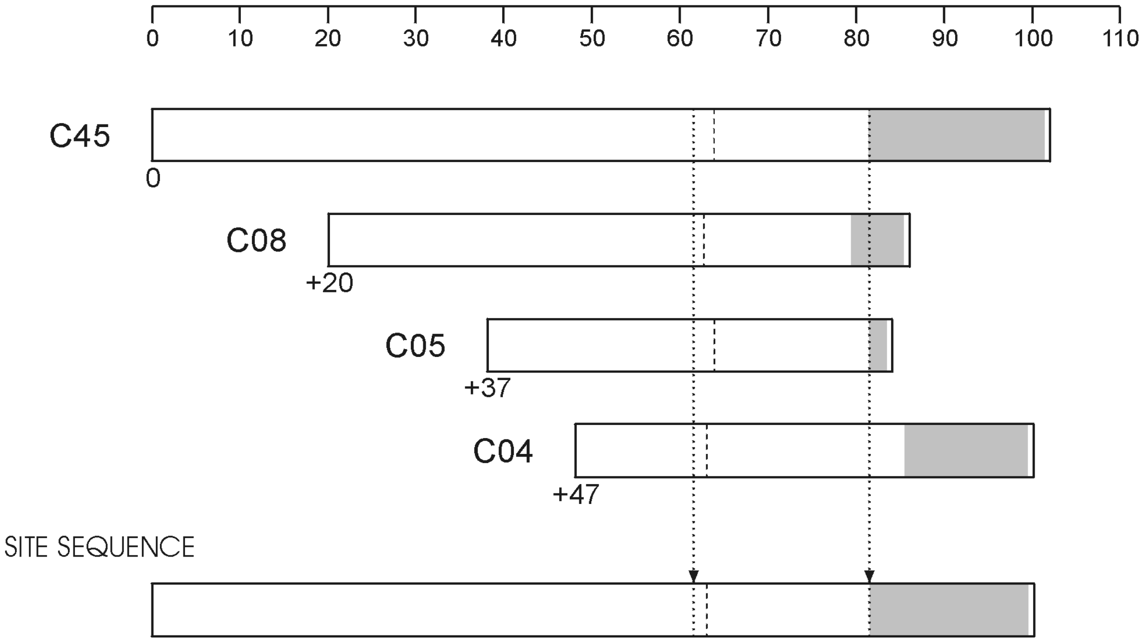


Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them

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.

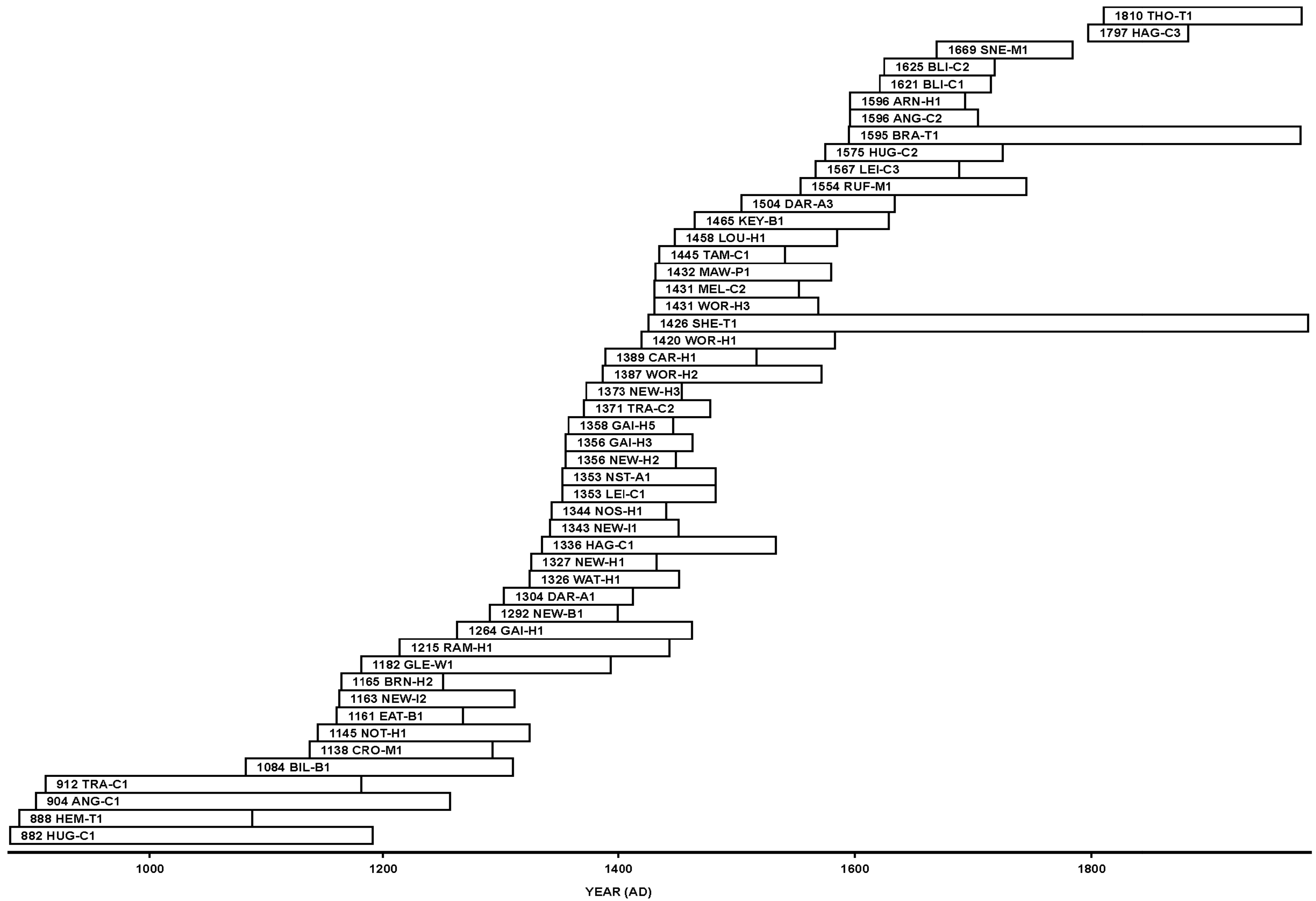
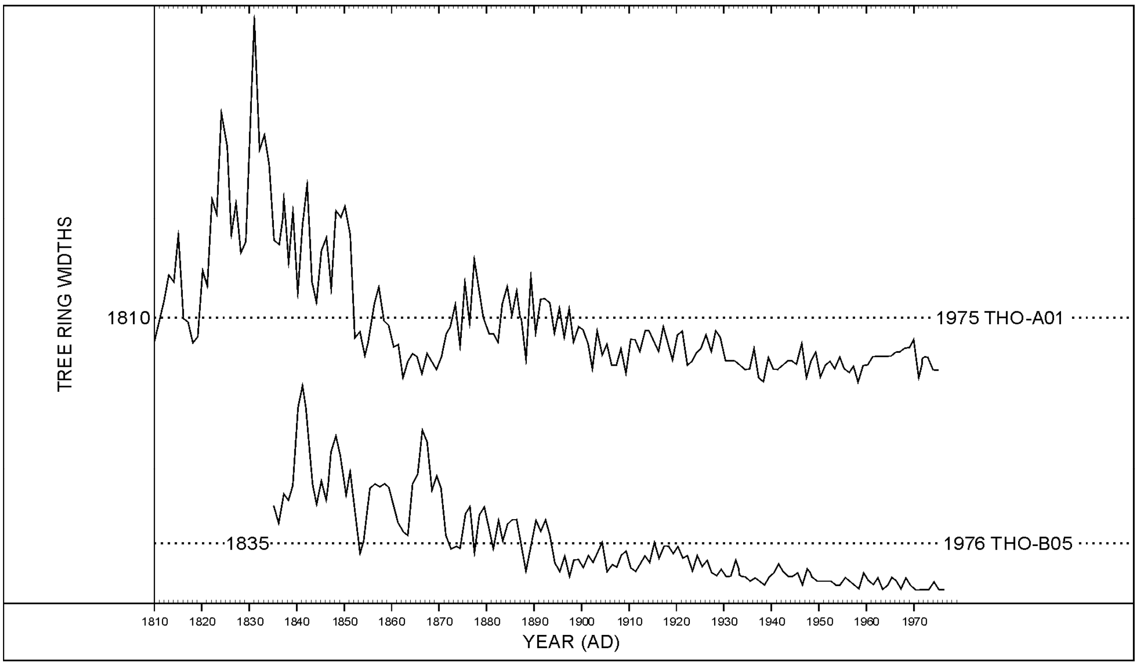


Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87

(a)



(b)

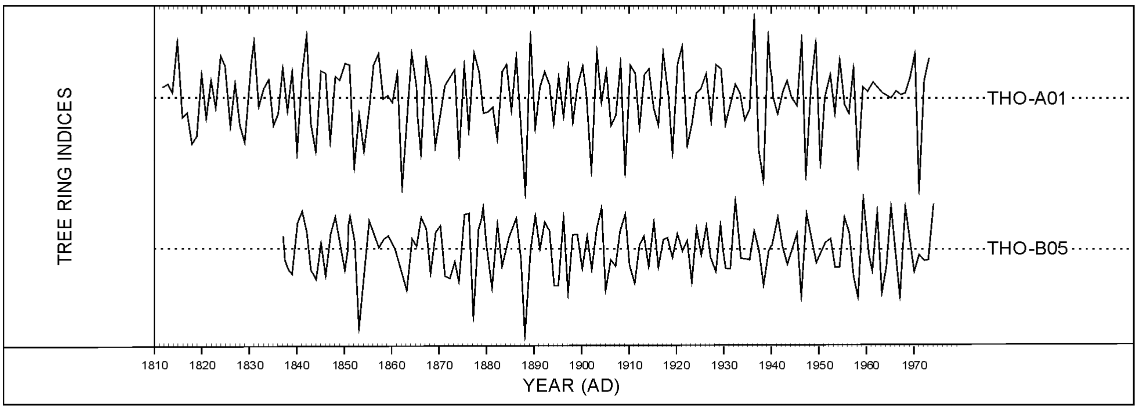


Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known

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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