Radiocarbon, Vol 00, Nr 00, 2023, p 1–11 DOI:10.1017/RDC.2023.24
Selected Papers from the 24th Radiocarbon and 10th Radiocarbon & Archaeology International Conferences, Zurich, Switzerland, 11–16 Sept. 2022


# SINGLE-YEAR $^{14}$C DATING OF THE LAKE-FORTRESS AT ĀRAIŠI, LATVIA

John Meadows[1,2]* • Māris Zunde[3] • Laura Lēģere[4] • Michael W Dee[5] • Christian Hamann[2]

[1]ZBSA (Centre for Baltic and Scandinavian Archaeology), Schleswig, Germany
[2]Leibniz-Laboratory for AMS Dating and Stable Isotope Research, Christian-Albrechts-University Kiel, Kiel, Germany
[3]Institute of Latvian History, University of Latvia, Riga, Latvia
[4]Cēsis Castle Archaeological Park, Cēsis, Latvia
[5]Centre for Isotope Research, University of Groningen, Groningen, Netherlands

**ABSTRACT.** Single-year $^{14}$C sampling of a spruce log from the timber platform on which the Āraiši lake-fortress was built dates this timber exactly, by synchronization with AD 774/5 Miyake event. Dendrochronological synchronisms between the dated log and other timbers provide annual precision for the construction of the site. The felling date obtained, AD 835, is 50–60 years later than that proposed previously (Meadows and Zunde 2014) on the basis of a wiggle-match between $^{14}$C ages of decadal blocks and the IntCal13 calibration curve (Reimer et al. 2013), although the same $^{14}$C data favor a felling date in the AD 830s when wiggle-matched to IntCal20 (Reimer et al. 2020). Our results appear to confirm doubts expressed by Philippsen et al. (2022) about IntCal20 values from ca. AD 825-835.

**KEYWORDS:** IntCal13, IntCal20, Miyake event, single-year sampling, wiggle-match.

## INTRODUCTION

A timber lake-fortress (Figure 1) on an island in Lake Āraiši, Latvia (57°15'07"N, 25°16'58"E, 121 m asl), was excavated in 1965–1969 and 1975–1979 by the archaeologist Jānis Apals, who recognized five construction phases, dated by artifacts to the late 1st millennium AD. Radiometric $^{14}$C dates (Punning et al. 1968; Zaitseva and Popov 1994) confirmed this attribution. A mixed-species conifer dendrochronology of Āraiši timbers was cross-matched to ring-width chronologies from Novgorod, Russia, suggesting a felling date of ca. AD 930 for timbers in the log platform underlying the earliest building phase (Chernyh 1996). Although this date coincided with the calibrated radiometric $^{14}$C results, doubts about the methodology employed led to a second dendrochronological investigation, using new ring-width measurements of 3–4 radii in more than 60 surviving wood samples from Āraiši, combined with the earlier ring-width measurements, for a total of 330 measured timbers (Zunde 2000). Of these, 60 Norway spruce (*Picea abies*) timbers were cross-matched to form a floating chronology spanning ca. 100 years, which provided relative dates for another 19 spruce timbers with anomalous growth patterns and for a floating chronology comprising 11 pine (*Pinus sylvestris*) timbers, permitting many of the structures to be synchronized (Zunde 2000; Figure 1 right). No absolutely dated ring-width reference chronologies covering the relevant period are available for either species, either from Latvia or from surrounding countries.

In 2012–2013, a spruce timber from the log platform was dated at the Kiel AMS $^{14}$C laboratory, by sampling 10 contiguous multi-annual blocks collectively spanning 92 years, ending with the final ring formed before tree-fall, "*year n*". Following the publication of

*Corresponding author. Email: jmeadows@leibniz.uni-kiel.de

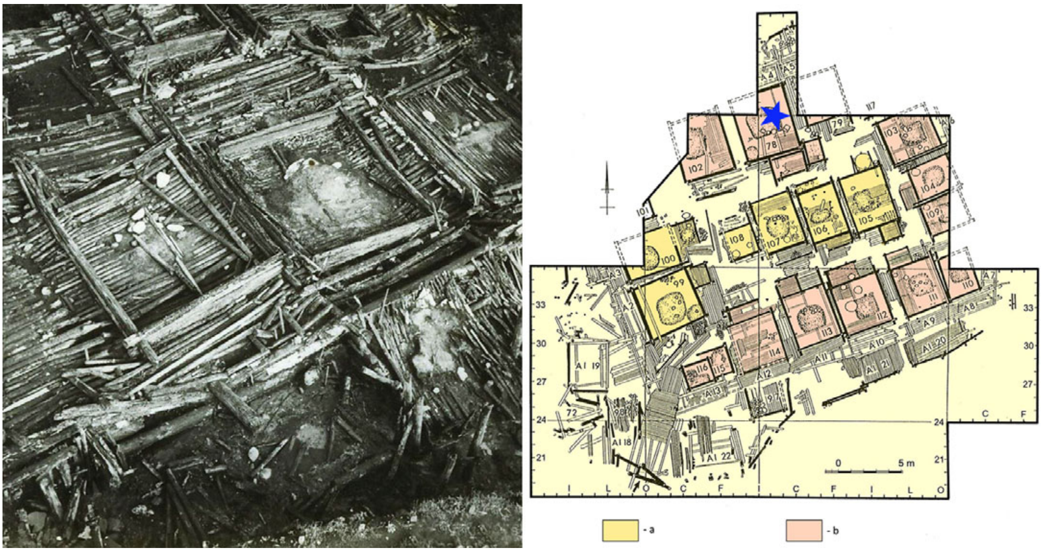


Figure 1 (Left) the Phase I log platform and buildings during excavation (J Apals); (right) Riga relative dendro-dating (Zunde 2000): (a, yellow) buildings made of timbers felled the same year as timbers from the log platform; (b, pink) buildings made of timbers felled 1–2 years later. The wiggle-matched timber was from the log platform, under house 78 (star). (Please see online version for color figures.)

the IntCal13 calibration curve (Reimer et al. 2013), a wiggle-match felling date of *cal AD 775–784* (95% probability) was proposed (Meadows and Zunde 2014). It should therefore have been possible to locate the AD 774/5 $^{14}$C production spike (Miyake et al. 2012) in single-year samples from the final decade of growth, and thus to date the Āraiši floating tree-ring chronologies to the exact year. Indeed, inconsistency between 2 $^{14}$C measurements (KIA-47639, 1265 ± 25 and 1150 ± 20 BP) of unhomogenized acid-base-acid (ABA) residue from the last 6 annual rings suggested that the Miyake event occurred between *year n-5* and *year n* (Meadows and Zunde 2014). Concerns about the reproducibility of $^{14}$C measurements in Kiel at the time (Meadows et al. 2015) delayed the dating of single-year samples from Āraiši until after the AD 774/5 Miyake event had been successfully located in known-age oak (Rakowski et al. 2015). Dating in 2015–2016 of 2 α-cellulose extracts from each annual ring between *year n-5* and *year n* did not reveal significant inter-annual shifts in $^{14}$C content, however (unpublished data).

## MATERIAL AND METHODS

Four contiguous biennial samples (KIA-50671-74; Table 1) from the oldest decade of the Āraiši timber (*years n-79/80* to *years n-85/86*) were extracted to α-cellulose in Kiel to check the accuracy of $^{14}$C ages from an ABA extract (KIA-49360, *years n-77* to *n-84*), which were rejected by Meadows and Zunde (2014); a single target from each sample was measured in early 2016 and the results appeared to confirm the 2014 wiggle-match. In 2019, therefore, a second attempt was made to locate the AD 774/5 Miyake event by extracting each of the last 11 annual rings (*year n-10* to *year n*) to α-cellulose and dating 2 targets made from separate combustions of the same extract on different AMS target wheels (KIA-54189-99). At the same time, alternate rings were replicated independently, at the Center for Isotope Research, Groningen University (GrM-19695-705). A further 16 single-year α-cellulose

Table 1 Analytical results. KIA-54189—99 double measurements of $F^{14}C$ were first averaged, following (Ward and Wilson 1978), before their weighted mean was combined with the GrM- $F^{14}C$ value for the same annual ring. Mean $^{14}C$ ages were calculated from the weighted mean $F^{14}C$ value for each annual ring, following (Stuiver and Polach 1977). The final columns indicate the calendar date(s) of each sample, based on the synchronization proposed in this paper, and the corresponding age-corrected $\Delta^{14}C$ value.

| Tree ring(s) | Lab code | Yield % | %C | AMS $\delta^{13}C$ | $F^{14}C$ | $^{14}C$ age BP | Mean $F^{14}C$ | Mean $^{14}C$ age | Calendar date | Age-corrected $\Delta^{14}C$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Years n-85/86 | KIA-50674 | 44.1 | 37.3 | –24.90 ± 0.13 | 0.8529 ± 0.0026 | 1278 ± 24 | | | 749.5 | –13.8 ± 2.6 |
| Years n-83/84 | KIA-50673 | 39.2 | 36.7 | –24.08 ± 0.17 | 0.8550 ± 0.0024 | 1259 ± 23 | | | 751.5 | –11.6 ± 2.4 |
| Years n-81/82 | KIA-50672 | 33.2 | 30.5 | –24.50 ± 0.10 | 0.8536 ± 0.0024 | 1272 ± 23 | | | 753.5 | –13.5 ± 2.4 |
| Years n-79/80 | KIA-50671 | 39.9 | 37.0 | –23.08 ± 0.12 | 0.8511 ± 0.0024 | 1295 ± 23 | | | 755.5 | –16.6 ± 2.4 |
| Year n-66 | KIA-56148 | 36.7 | 41.6 | –19.03 ± 0.12 | 0.8528 ± 0.0023 | 1279 ± 22 | | | 769 | –16.2 ± 2.3 |
| Year n-65 | KIA-56147 | 38.2 | 41.9 | –20.69 ± 0.14 | 0.8480 ± 0.0022 | 1324 ± 21 | | | 770 | –21.9 ± 2.2 |
| Year n-64 | KIA-56367 | 38.8 | 38.7 | –18.50 ± 0.10 | 0.8498 ± 0.0024 | 1308 ± 23 | 0.8509 ± 0.0019 | 1297 ± 18 | 771 | –18.7 ± 1.9 |
| | | | 42.3 | –20.08 ± 0.15 | 0.8527 ± 0.0030 | 1280 ± 28 | | | | |
| Year n-63 | KIA-56366 | 39.3 | 48.5 | –20.54 ± 0.11 | 0.8580 ± 0.0025 | 1231 ± 23 | 0.8543 ± 0.0019 | 1264 ± 18 | 772 | –14.9 ± 1.9 |
| | | | 43.1 | –18.97 ± 0.19 | 0.8493 ± 0.0029 | 1312 ± 28 | | | | |
| Year n-62 | KIA-56365 | 38.3 | 43.1 | –18.23 ± 0.11 | 0.8502 ± 0.0027 | 1304 ± 25 | 0.8507 ± 0.0020 | 1299 ± 19 | 773 | –19.1 ± 2.0 |
| | | | 40.8 | –19.24 ± 0.18 | 0.8513 ± 0.0030 | 1293 ± 28 | | | | |
| Year n-61 | KIA-56364 | 35.7 | 43.5 | –19.68 ± 0.21 | 0.8544 ± 0.0024 | 1264 ± 23 | 0.8524 ± 0.0018 | 1283 ± 18 | 774 | –17.3 ± 1.8 |
| | | | 41.6 | –20.02 ± 0.14 | 0.8496 ± 0.0028 | 1309 ± 27 | | | | |
| Year n-60 | KIA-56363 | 35.7 | 38.9 | –19.10 ± 0.15 | 0.8616 ± 0.0024 | 1196 ± 23 | 0.8635 ± 0.0018 | 1178 ± 18 | 775 | –4.6 ± 1.8 |
| | | | 41.8 | –19.60 ± 0.10 | 0.8662 ± 0.0029 | 1154 ± 27 | | | | |
| Year n-59 | KIA-56362 | 36.0 | 34.7 | –20.28 ± 0.11 | 0.8715 ± 0.0025 | 1105 ± 23 | 0.8702 ± 0.0019 | 1117 ± 18 | 776 | 3.0 ± 1.9 |
| | | | 42.1 | –19.29 ± 0.24 | 0.8681 ± 0.0031 | 1136 ± 29 | | | | |
| Year n-58 | KIA-56361 | 34.7 | 42.8 | –20.01 ± 0.09 | 0.8586 ± 0.0024 | 1225 ± 22 | 0.8623 ± 0.0019 | 1189 ± 17 | 777 | –6.2 ± 1.9 |
| | | | 42.0 | –19.72 ± 0.27 | 0.8686 ± 0.0031 | 1131 ± 28 | | | | |
| Year n-57 | KIA-56360 | 32.9 | 44.3 | –20.83 ± 0.10 | 0.8653 ± 0.0025 | 1162 ± 23 | 0.8650 ± 0.002 | 1165 ± 18 | 778 | –3.3 ± 2.0 |
| | | | 41.1 | –18.12 ± 0.14 | 0.8646 ± 0.0033 | 1169 ± 30 | | | | |
| Year n-56 | KIA-56146 | 33.8 | 40.2 | –19.56 ± 0.19 | 0.8643 ± 0.0023 | 1172 ± 21 | | | 779 | –4.2 ± 2.3 |
| Year n-55 | KIA-56145 | 37.0 | 41.5 | –21.07 ± 0.16 | 0.8621 ± 0.0022 | 1192 ± 21 | | | 780 | –6.8 ± 2.2 |
| Year n-54 | KIA-56359 | 30.4 | 43.0 | –21.34 ± 0.19 | 0.8631 ± 0.0024 | 1182 ± 23 | 0.8610 ± 0.0018 | 1202 ± 18 | 781 | –8.2 ± 1.8 |
| | | | 42.3 | –16.66 ± 0.34 | 0.8579 ± 0.0029 | 1231 ± 28 | | | | |
| Year n-53 | KIA-56358 | 30.4 | 41.4 | –21.97 ± 0.07 | 0.8616 ± 0.0024 | 1197 ± 23 | 0.8612 ± 0.0019 | 1201 ± 18 | 782 | –8.1 ± 1.9 |
| | | | 41.9 | –20.59 ± 0.35 | 0.8604 ± 0.0032 | 1208 ± 30 | | | | |

*(Continued)*

Table 1 (*Continued*)

| Tree ring(s) | Lab code | Yield % | %C | AMS $\delta^{13}C$ | $F^{14}C$ | $^{14}C$ age BP | Mean $F^{14}C$ | Mean $^{14}C$ age | Calendar date | Age-corrected $\Delta^{14}C$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Year n-17 | KIA-56144 | 27.5 | 40.6 | –21.15 ± 0.10 | 0.8594 ± 0.0022 | 1217 ± 21 | | | 818 | –14.5 ± 2.2 |
| Year n-16 | KIA-56143 | 18.9 | 40.2 | –21.21 ± 0.17 | 0.8562 ± 0.0022 | 1247 ± 21 | | | 819 | –18.3 ± 2.2 |
| Year n-10 | KIA-54199 | 11.0 | 40.7 | –24.16 ± 0.09 | 0.8581 ± 0.0020 | 1230 ± 19 | 0.8594 ± 0.0016 | 1217 ± 15 | 825 | –17.0 ± 1.3 |
| | | | 41.3 | –25.21 ± 0.23 | 0.8615 ± 0.0026 | 1197 ± 24 | | | | |
| | GrM-19705 | 22.6 | 40.3 | –24.24 ± 0.15 | 0.8552 ± 0.0021 | 1257 ± 20 | 0.8579 ± 0.0013 | 1231 ± 12 | | |
| Year n-9 | KIA-54198 | 16.2 | 40.7 | –25.25 ± 0.19 | 0.8598 ± 0.0021 | 1214 ± 20 | 0.8602 ± 0.0016 | 1210 ± 15 | 826 | –14.5 ± 1.6 |
| | | | 41.9 | –25.24 ± 0.09 | 0.8607 ± 0.0024 | 1205 ± 23 | | | | |
| Year n-8 | KIA-54197 | 13.5 | 40.5 | –24.09 ± 0.08 | 0.8567 ± 0.0021 | 1242 ± 20 | 0.8581 ± 0.0016 | 1229 ± 15 | 827 | –18.2 ± 1.2 |
| | | | 41.4 | –24.56 ± 0.09 | 0.8600 ± 0.0024 | 1211 ± 23 | | | | |
| | GrM-19702 | 26.5 | 37.9 | –24.62 ± 0.15 | 0.8558 ± 0.0019 | 1250 ± 18 | 0.8571 ± 0.0012 | 1238 ± 12 | | |
| Year n-7 | KIA-54196 | 11.6 | 42.8 | –24.32 ± 0.12 | 0.8571 ± 0.0020 | 1238 ± 19 | 0.8578 ± 0.0016 | 1232 ± 15 | 828 | –17.5 ± 1.6 |
| | | | 41.9 | –25.74 ± 0.13 | 0.8590 ± 0.0026 | 1221 ± 25 | | | | |
| Year n-6 | KIA-54195 | 17.1 | 42.1 | –24.62 ± 0.08 | 0.8586 ± 0.0022 | 1225 ± 20 | 0.8573 ± 0.0016 | 1236 ± 14 | 829 | –18.8 ± 1.2 |
| | | | 41.7 | –24.65 ± 0.07 | 0.8560 ± 0.0022 | 1249 ± 21 | | | | |
| | GrM-19700 | 22.3 | 38.5 | –25.24 ± 0.15 | 0.8560 ± 0.0020 | 1249 ± 19 | 0.8568 ± 0.0012 | 1241 ± 11 | | |
| Year n-5 | KIA-54194 | 17.0 | 41.6 | –23.80 ± 0.10 | 0.8582 ± 0.0021 | 1229 ± 20 | 0.8565 ± 0.0016 | 1245 ± 15 | 830 | –19.2 ± 1.6 |
| | | | 41.6 | –23.73 ± 0.22 | 0.8544 ± 0.0023 | 1264 ± 22 | | | | |
| Year n-4 | KIA-54193 | 17.0 | 42.4 | –23.71 ± 0.09 | 0.8590 ± 0.0021 | 1221 ± 20 | 0.859 ± 0.0016 | 1221 ± 15 | 831 | –18.0 ± 1.2 |
| | | | 40.3 | –24.16 ± 0.11 | 0.8590 ± 0.0025 | 1221 ± 23 | | | | |
| | GrM-19699 | 18.3 | 39.5 | –23.96 ± 0.15 | 0.8556 ± 0.0020 | 1252 ± 19 | 0.8577 ± 0.0012 | 1233 ± 12 | | |
| Year n-3 | KIA-54192 | 16.7 | 42.9 | –23.88 ± 0.11 | 0.8525 ± 0.0021 | 1282 ± 20 | 0.8543 ± 0.0016 | 1264 ± 14 | 832 | –22.0 ± 1.6 |
| | | | 39.8 | –23.47 ± 0.16 | 0.8565 ± 0.0023 | 1245 ± 21 | | | | |
| Year n-2 | KIA-54191 | 13.5 | 42.4 | –23.52 ± 0.08 | 0.8522 ± 0.0021 | 1285 ± 20 | 0.8531 ± 0.0016 | 1276 ± 15 | 833 | –22.5 ± 1.2 |
| | | | 42.4 | –24.05 ± 0.09 | 0.8542 ± 0.0024 | 1265 ± 22 | | | | |
| | GrM-19697 | 23.9 | 39.3 | –24.83 ± 0.15 | 0.8553 ± 0.0020 | 1255 ± 19 | 0.8540 ± 0.0012 | 1268 ± 12 | | |
| Year n-1 | KIA-54190 | 17.9 | 42.3 | –23.21 ± 0.13 | 0.8571 ± 0.0022 | 1239 ± 21 | 0.8557 ± 0.0016 | 1253 ± 15 | 834 | –20.6 ± 1.6 |
| | | | 42.4 | –23.87 ± 0.16 | 0.8542 ± 0.0022 | 1266 ± 21 | | | | |
| Year n | KIA-54189 | 10.8 | 42.0 | –22.56 ± 0.15 | 0.8576 ± 0.0021 | 1234 ± 20 | 0.8593 ± 0.0016 | 1217 ± 14 | 835 | –17.8 ± 1.3 |
| | | | 42.6 | –22.58 ± 0.12 | 0.8614 ± 0.0023 | 1199 ± 21 | | | | |
| | GrM-19695 | 19.9 | 39.8 | –23.67 ± 0.15 | 0.8566 ± 0.0021 | 1244 ± 19 | 0.8583 ± 0.0013 | 1227 ± 11 | | |

samples from earlier decades of the same timber were dated in Kiel in 2020–22 (KIA-56143-48, KIA-56358-67).

In Kiel, α-cellulose was extracted by washing fine strips of wood in an ultrasonic bath in a hot (70°C) solution of $NaClO_2$, activated with HCl, 5 times for 1 hr each time; soaking overnight in ultrapure water, followed by repeated rinsing in an ultrasonic bath with ultrapure water (70°C); extraction in an ultrasonic bath with 10% NaOH (70°C, 1 hr), rinsing with cold ultrapure water; a further extraction in an ultrasonic bath with 17% NaOH (70°C, 1 hr), rinsing with cold ultrapure water; extraction overnight with 1% HCL at pH $<1$, followed by rinsing with ultrapure water to pH $>4$, freezing and freeze-drying. In 2015, the sodium chlorite was activated with a dose of 100% $CH_3COOH$ (acetic acid), rather than HCl. In Groningen, α-cellulose was obtained following (Dee et al. 2019): fine strips of wood were first extracted using an ABA sequence (1.5M HCl, 80°C, 20 min; 17.5% NaOH, room temperature, 1 hr; 1.5M HCl, 80°C, 20 min), and the resulting insoluble residue was treated in $NaClO_2$, activated with HCl (80°C, 16 hr, and again for 4 hr in a fresh solution), followed by rinsing, freezing and freeze-drying.

Extracts were combusted and reduced to graphite following each laboratory's standard procedures (Nadeau et al. 1998; Dee et al. 2019). Carbon content (%C) was measured by pressure-gauge readings during combustion in Kiel, and by Elemental Analyser in Groningen. Graphite $^{14}C$ and $\delta^{13}C$ were measured on a 3MV accelerator mass spectrometer (Kiel, HVEE Tandetron 4130) or a 200 kV compact accelerator (Groningen, Ionplus AG MICADAS). $^{14}C$ contents were corrected for fractionation using AMS $\delta^{13}C$ values and expressed as $F^{14}C$ values and $^{14}C$ ages. Reported uncertainties include both measurement scatter and uncertainties in fractionation correction and blank correction (Aerts-Bijma et al. 2020). Weighted means of multiple $F^{14}C$ results for the same annual rings were calculated following Ward and Wilson (1978).

$^{14}C$ ages of multi-annual samples (Meadows and Zunde 2014) were fitted to calibration curves by wiggle-matching (Bronk Ramsey et al. 2001), using OxCal v.4.4 (Bronk Ramsey 2009a), and specifically the D_Sequence (Bronk Ramsey 2001) and Outlier_Model (Bronk Ramsey 2009b) functions. To locate the AD 774/5 Miyake event, the Āraiši single-year $F^{14}C$ values were compared to Northern Hemisphere mean annual $F^{14}C$ values for up to 11 consecutive years, AD 770–780, recorded in known-age wood from 27 sites (Büntgen et al. 2018). The least-squares method (applied by e.g., Bronk Ramsey et al. 2001; Wacker et al. 2014; Kuitems et al. 2020, 2022) was used to determine which annual ring in the Āraiši floating chronology corresponds to AD 775 in the Northern Hemisphere mean series.

## RESULTS

Analytical results are reported in Table 1. α-cellulose yields in samples from earlier decades (30–40%) were higher than those for the final decade (10–25%), suggesting that wood was better preserved in the center of the log than closer to its surface. This is unsurprising; the exterior wood would have started to decay while the platform was in use and continued to decay after excavation. The carbon content of α-cellulose from the final decade is similar to that of α-cellulose from earlier decades (and IAEA C3 cellulose) combusted in the same apparatus at Kiel, and is similar between Kiel and Groningen extracts, despite differences in extraction and %C measurement protocols.

https://doi.org/10.1017/RDC.2023.24 Published online by Cambridge University Press

The 4 biennial α-cellulose samples for *years n-79/80* to *years n-85/86* gave similar $^{14}C$ ages (ca. 1280 BP), confirming that the KIA-49360 ABA results (1360 ± 25 and 1375 ± 25 BP) were too old, as assumed by Meadows and Zunde (2014). All 11 pairs of results from the single years *year n-10* to *year n* measured in Kiel are statistically consistent, and their weighted mean $F^{14}C$ values are statistically consistent with Groningen's $F^{14}C$ values for the 6 annual samples measured in both laboratories (Table 1 and Supplementary Figure 1). None of the year-to-year $F^{14}C$ differences is more than twice the uncertainty in the difference, so there is no evidence of a $^{14}C$ production spike. With average $^{14}C$ ages of ca. 1235 BP, however, these results are slightly too old for the early 9th century AD in IntCal20, but too young for any earlier decade.

Kiel double measurements of annual samples spanning *years n-66* to *n-53* agree with IntCal20 values in the AD 770s, and include statistically significant increases in $F^{14}C$ from *year n-61* to *n-60*, and again from *year n-60* to *n-59*. The combined increase, equivalent to 20.3 ± 2.6‰, is similar to, or slightly greater than the Northern Hemisphere average amplitude (15.9 ± 0.3‰) of the AD 774/5 $^{14}C$ spike (Büntgen et al. 2018). Least-squares synchronization of the 14 $F^{14}C$ values for *years n-66* to *n-53* with NH mean $F^{14}C$ values spanning AD 770–780 (Büntgen et al. 2018) allows us to test 4 potential matching positions, with 10 degrees of freedom. Synchronization of the 14 Āraiši $F^{14}C$ values with the 9 NH mean $F^{14}C$ values spanning AD 771–779 gives 6 potential matching positions, with 8 degrees of freedom. Both approaches minimize $\chi^2$ when *year n-60* corresponds to AD 775 in the NH mean values, and $\chi^2$ falls below the critical value of $\chi^2$ at the 95% significance level (15.5 for 8 degrees of freedom) only when AD 775 corresponds to *year n-60* (Figure 2 top).

## DISCUSSION

By locating the AD 774/5 event 60 years before the felling date, the single-year results date *year n* to AD 835 (Figure 2). This means that the platform was built from trees felled in winter-spring AD 835–836.

Exact dating allows age-corrected $\Delta^{14}C$ values to be calculated for all the Āraiši samples. In the AD 770s, Āraiši $\Delta^{14}C$ values agree with those in the NH mean curve (Figure 2 right). Jull et al. (2014) first noted a latitudinal difference in the timing and intensity of the AD 774/5 Miyake event, which was confirmed in the 2018 compilation of $\Delta^{14}C$ records from known-age wood (Büntgen et al. 2018). Although Āraiši (57.25°N, 25.28°E) is close to the proposed 60°N boundary between NH zone 1 and NH zone 0, there is no indication that a shorter growing season at this latitude produced a regional $\Delta^{14}C$ offset.

Exact dating shows that the earlier wiggle-match of the same timber (Meadows and Zunde 2014) was wrong by 50–60 years, which is unacceptable in this proto-historic period. The 2014 wiggle-match omitted 4 of the 20 then-available $^{14}C$ ages, because they did not fit the calibration curve. Using IntCal13 (Reimer et al. 2013) or earlier iterations of IntCal to calibrate the selected results, the model gave a unimodal solution of ca. AD 780 for the felling date. Using IntCal20, however, the same model correctly prefers a felling date in the AD 830s (Table 2 and Figure 3). A model which uses all 20 ABA $^{14}C$ ages, but treats them all as potential outliers (using OxCal's RScaled Outlier_Model; Bronk Ramsey 2009b) again favors a felling date of ca. AD 780 using IntCal13, and a date in the AD 830s using IntCal20.

Thus, the misleading 2014 wiggle-match was due to the IntCal13 curve, not to the way outliers were handled. Other published case-studies relying on wiggle-matches with IntCal13 or earlier

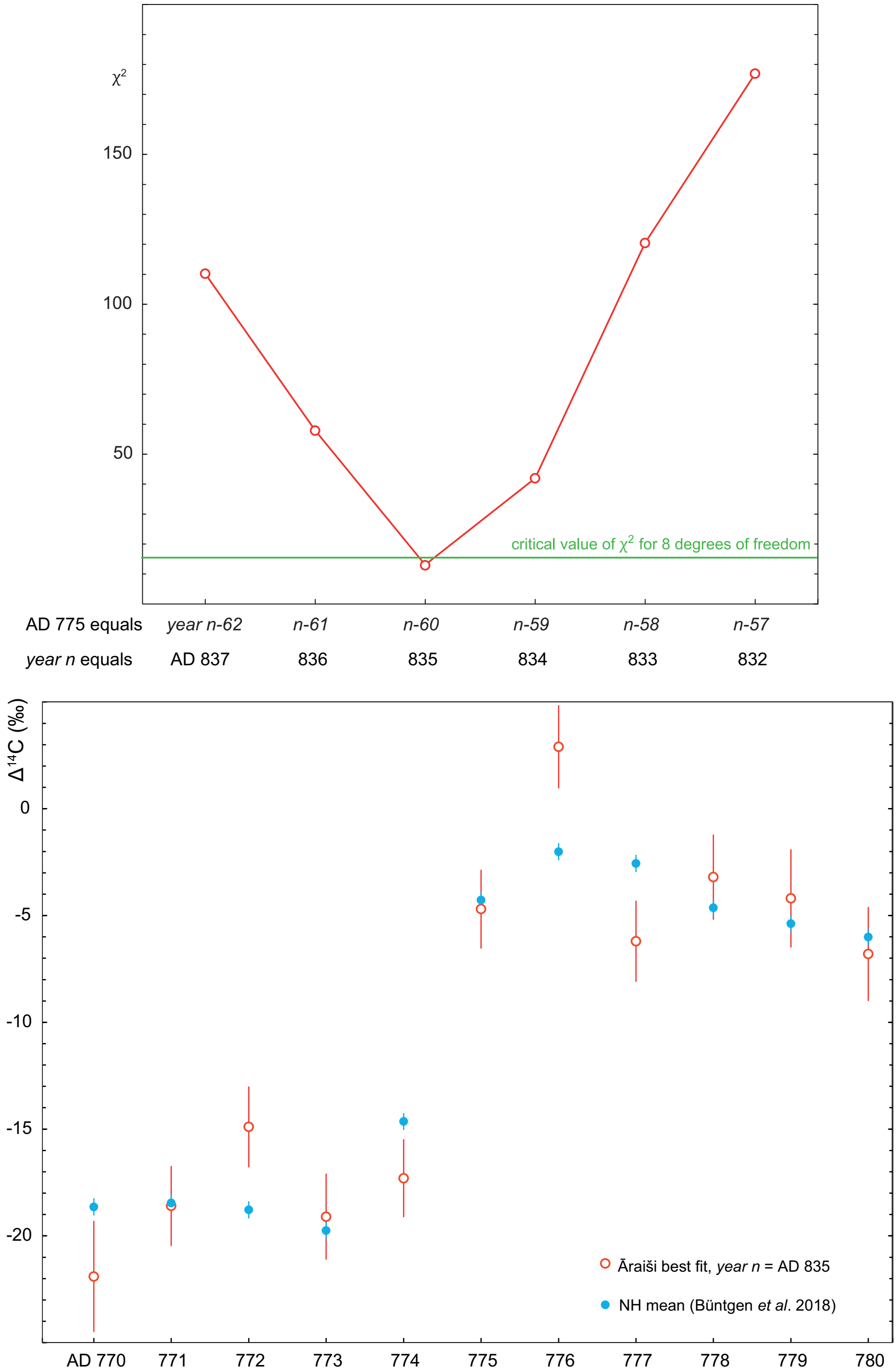


Figure 2 (Top) differences between Āraiši single-year $F^{14}C$ (*years n-66* to *n-53*) and Northern Hemisphere mean $F^{14}C$ in AD 771–779 (Büntgen et al. 2018), expressed as $\chi^2$ values; the critical value of $\chi^2$ (95%) for 8 degrees of freedom is 15.5 (green line); (bottom) comparison of Āraiši age-corrected $\Delta^{14}C$ values (when *year n* is set to AD 835) to those in NH average single-year $^{14}C$ data (Büntgen et al. 2018).

https://doi.org/10.1017/RDC.2023.24 Published online by Cambridge University Press

Table 2 Wiggle-matching of $^{14}C$ ages of decadal blocks (published in Meadows and Zunde 2014) against IntCal13 and IntCal20. See Supplementary Information for precise details of these models and Figure 3 for output.

| Model | Data | IntCal13 estimated date for *year n* | IntCal20 estimated date for *year n* |
|---|---|---|---|
| 1. 2014 published wiggle-match | Weighted means of multiple $^{14}C$ ages from same extracts, manual removal of 4 outliers out of 20 results | Unimodal, AD 775–784, 95% probability | Bimodal, AD 830–836, 84% probability |
| 2. Outlier_Model RScaled wiggle-match | All 20 results included, automatic down-weighting of outliers before combining multiple measurements | Bimodal, AD 744–749 (9%) or AD 769–787 (59% probability) | Multimodal, AD 822–838, 69% probability |

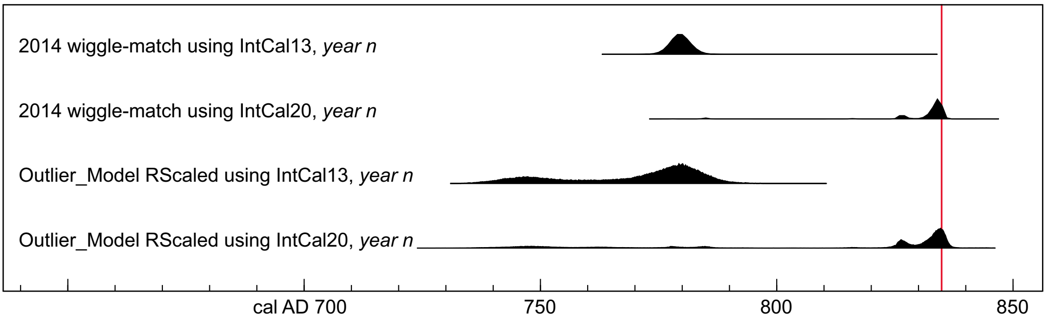


Figure 3 Wiggle-matching of multi-annual ABA samples dated at Kiel in 2012–2013, against IntCal13 and IntCal20: (above) 2014 published model, outliers removed manually; (below) all results treated as potential outliers in $^{14}$C age, using OxCal's Outlier_Model RScaled with default settings. The red line (AD 835) is the correct date of *year n*, based on synchronization with the AD 774/5 Miyake event (Figure 2).

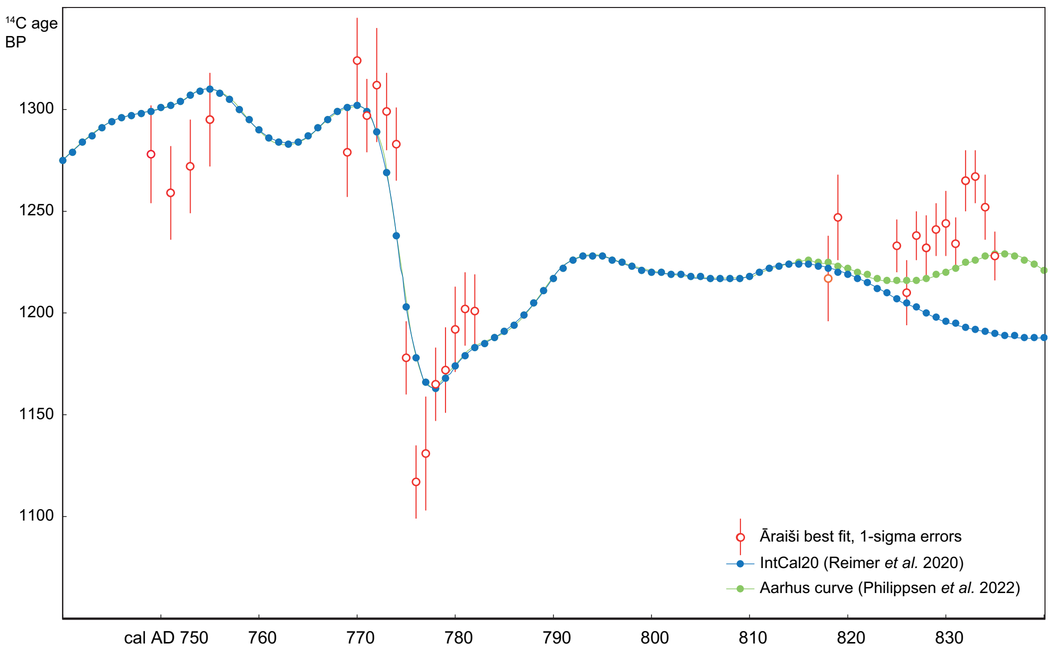


Figure 4 Cellulose $^{14}$C ages from the Āraiši timber (Table 1), plotted against IntCal20 (Reimer et al. 2020) and the Aarhus calibration curve (Philippsen et al. 2022), with the final tree-ring (*year n*) placed at AD 835.

curves in the period ca. AD 700–840 also need to be reviewed. Thanks to the inclusion of new annual-resolution $^{14}$C data sets from the decades surrounding the AD 774/5 Miyake event, IntCal20 is significantly more detailed than IntCal13 in this period and is shifted towards older $^{14}$C ages. Similar issues may come to light in other periods, as more precise high-resolution data are included in future iterations of IntCal.

The Āraiši single-year $^{14}$C ages for *year n-10* to *year n* appear to be robust, but they are older than annually interpolated values of IntCal20 for AD 825–835 (Figure 4). High-resolution

https://doi.org/10.1017/RDC.2023.24 Published online by Cambridge University Press

$^{14}C$ sampling of known-age Danish oak also indicates an offset from IntCal in this interval, leading to the creation of the "Aarhus curve" (Philippsen et al. 2022), which, however, also includes the IntCal raw data. Where direct comparison is possible, the Āraiši results are compatible with the Danish oak data for the corresponding years. As Philippsen et al. (2022) suggest, therefore, IntCal20 may be too low in the AD 820s–830s. These decades span an interval in which, in the absence of new high-resolution calibration data, IntCal20 converges with IntCal13. In the preceding 2–3 decades, the new calibration data has shifted IntCal20 towards older $^{14}C$ ages relative to IntCal13, and future iterations of IntCal may validate the Āraiši results for AD 825–835.

## CONCLUSION

Both these issues highlight the need to update IntCal calibration curves with annual resolution data sets for all historic and proto-historic periods. Decadal-resolution calibration data from radiometric laboratories, which dominated IntCal13 and earlier curves, produced a wiggle-match date for the Āraiši lake-fortress at least 50 years too early. Several years, and considerable resources, were expended attempting to locate the AD 774/5 Miyake event in the wrong decade of the Āraiši timber. Had IntCal20 been available in 2015, it would have been recognized that the final decade of the Āraiši timber was 50–60 years later than indicated in the 2014 model, allowing the Miyake event to be located much sooner. Had we not attempted to locate the Miyake event, however, the spuriously early wiggle-match date would have been accepted uncritically and could have been applied to other sites dated by dendrochronological synchronization.

## ACKNOWLEDGMENTS

Funding for $^{14}C$ analyses was provided by the ZBSA's Man and Environment research theme. We thank past and present staff of the Leibniz-Labor, CAU Kiel, for persisting with these samples, and Bente Philippsen for the Aarhus curve raw data.

## SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit https://doi.org/10.1017/RDC.2023.24

## REFERENCES

Aerts-Bijma AT, Paul D, Dee MW, Palstra SWL, Meijer HAJ. 2020. An independent assessment of uncertainty for radiocarbon analysis with the new generation high-yield accelerator mass spectrometers. Radiocarbon 63(1):1–22.

Bronk Ramsey C. 2001. Development of the radiocarbon calibration program. Radiocarbon 43(2a):355–363.

Bronk Ramsey C, van der Plicht J, Weninger B. 2001. "Wiggle matching" radiocarbon dates. Radiocarbon 43(2a):381–389.

Bronk Ramsey C. 2009a. Bayesian analysis of radiocarbon dates. Radiocarbon 51(1):337–360.

Bronk Ramsey C. 2009b. Dealing with outliers and offsets in radiocarbon dating. Radiocarbon 51(3):1023–1045.

Büntgen U, Wacker L, Galván JD, Arnold S, Arseneault D, Baillie M, Beer J, Bernabei M, Bleicher N, Boswijk G, et al. 2018. Tree rings reveal globally coherent signature of cosmogenic radiocarbon events in 774 and 993 CE. Nature Communications 9(1):3605.

Chernyh NB. 1996. Dendrohronologiya i arheologiya. Moscow: NOX. 215 p.

Dee MW, Palstra SWL, Aerts-Bijma AT, Bleeker MO, de Bruijn S, Ghebru F, Jansen HG, Kuitems M, Paul D, Richie RR, et al. 2019. Radiocarbon dating at Groningen: new and updated chemical pretreatment procedures. Radiocarbon 62(1):63–74.

Jull AJT, Panyushkina IP, Lange TE, Kukarskih VV, Myglan VS, Clark KJ, Salzer MW, Burr GS, Leavitt SW. 2014. Excursions in the $^{14}C$ record at AD 774–775 in tree rings from Russia and America. Geophysical Research Letters 41(8):3004–3010.

Kuitems M, Panin A, Scifo A, Arzhantseva I, Kononov Y, Doeve P, Neocleous A, Dee M. 2020. Radiocarbon-based approach capable of subannual precision resolves the origins of the site of Por-Bajin. Proceedings of the National Academy of Sciences: 201921301.

Kuitems M, Wallace BL, Lindsay C, Scifo A, Doeve P, Jenkins K, Lindauer S, Erdil P, Ledger PM, Forbes V, Vermeeren C, Friedrich R, Dee MW. 2022. Evidence for European presence in the Americas in AD 1021. Nature 601(7893): 388–391.

Meadows J, Zunde M. 2014. A lake fortress, a floating chronology, and an atmospheric anomaly: the surprising results of a radiocarbon wiggle-match from Āraiši, Latvia. Geochronometria 41(3):223–233.

Meadows J, Hüls M, Schneider R. 2015. Accuracy and reproducibility of $^{14}C$ measurements at the Leibniz-Labor, Kiel: a first response to Lull et al., “When $^{14}C$ dates fall beyond the limits of uncertainty: an assessment of anomalies in western Mediterranean Bronze Age $^{14}C$ series”. Radiocarbon 57(5):1041–1047.

Miyake F, Nagaya K, Masuda K, Nakamura T. 2012. A signature of cosmic-ray increase in AD 774–775 from tree rings in Japan. Nature 486(7402):240–242.

Nadeau M-J, Grootes P, Schleicher M, Hasselberg P, Rieck A, Bitterling M. 1998. Sample throughput and data quality at the Leibniz-Labor AMS facility. Radiocarbon 40(1):239–245.

Philippsen B, Feveile C, Olsen J, Sindbæk SM. 2022. Single-year radiocarbon dating anchors Viking Age trade cycles in time. Nature 601(7893):392–396.

Punning JM, Liiva A, Ilves E. 1968. Tartu radiocarbon dates III. Radiocarbon 10(2): 379–383.

Rakowski AZ, Krąpiec M, Huels M, Pawlyta J, Dreves A, Meadows J. 2015. Increase of radiocarbon concentration in tree rings from Kujawy (SE Poland) around AD 774–775. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 361:564–568.

Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Cheng H, Edwards RL, Friedrich M, et al. 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55(4):1869–1887.

Reimer PJ, Austin WEN, Bard E, Bayliss A, Blackwell PG, Bronk Ramsey C, Butzin M, Cheng H, Edwards RL, Friedrich M, et al. 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon 62(4):725–757.

Stuiver M, Polach HA. 1977. Discussion: reporting of $^{14}C$ data. Radiocarbon 19(3):355–363.

Wacker L, Güttler D, Goll J, Hurni JP, Synal HA, Walti N. 2014. Radiocarbon dating to a single year by means of rapid atmospheric $^{14}C$ changes. Radiocarbon 56(2):573–579.

Ward GK, Wilson SR. 1978. Procedures for comparing and combining radiocarbon age-determinations – a critique. Archaeometry 20(1):19–31.

Zaitseva GI, Popov SG. 1994. Radiocarbon dating sites of northwest Russia and Latvia. Radiocarbon 36(3):377–389.

Zunde M. 2000. Par Āraišu ezerpils dendrohronoloģisko datēšanu. Arheologs Dr. hist., Dr. hist. h.c. Jānis Apals: Bibliogrāfija, darbabiedru veltījumi 70 gadu jubilejā. Rīga: Latvijas vēstures institūta apgāds. p 144–157.

https://doi.org/10.1017/RDC.2023.24 Published online by Cambridge University Press