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Discovery, Innovation and Science in the Historic Environment

Research Report Series no. 40-2022

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NGR: TR 37771 52197



ISSN 2059-4453 (Online)

SUMMARY
Independent validation of tentative tree-ring dating for a previously undated site chronology, DELCSQ02, from Deal Castle, Kent, has been obtained by radiocarbon wiggle-matching and it can now be considered as a radiocarbon-supported dendrochronological date that spans AD 1401–1518$_{DR}$, with its timbers having an estimated felling date in the range AD 1530$_{DR}$–1555$_{DR}$. This important result now demonstrates that the main ceiling beams of the Central Tower forming the ground-floor ceiling are all original, while its consoles date to the early seventeenth century.

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ACKNOWLEDGEMENTS
The Nottingham Tree-ring Dating Laboratory would like to thank those people whole helped during the original sampling undertaken in AD 2014–2015: both Martin Byrne, English Heritage Site Manager, for allowing access to Deal Castle, and Roy Porter, English Heritage Territory Properties Curator South, for his assistance during sampling and the valuable information provided on the possible phasing of the timbers here.



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DATE OF INVESTIGATION
2021–2022

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# INTRODUCTION

## Deal Castle

Deal Castle (Fig 1) is a scheduled ancient monument (List Entry Number 1013380) and was the middle of three such fortifications built by Henry VIII *c* AD 1539–42. These are 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, which are now also obliterated. The castle at Deal consists of a six-lobed keep with a three-storeyed central tower, surrounded by a six-lobed curtain wall and moat.

## Original tree-ring analysis

The castle has been subject to alteration and repairs over the centuries, and a substantial programme of dendrochronology was undertaken in AD 2014–15 in order to better understand the historical development of its fabric (Arnold and Howard 2015).

Dendrochronological analysis, undertaken on 51 of the 54 core samples obtained, as well as the measurements, carried out *in situ*, of three boards from a door, 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 on the ground floor of the Central Tower, is 137 rings long and spans AD 1465–1601. Interpretation of the sapwood gives these oak timbers an estimated felling date range of AD 1604–29. A second dated oak chronology comprises two door boards, one of which is derived from a timber likely to have been felled after AD 1452, and the second from a timber likely to have been felled after AD 1535. The single pine chronology, comprising six samples from the timbers of the Gatehouse roof is 170 rings long and spans 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* remained ungrouped and undated (Arnold and Howard 2015).

# RADIOCARBON DATING

As tree-ring analysis has dated relatively few timbers, with an unusually high number of samples (75%) remaining undated (Arnold and Howard 2015), it was thought justified to submit samples from the longest and best replicated of the undated site chronologies, DELCSQ02, for radiocarbon wiggle-matching. DELCSQ02 contains all six of the ground-floor oak ceiling beams sampled and is 118-years long. Providing independent scientific dating evidence for the timbers in this chronology is important as it would resolve whether they are original, or related to the repairs undertaken in the AD 1950s.

The relative position of the heartwood/sapwood boundary, where it survives, on five of the six constituent samples of undated site chronology DELCSQ02, varies by only seven years, which suggests that these timbers were cut as a single programme of felling. DEL-C22, from ceiling beam 8, the longest ring-series spanning relative years 1–116 of the master sequence and ending at the heartwood/sapwood boundary of the parent tree, was selected for radiocarbon dating.

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 1, 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).

Radiocarbon measurements have been obtained from seven single annual tree-rings from timber DEL-C22 (Table 1). 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, the Netherlands in 2021. 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 AMS (Synal *et al* 2007; Salehpour *et al* 2016). Data reduction was undertaken as described by Wacker *et al* (2010).

The Centre for Isotope Research 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 1). 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.

## REVISED TREE-RING ANALYSIS

Given the ever-increasing number of references chronologies for oak in England regular attempts are made to date undated site sequences. As part of this programme, following submission of the samples for the radiocarbon wiggle-match, a low but consistent correlation was noted against a number of reference chronologies for DELCSQ02 when it spans AD 1401–1518 (Table 2)

## 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 DELCSQ02 derived from the probability method (Stuiver and Reimer 1993), are shown in outline in Figure 2.

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 Figure 2 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 its position in the sequence (most values in a model should be equal to or greater than 60).

Figure 2 illustrates the chronological model for DELCSQ02. This model incorporates the gaps between each dated annual ring known from tree-ring counting (eg that the carbon in ring 87 of the measured tree-ring series (GrM-26287) was laid down eight years before the carbon in ring 95 of the series (GrM-26288), with the radiocarbon measurements (Table 1) calibrated using the internationally agreed radiocarbon calibration data for the northern hemisphere, IntCal20 (Reimer *et al* 2020).

The model has good overall agreement (Acomb: 196.2, An: 26.7, n: 7; Fig 2), with all the radiocarbon dates having good individual agreement (A > 60). It suggests that the final ring of DELCSQ02 formed in *cal AD 1508–1523* (*95% probability*; *ring 118*; Fig 2), probably in *cal AD 1511–1519* (*68% probability*) compatible with the last measured ring being formed in AD 1518 (Table 2). When the last ring of the wiggle-match is constrained to be AD 1518, the model has good overall agreement (Acomb: 189.2, An: 25.0, n: 8), with all the radiocarbon dates having good individual agreement (A > 60).

This allows confirmation of the ring-width dendrochronology and it to be considered as a radiocarbon-supported dendrochronological date, that spans AD 1401–1518 (Table 2), with the final ring of DELCSQ02 having been formed in AD$1518_{\mathrm{DR}}$. The superscript $_{\mathrm{DR}}$ indicates that this is not a date determined independently by ring-width dendrochronology, and that the master sequence, DELCSQ02, should not be utilised as a ring-width master sequence for dating other sites. The relative position of the heartwood/sapwood boundary for the five samples where it survives appears to be consistent, with an average date of AD $1515_{\mathrm{DR}}$. Using a 95% confidence limit for the amount of sapwood on mature oaks from Kent of 15–40 rings would give these timbers an estimated felling date in the range AD $1530_{\mathrm{DR}}$ –$1555_{\mathrm{DR}}$.

## DISCUSSION

Tree-ring analysis and radiocarbon wiggle-matching of timbers has now dated three oak site chronologies, DELCSQ01, DELCSQ02, and DELCSQ06, from Deal Castle and a single pine site chronology (DELCSQ07). Site chronology DELCSQ01 exclusively comprises samples from the consoles of the ground-floor ceiling in the Central Tower with all of the timbers having an estimated likely felling date range of AD 1604–29 and therefore indicate a programme of building works in the early seventeenth century. Site chronology DELCSQ02, also comprises six samples (Fig 4), all of them exclusively from the ground-floor ceiling beams of the Central Tower, with these timbers having an estimated likely felling date range of $1530_{\mathrm{DR}}$ –$1555_{\mathrm{DR}}$. This result is important as it clearly demonstrates that these main ceiling beams radiating, like the spokes of a wheel, from the middle of the tower to the outer walls and forming the ground-floor ceiling are all original and do not represent repairs from the AD 1950s as had previously been suspected.

Neither of the two dated series from boards of the first-floor door (DELCSQ06) retains any sapwood or the heartwood/sapwood boundary (Arnold and Howard 2015, 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, and the board represented by DEL-C57 was felled after AD 1452.

Pine site chronology DELCSQ07 exclusively comprises samples from the roof of the Gatehouse (Arnold and Howard 2015, fig 11), its 170 rings spanning the years AD 1520–1689. 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.

Tree-ring and radiocarbon dating now demonstrates that the main ceiling beams of the Central Tower forming the ground-floor ceiling are all original, while its consoles are not original as they date to the early seventeenth century. It is also possible that that the boarded first-floor door to the Central Tower may be also an early survival from the original construction of the fortification. While the Gatehouse roof underwent an undocumented period of rebuilding or significant repair at the end of the seventeenth century.

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# TABLES

*Table 1: Radiocarbon measurements and associated δ¹³C values from oak sample DEL-C22 part of undated site chronology DELCSQ02*

| Laboratory Number | Sample | Radiocarbon Age (BP) | $\delta^{13}C_{IRMS}$ (‰) |
|---|---|---|---|
| GrM-26282 | DEL-C22, ring 5, *Quercus* sp., heartwood, relative ring 5 of site chronology DELCSQ02 | 554±19 | −23.0±0.15 |
| GrM-26283 | DEL-C22, ring 22, *Quercus* sp., heartwood, relative ring 22 of site chronology DELCSQ02 | 510±18 | −23.7±0.15 |
| GrM-26284 | DEL-C22, ring 44, *Quercus* sp., heartwood, relative ring 44 of site chronology DELCSQ02 | 470±18 | −24.8±0.15 |
| GrM-26286 | DEL-C22, ring 66, *Quercus* sp., heartwood, relative ring 66 of site chronology DELCSQ02 | 381±18 | −25.7±0.15 |
| GrM-26287 | DEL-C22, ring 87, *Quercus* sp., heartwood, relative ring 87 of site chronology DELCSQ02 | 370±18 | −24.5±0.15 |
| GrM-26288 | DEL-C22, ring 95, *Quercus* sp., heartwood, relative ring 95 of site chronology DELCSQ02 | 368±18 | −25.3±0.15 |
| GrM-26289 | DEL-C22, ring 107, *Quercus* sp., heartwood, relative ring 107 of site chronology DELCSQ02 | 357±19 | −25.5±0.15 |

*Table 2: Results of the cross-matching of site sequence DELCSQ02 and the reference chronologies when the first-ring date is AD 1401 and the last-measured ring date is AD 1518*

| Reference chronology | *t*-value | Span of chronology (AD) | Reference |
|---|---|---|---|
| Littlebourne Barn, Canterbury, Kent | 7.1 | 1382–1582 | Arnold *et al* 2003 |
| Hales Hall, Loddon Norfolk | 4.9 | 1236–1494 | Arnold and Howard 2014 |
| Cann Hall, Clacton, Essex | 4.8 | 1301–1511 | Tyers 1998 |
| Otley Hall, Suffolk | 4.5 | 1415–1587 | Bridge 2000 |
| Old Pound Cottage, Chobham, Surrey | 4.3 | 1446–1543 | Miles and Worthington 2000 |
| All Saints bellframe, Little Totham, Essex | 4.2 | 1380–1517 | Tyers 1996 |
| Abbey Farm Barn and Cottage, Thetford, Norfolk | 4.1 | 1332–1536 | Howard *et al* 2000 |

# FIGURES

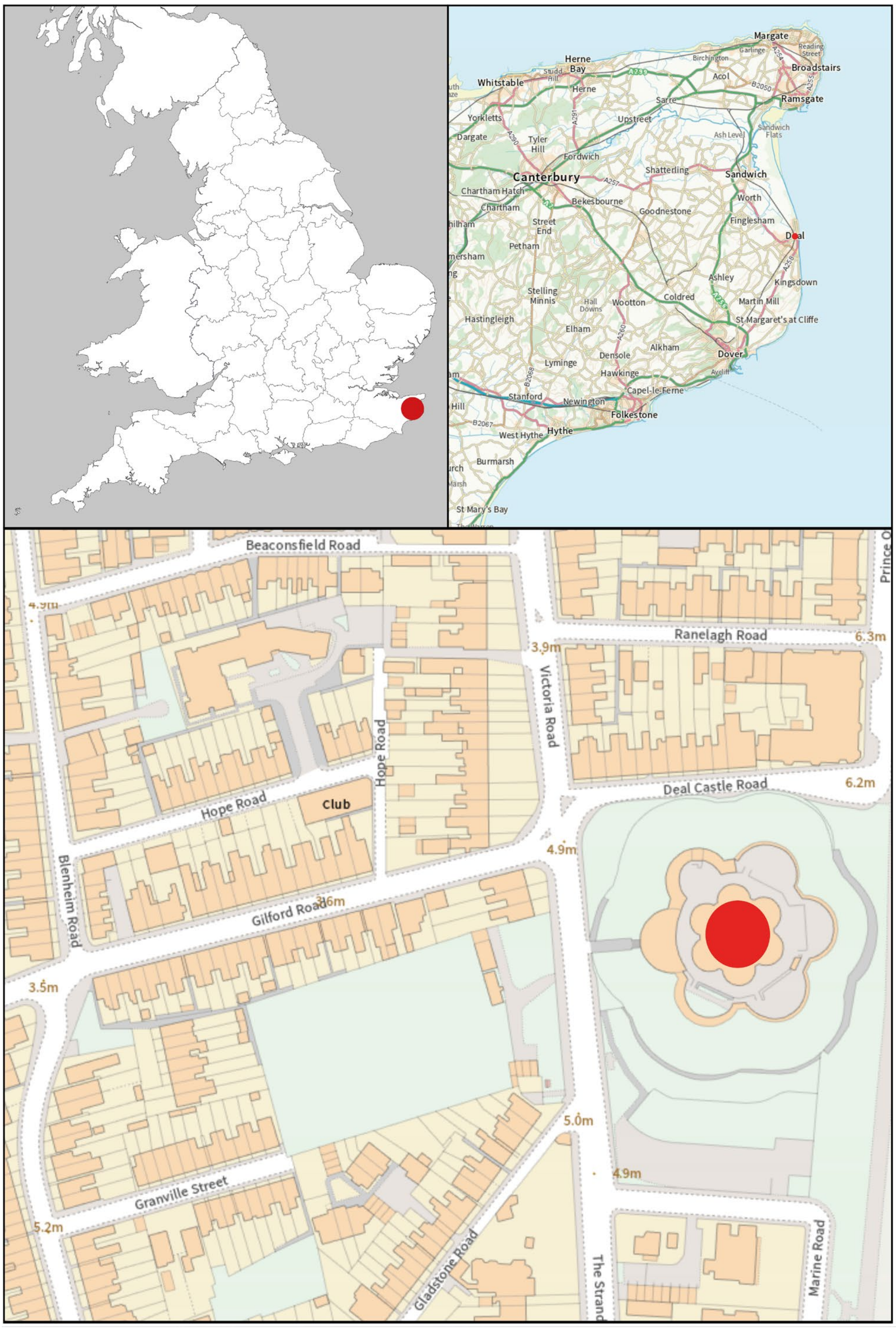



*Figure 1: Maps to show the location of Deal and Deal Castle (red dot). Scale: top right 1:211654; bottom 1:1654. © Crown Copyright and database right 2022. All rights reserved. Ordnance Survey Licence number 100024900*

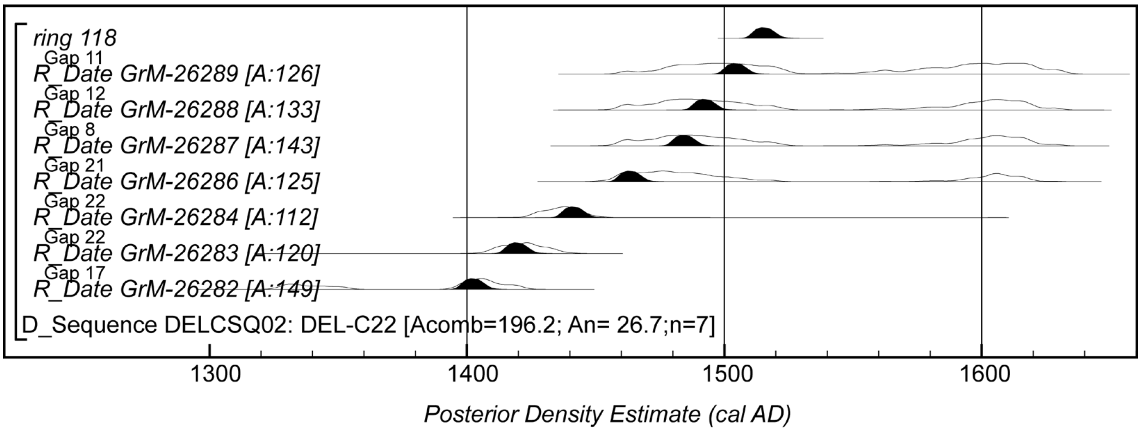



*Figure 2: Probability distributions of dates from the undated site sequence DELCSQ02. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the simple radiocarbon calibration, and a solid one, based on the wiggle-match sequence. The large square brackets down the left-hand side along with the OxCal keywords define the overall model exactly*

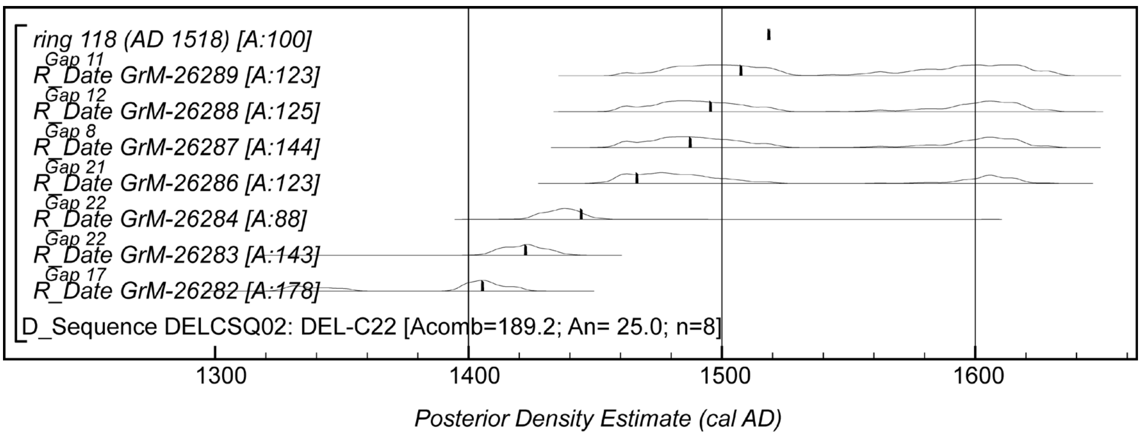



*Figure 3: Probability distributions of dates from site sequence DELCSQ02 when its last ring is constrained to have formed in AD 1518. The format is identical to that of Figure 2. The large square brackets down the left-hand side along with the OxCal keywords and the description of the sapwood estimates in the text defines the overall model exactly*

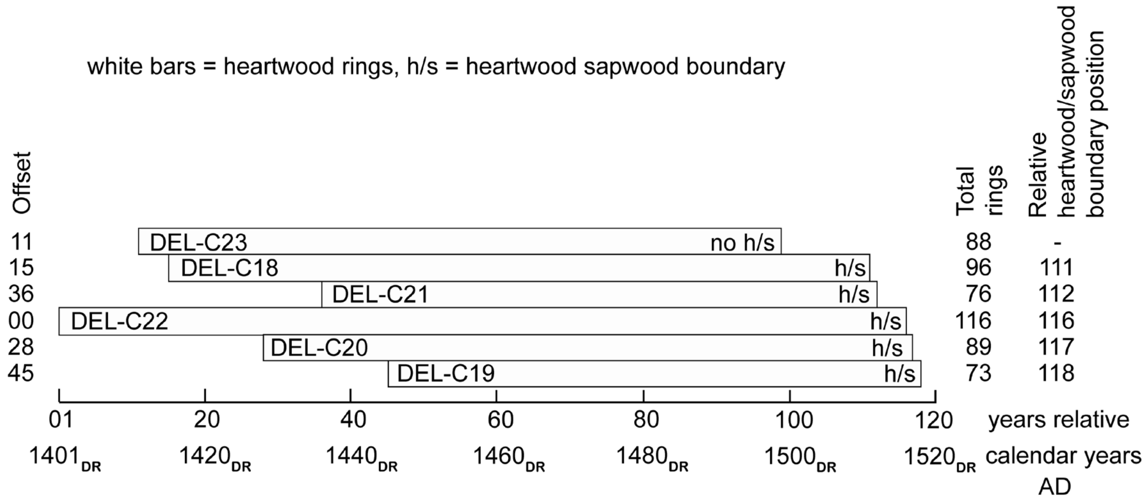
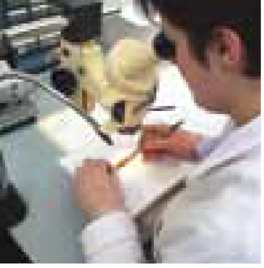
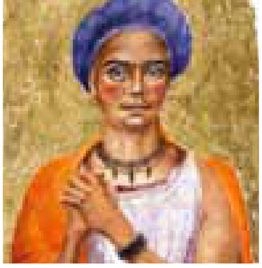
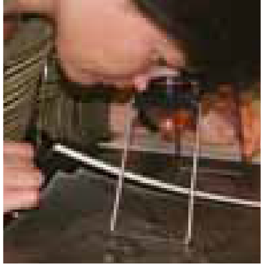



*Figure 4: Bar diagram of the oak samples, all from ground-floor ceiling beams in the Central Tower, in site chronology DELCSQ02*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