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A prehistoric Japanese building constructed with wooden pillars that have an age range spanning 700 years

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ABSTRACT

Sixteen pillars in a prehistoric building in Osaka, Japan, were precisely dated using a 4354-year-long tree-ring δ^{18}O master chronology. The building was previously thought to have been constructed in the 1st century BCE (i.e., the middle Yayoi Period), when the metal-working culture in the Japan archipelago expanded rapidly and large-scale agricultural settlements with large moats and agricultural rituals using bronze became prominent. Fifteen of the 16 pillars have no sapwood, and thus their felling dates cannot be determined. Despite this constraint, our analysis demonstrated that the building was constructed using pillars that yield ages from 782 to 52 BCE. Our δ^{18}O-based dates were successfully verified by reproducing the rapid ^{14}C increase observed at 665–663 BCE, which provides independent support for the tree-ring dating. We propose three potential explanations for the 700-year range in the pillar ages. Firstly, the outer layers of the tree trunks may have been removed prior to the construction of the building. Secondly, the Yayoi people might have utilized wood from buried trees, which could have originated from landslides occurring intermittently over extended periods of time. Thirdly, some of the pillars may have been repurposed from other structures. The pillar dated to 52 BCE, which contains complete sapwood rings, was likely logged shortly before construction of the building, whereas some of the remaining pillars may have been sourced from dead wood. Our findings suggest that the use of wood during the middle Yayoi Period was more complex than the simple harvesting of living trees.

1. Introduction

The Yayoi Period began when irrigated rice cultivation was introduced to Japan from the Korean Peninsula, after the Jomon Period that was dominated by a hunter–gatherer lifestyle. A series of ^{14}C measurements of the remnants of early paddy fields has revealed that irrigated rice cultivation was initially the result of contact between ancient Korean people of Bronze Age culture and Jomon people in northern Kyushu in the 10th century BCE, and then gradually spread eastward (Fujio, 2021). In the middle Yayoi Period, beginning in the 4th century BCE, large agricultural settlements encircled by large moats were formed throughout the Japan archipelago, indicating an increase in population. With the spread of bronze artifacts, tombs of chiefs with numerous bronze mirrors, swords, and spears appeared in northern Kyushu, and agricultural rituals using bronze bells were developed in the Kinki region, including Osaka. After the Han Dynasty established the Lelang Commandery in 108 BCE on the Korean Peninsula, the influx of Chinese artifacts, such as Chinese mirrors, into the Japan archipelago increased. In addition, a major change occurred in long-distance trade during the latter half of the middle Yayoi Period. Iron tools were brought to northern Kyushu via the Korean Peninsula in the 4th century BCE (Fujio, 2014), and then spread across the Japan archipelago. Manufacturing sites of iron tools have been unearthed in the Kinki region that date to the 2nd century CE (Negita, 2013). The late Yayoi Period, beginning in the 1st century CE, was characterized by the decline of mid-Yayoi settlements and the establishment of new settlements and interregional relations. The Yayoi Period was followed by the Kofun Period in the 3rd century CE, during which large burial mounds for the tombs of kings were constructed in the Kinki region.

Accelerator mass spectrometry radiocarbon (AMS ^{14}C) dating of

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biological remnants of the Yayoi Period, along with pottery typology, have advanced our understanding of the chronology of this period (Fujio, 2021). However, calibrated AMS dates often have a relatively large uncertainty, which depends on the shape of the wiggles in calibration curves, including IntCal20 (Reimer et al., 2020).

Tree rings have been used to precisely identify the ages in calendar years of wooden materials in Japan. Several tree-ring width chronologies have been developed in Japan (Maeda et al., 2024; Ohyama et al., 2007; Sweda and Takeda, 1993; Yonenobu and Eckstein, 2006). The two longest tree-ring width chronologies for Japan extend back to 1313 and 912 BCE, based on *Cryptomeria japonica* and *Chamaecyparis obtuse*, respectively (Mitsutani, 2000). While tree-ring dates of wooden materials have been successfully determined using these chronologies, there are limitations (Nara National Research Institute for Cultural Properties, 1990). Firstly, climatic factors affecting tree growth vary with the tree species, and thus pattern matching of ring widths between inter-species samples are not usually successful. Secondly, even for the same species, robust pattern matching is usually only possible for samples that comprise at least 100 rings, since ecological interactions between neighboring trees also modulate tree-ring growth. Thirdly, millennia-long tree-ring records that cover an archaeological timescale are limited to the two coniferous species in Japan noted above; consequently, many wooden materials produced from broadleaf trees cannot be dated.

Recent progress in oxygen isotope dendrochronology has enabled advances in tree-ring dating (Loader et al., 2019; Loader et al., 2021; Loader et al., 2020; McCarroll et al., 2019; Sano et al., 2022). For example, even for a case where the samples only had 50 rings and comprised multiple species, including broadleaf trees, tree-ring $\delta^{18}O$ time-series were successfully cross-dated against a cypress $\delta^{18}O$ chronology (Sano et al., 2022). This is possible because tree-ring $\delta^{18}O$ values are controlled mainly by only two climatic factors (i.e., relative humidity, which is linked to vapor pressure deficit, and the $\delta^{18}O$ values of precipitation) during the growing season, which are independent of the tree species and ecological conditions. This has led to the rapid development of tree-ring $\delta^{18}O$ chronologies for use in tree-ring dating and climate reconstructions in Asia (Xu et al., 2024). A tree-ring $\delta^{18}O$ dataset that covers the past 4354 years has been produced using samples collected from northern and central Japan (Nakatsuka et al., 2020; Sano et al., 2023; Sano et al., 2022; Sano et al., 2024). Given that regional hydroclimatic signals are similar in some regions of East Asia, and are recorded by tree-ring $\delta^{18}O$ values, this dataset enables the dating of wood samples from Japan, Korea (Seo et al., 2019), and China (Shi et al., 2025).

One of the most important remains of the Yayoi Period was excavated in the 1970s and 1990s at the Ikegami–Sone site in southern Osaka (Fig. 1). A settlement that was surrounded by a circular moat (320 m in diameter) was found to be enclosed by an outer moat (estimated to be > 450 m in diameter). Groups of square burial mounds were also excavated outside of the outer moat. Remnants of a large building supported by 26 pillars and a well were excavated at the center of the settlement. Based on archaeological observations, the building is assumed to have been a sanctuary or well-organized workshop (Akiyama, 2006). One of the pillars was dendrochronologically dated to 52 BCE in the 1990s (Mitsutani, 1997). The building was thus considered to have been constructed soon after 52 BCE, which has been used as one of the most important time markers for the Yayoi Period in Japan. However, the other pillars remain to be precisely dated.

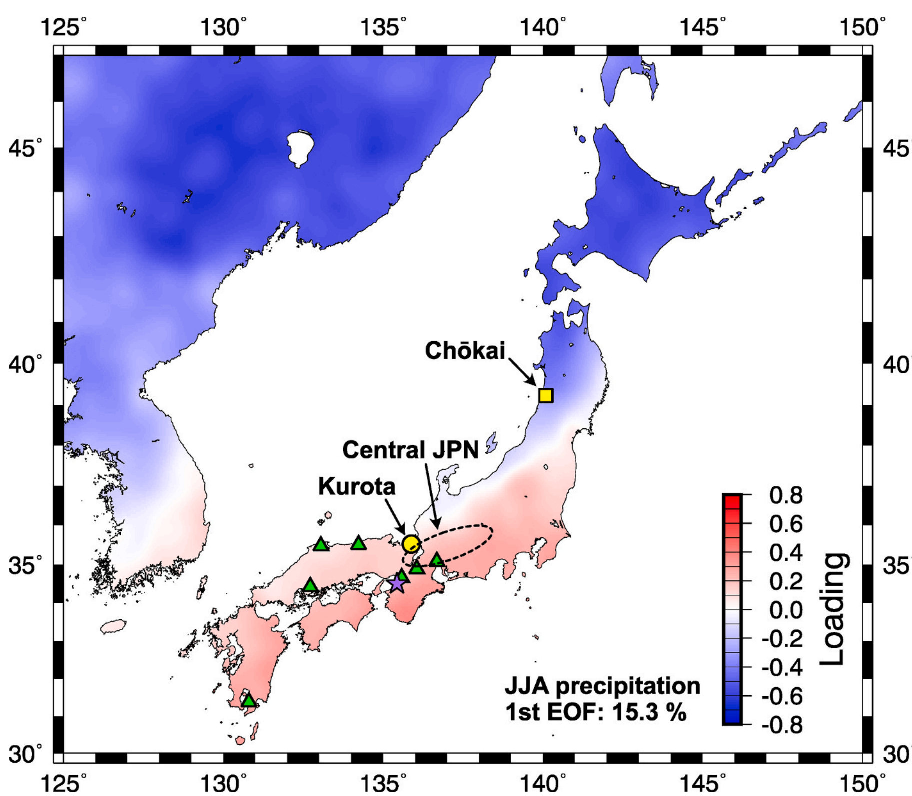

Fig. 1. Map of Japan showing the locations of (1) the Ikegami–Sone site (star), where 16 samples were collected from pillars for this study; (2) the Kurota site (circle), where 22 samples were collected for the 1341-year-long master chronology that covers the period 2349–1009 BCE (Sano et al., 2023); (3) the central Japan site (ellipse), where 67 samples were collected for the 2617-year-long master chronology that extends from 612 BCE to 2005 CE (Nakatsuka et al., 2020; Sano et al., 2022); (4) the Chōkai site (square), where 17 samples were collected for the 947-year-long master chronology that covers the period 1412–466 BCE (Sano et al., 2023); and (5) seven sites (triangles), where nine sample were collected for bridging the data gap between the two master chronologies from the Kurota and central Japan sites. Background colors show the first EOF loadings based on June–August precipitation data from the Global Precipitation Climatology Centre (GPCC) Full Data Monthly Product Version 2020 (Schneider et al., 2020) for the period 1891–2019 CE.

In this study, we conducted tree-ring $\delta^{18}O$ dating of the pillars that were used for this large building constructed during the middle Yayoi Period. To do this, we developed a 4354-year-long master chronology by merging previously published data with nine newly measured time-series. Our $\delta^{18}O$-based dates were verified by reproducing the rapid ^{14}C increase observed at 665–663 BCE (Sakurai et al., 2020; Sano et al., 2023). Our analysis revealed that the building was constructed using pillars with an age range of 782–52 BCE. We discuss the reasons for the 700-year age range of the dated pillars.

2. Materials and methods

2.1. Construction of a master chronology

We developed a 4354-year-long master chronology based on 98 trees collected mainly from central Japan. Specifically, previously published 2617-year-long (67 trees; Nakatsuka et al., 2020; Sano et al., 2022) and 1341-year-long (22 trees; Sano et al., 2023) master chronologies that cover the periods 612 BCE–2005 CE and 2349–1009 BCE, respectively, were correlated using nine new tree-ring $\delta^{18}O$ time-series obtained in this study from seven sites, in order to develop the four-millennia-long master chronology (Fig. 1). Although the nine samples are from a wide area in western Japan, the tree-ring dating was successfully undertaken (Supplementary Fig. 1). A composite chronology, based on the nine samples, is well correlated with the master chronology from central Japan (Fig. 2; $r = 0.72$, n = 242). The Meiyu–Baiu front, which is a zonally oriented rain band, prevails in the growing season over western Japan (Fig. 1), and this hydroclimatic factor is an important control on tree-ring $\delta^{18}O$ values in this region. While the climate of the Chōkai site in northern Japan differs somewhat from that in western Japan, a chronology based on the nine samples is significantly correlated with the master chronology from the site (Fig. 2; $r = 0.28$, n = 620). This result also indicates that our dating is robust.

Based on the standard methodology for chronology development by tree-ring $\delta^{18}O$ dating (Loader et al., 2019), we used a rectangular filter to standardize the raw tree-ring $\delta^{18}O$ time-series. Each of the raw tree-ring

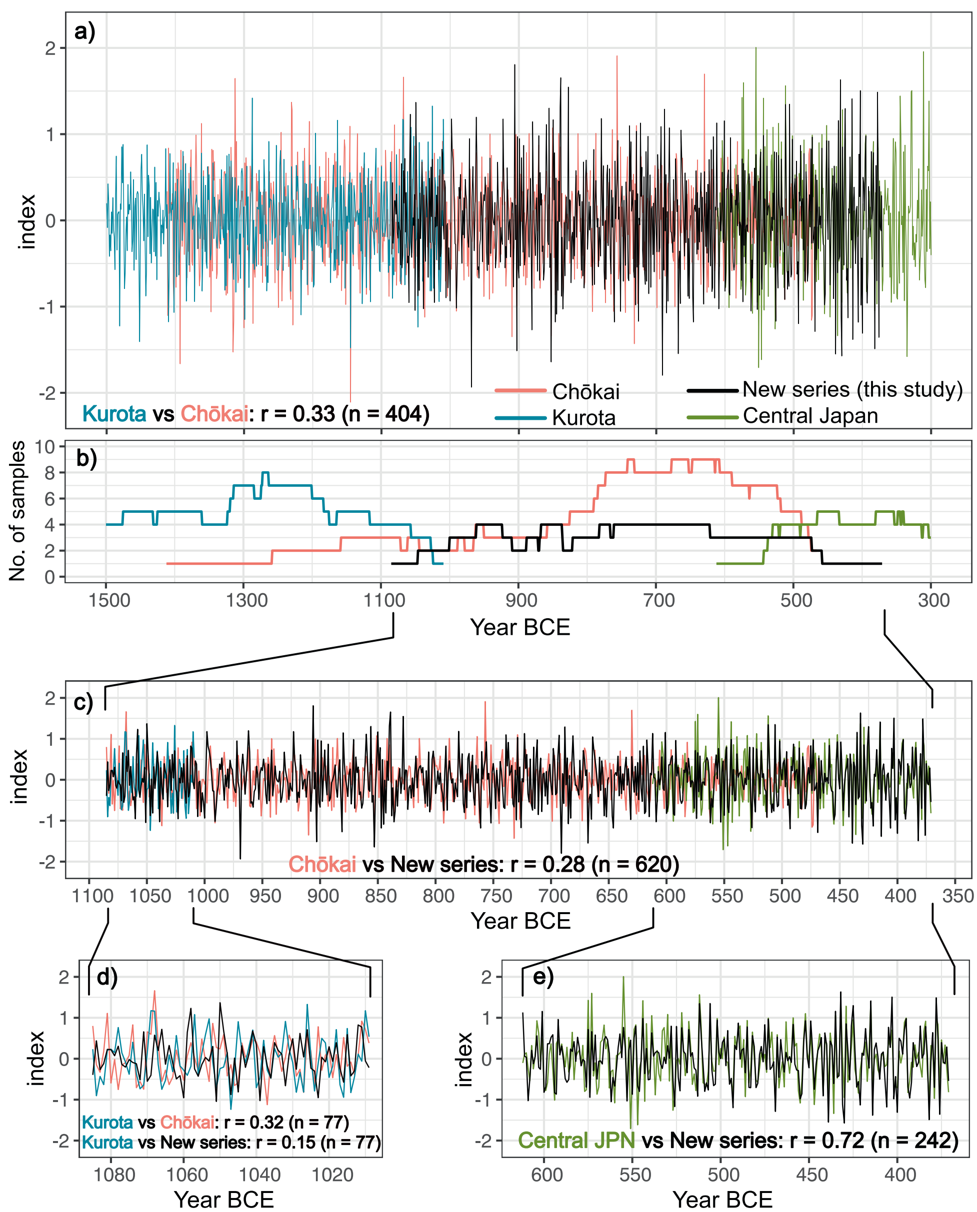

Fig. 2. (a) Cross-dated chronology consisting of nine new series, with master chronologies from the Kurota site (Sano et al., 2023), Chōkai site (Sano et al., 2023), and central Japan site (Nakatsuka et al., 2020; Sano et al., 2022) for the period 1500–300 BCE. (b) Number of samples used for each chronology. (c–e) Enlarged plots showing correlations and overlap periods between chronologies.

$\delta^{18}O$ time-series was filtered and subtracted to produce anomalies with a mean of zero using an 11-year rectangular filter, which is the same procedure as applied previously to tree-ring $\delta^{18}O$ data for Japan (Sano et al., 2023; Sano et al., 2022). All the 98 standardized time-series were then averaged to construct the 4354-year-long master chronology.

The strength of the common variations in the tree-ring $\delta^{18}O$ data for the different samples was evaluated by computing the mean inter-series correlation (Rbar) and the expressed population signal (EPS), with the latter being calculated using the Rbar value and sample size (Wigley et al., 1984). As shown in Supplementary Fig. 2, the Rbar values range from 0.33 to 0.80 throughout the 4354 years, with stronger correlations (>0.5) observed, except for 1000–800 BCE. Similarly, the EPS values exceed a generally accepted threshold of 0.85 over the entire period, except for 1000–800 BCE. The period with lower Rbar and EPS values falls within the 396-year-long gap (1008–613 BCE) between our two master chronologies obtained for the Kurota and central Japan sites, and therefore our chronology still needs to be updated using additional samples to obtain a robust chronology. Despite these limitations, the reliability of our tree-ring dates was independently verified by reproducing the ^{14}C spike at 665–663 BCE using a sample utilized for the Chōkai chronology from northern Japan (Sano et al., 2023, see Fig. 6).

2.2. Archaeological site and samples

Pillar pits that are considered to be remnants of a large building were excavated in 1995 at the Ikegami–Sone site in southern Osaka, Japan. As shown in Fig. 3, the area contains 26 pillar pits and the building is estimated to have been 6.9 m wide and 19.2 m long. Seventeen

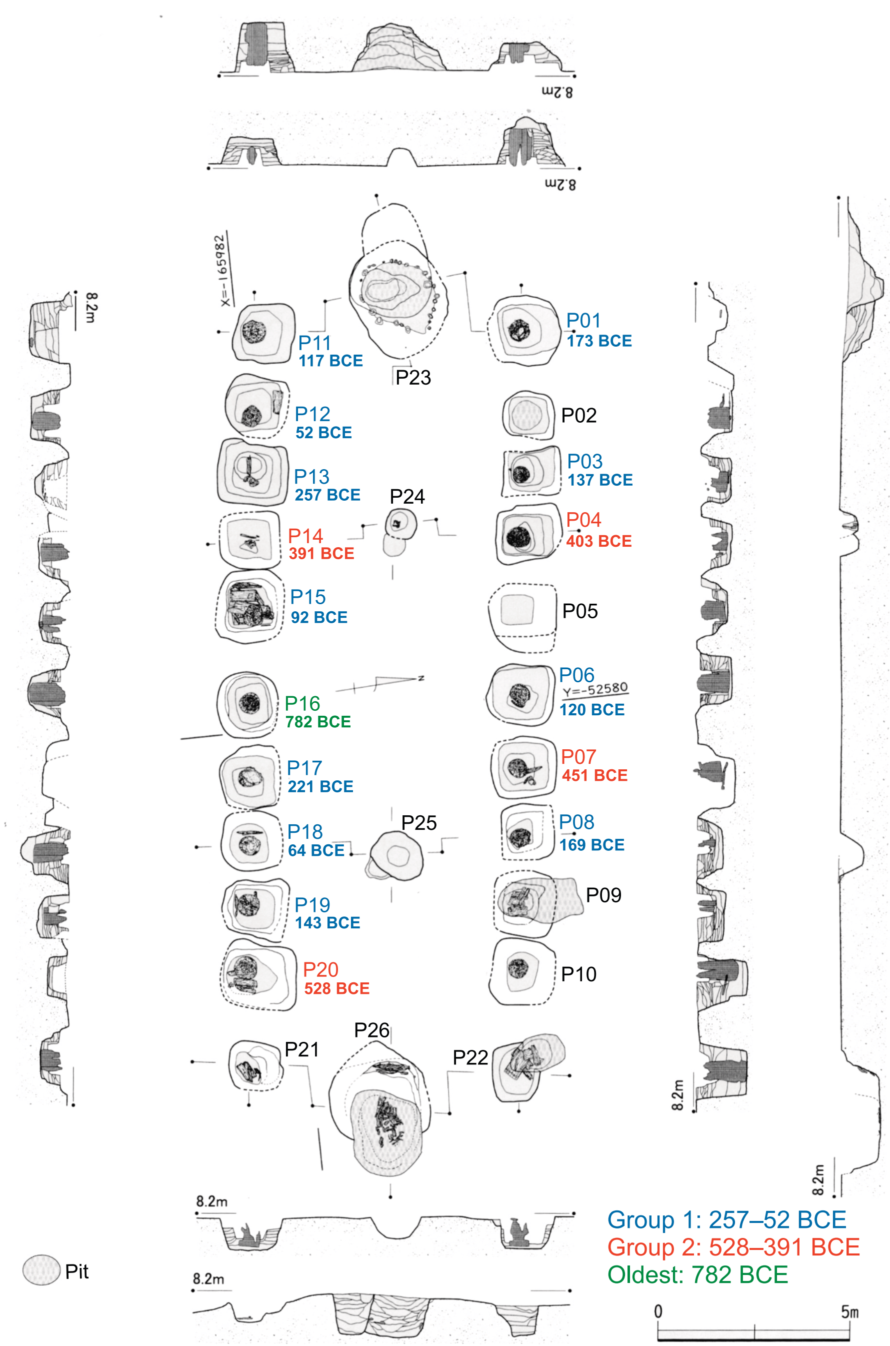

Fig. 3. Plan of the excavated pillars used for the building at the Ikegami–Sone site.

preserved pillars (20–65 cm in diameter and 45–115 cm in height) that were identified to be *Chamaecyparis obtusa* (15 pillars) and *Zelkova serrata* (2 pillars) were found to be embedded in these pits (Izumi City, 2024, see Supplementary Fig. 3). Many pottery shards that can be used to establish relative ages using pottery typology were also excavated along with the pillars in the pits. Each of the pillars has a large hole in the trunk that was used to move the pillar (Supplementary Fig. 3). The bottoms of the pillars were carved out and flattened using a chisel-like tool. A large water well was hollowed out of a single massive log trunk that was 2 m in diameter (*Cinnamomum camphora*), located 3.5 m from the building. In addition, stone axes, whetstones, large pieces of pottery, and octopus pots were unearthed just to the south of the building (Akiyama, 2006). The site was therefore assumed to be a sanctuary. Subsequently, the site was interpreted to have been a well-organized workshop in a well-developed farming village (Akiyama, 2006).

Based on the pottery chronology developed in Japan at the time of excavation, the building was estimated to have been constructed in the 1st century CE (Akiyama, 1996). To evaluate this date by dendrochronology, cores were collected from five pillars (samples P04, P12, P16, P17, and P20) in 1998. Only pillar P12 included complete sapwood rings at the time of excavation (Mitsutani, 1997). The outermost ring, corresponding to the year in which the tree died, was successfully dated to 52 BCE using a tree-ring width master chronology (Mitsutani, 1997). The remaining four samples that did not include sapwood rings were not able to be robustly dated, although possible dates were reported by Mitsutani (1997). The building was thus considered to have been constructed in 52 BCE or shortly thereafter, which is ~100 years earlier than the date from the pottery chronology. This marked the first time that the calendar year of a building from the Yayoi Period had been precisely determined, and represents one of the most important time markers in Japanese archaeology.

Recent progress in isotope dendrochronology encouraged us to reassess the tree-ring dating of the pillars. Fortunately, soon after excavation, the pillar remnants were treated with polyethylene glycol to ensure their permanent preservation. Therefore, we decided to conduct $\delta^{18}O$-based tree-ring dating of the pillars, most of which cannot be cross-dated using the tree-ring width approach. Disc or block samples were collected from all of the 17 pillars mentioned above using a saw in 2023 and 2024, while minimizing the loss of the original shapes of the pillars. Four samples (P04, P12, P16, and P20) contained nearly all the rings of the pillars (304–452 rings), whereas the other 13 samples only contained the outermost 61–163 rings. Based on our observations of the radial growth direction, block samples were collected to encompass as many outermost rings of the pillars as possible. Except for pillar P12, no other pillars contain sapwood rings. One sample (P10) was found to be degraded, and it was difficult to identify tree-ring boundaries in this sample. Therefore, the remaining 16 samples were subjected to further analysis. Tree-ring width data for the five samples collected and measured in 1998 were provided by Mitsutani (pers. comm.) for comparison. In this study, we report calendar years based on the Gregorian calendar (i.e., with no year zero, whereby 1 BCE is followed by 1 CE).

2.3. Sample preparation and tree-ring data

Tree-ring samples from the Ikegami–Sone archaeological site were polished with progressively finer sandpaper until the cellular structure was clear. Tree-ring widths were then measured using scanned images of the samples at a resolution of 0.01 mm (2400 dots per inch). Based on the established protocol for isotope dendrochronology, cellulose was isolated directly from 1 mm-thick wood plates whilst preserving the original cellular structure during the chemical treatment (Kagawa et al., 2015). Each annual ring in the cellulose plates was manually separated from neighboring rings using a blade under a stereomicroscope. The annual ring samples (100–250 μg) were loaded into silver foil. The oxygen isotope ratios ($^{18}O/^{16}O$) of the tree-ring samples were then determined using two continuous flow mass spectrometers interfaced with pyrolysis-type elemental analyzers (Thermo Fisher Scientific Delta V Advantage with TC/EA at Nagoya University, Nagoya, Japan; Delta Q with EA IsoLink OH at the National Museum of Japanese History, Sakura, Japan). The $^{18}O/^{16}O$ ratios are expressed as $\delta^{18}O$ values (in ‰), which are the deviations relative to Vienna Standard Mean Ocean Water (VSMOW). The analytical uncertainty based on repeated measurements of a laboratory standard material (Merck cellulose), which was analyzed after every eight samples, is less than ± 0.20 ‰ (1 standard deviation).

2.4. Cross-dating procedure

We used the dating procedure and statistical tests proposed by Loader et al. (2019). The methodology has been shown to work well for archaeological samples from Japan (Sano et al., 2022). Firstly, individual tree-ring $\delta^{18}O$ time-series of the pillar samples were standardized using an 11-year rectangular filter, which was also applied when developing the 4354-year-long master chronology. Each of the standardized time-series was individually correlated with all possible segments of the master chronology to find a best-matching segment. A series of statistical parameters associated with this analysis were computed to evaluate the pattern matching results. Student's t-values were calculated using correlation coefficients and degrees of freedom that were corrected for autocorrelation and the statistical cost of the filter used for standardization, such that they followed Student's t distribution. The Student's t-values were then converted into one-tailed probabilities (reported as $1/p$ for convenience) that were corrected for multiple tests of significance using the Bonferroni correction (Dunn, 1961). In addition, the isolation factor (IF) was calculated as the ratio of corrected probabilities for the first- and second-strongest matches. The critical thresholds of $1/p \geq 100$ and IF ≥ 10, proposed by Loader et al. (2019), were applied to the pattern matching statistics. We conservatively used the entire period of the master chronology (4354 years) for the pattern matching search.

In the next step, robustly dated tree-ring $\delta^{18}O$ time-series from the pillar samples were averaged to produce a local chronology. Tree-ring $\delta^{18}O$ time-series that failed to pass the statistical tests during pattern matching were then correlated against all possible segments of the local chronology. The same statistical tests for pattern matching were applied in this analysis. Finally, time ranges and the years of the outermost rings for all 16 samples were plotted to determine the age range of the pillars used for the large building. Our analysis was conducted using dplR (Bunn, 2008, 2010) and other packages in the R environment (R Core Team, 2020).

2.5. Radiocarbon measurements

We carried out radiocarbon measurements at annual resolution to verify our tree-ring oxygen isotope dates by reproducing the ^{14}C spike observed at 665–663 BCE in northern Japan (Sakurai et al., 2020; Sano et al., 2023). Segments spanning the period 667–656 BCE, as inferred from the oxygen isotope dates, were selected from samples of two pillars (P04 and P20). Similar to the oxygen isotope measurements, each annual ring of cellulose in thin plates was separated from adjacent rings. The graphite extraction and radiocarbon measurements were conducted at the Laboratory of Radiocarbon Dating, The University of Tokyo, Tokyo, Japan. We then compared our tree-ring ^{14}C data with those from northern Japan (Sakurai et al., 2020; Sano et al., 2023).

3. Results

The results of our tree-ring dating against the 4354-year-long master chronology are presented in Fig. 4, which shows the distributions of Student's t-values for all possible segments. In addition, all the statistical parameters associated with the pattern matching are listed in Table 1. Prominent peaks in t-values are evident for 14 pillar samples (Fig. 4), all

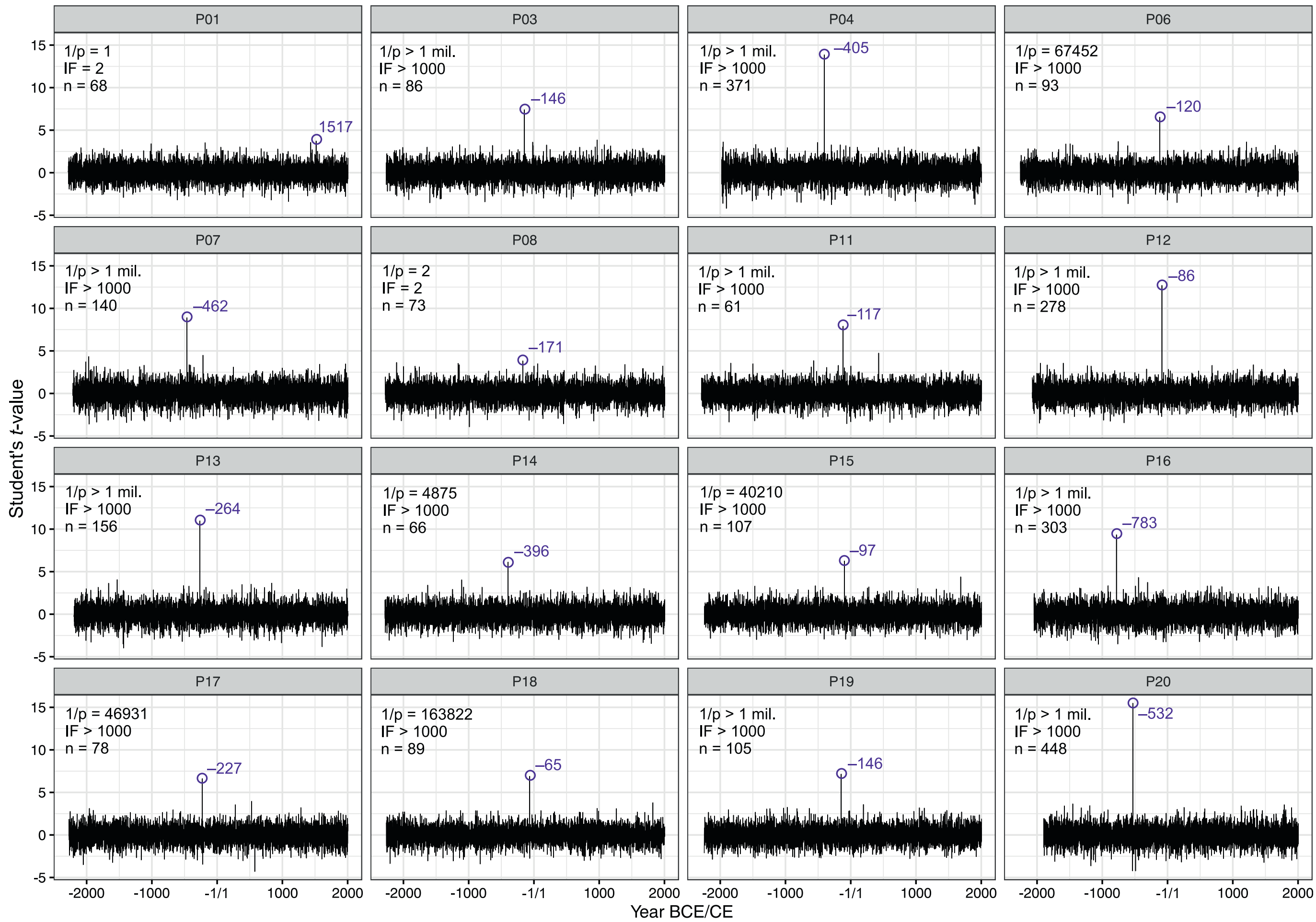

Fig. 4. Distribution of Student's *t*-values for all possible dates through time, with the dating results of individual samples obtained from the 4354-year-long master chronology. The highest *t*-values are marked by purple circles, along with the corresponding dates. Negative values for the calendar year represent BCE.

Table 1
Dating results for the 16 samples based on the 4354-year-long master chronology.

ID	Diameter (m)	Species	n	df	*r* value	*t* value	1/*p*	IF	Last ring	n+
P01	0.55	*C. obtusa*	68	55	0.449	3.73	1	2	1517	11
P03	0.50	*C. obtusa*	86	73	0.655	7.40	>1 mil.	>1000	**–146**	9
P04	0.55	*C. obtusa*	371	330	0.606	13.85	>1 mil.	>1000	**–405**	2
P06	0.55	*C. obtusa*	93	76	0.599	6.52	67,452	>1000	**–120**	0
P07	0.50	*C. obtusa*	140	124	0.624	8.90	>1 mil.	>1000	**–462**	11
P08	0.50	*C. obtusa*	73	62	0.437	3.82	2	2	–171	2
P11	0.65	*Z. serrata*	61	52	0.739	7.90	>1 mil.	>1000	**–117**	0
P12	0.55	*C. obtusa*	278	247	0.628	12.70	>1 mil.	>1000	**–86**	34
P13	0.30	*C. obtusa*	156	135	0.686	10.96	>1 mil.	>1000	**–264**	7
P14	0.20	*C. obtusa*	66	56	0.633	6.12	4875	>1000	**–396**	5
P15	0.55	*C. obtusa*	107	94	0.542	6.25	40,210	>1000	**–97**	5
P16	0.55	*C. obtusa*	303	271	0.493	9.34	>1 mil.	>1000	**–783**	1
P17	0.60	*C. obtusa*	78	62	0.643	6.61	46,931	>1000	**–227**	6
P18	0.55	*C. obtusa*	89	64	0.653	6.89	163,822	>1000	**–65**	1
P19	0.55	*C. obtusa*	105	91	0.600	7.15	>1 mil.	>1000	**–146**	3
P20	0.60	*C. obtusa*	448	404	0.610	15.49	>1 mil.	>1000	**–532**	4

Notes: The table lists the number of rings measured for oxygen isotopes (n), corrected degrees of freedom (df), highest correlation coefficient (*r* value) and its corresponding *t* value, probability corrected for multiplicity (1/*p*), isolation factor (IF), calendar year of the isotopically measured outermost ring ("Last ring"; a negative value represents BCE) for the first strongest match, and number of additional outermost rings that could not be measured isotopically (n +). Bold and underlined text in the "Last ring" column indicates the cross-dating was robust.

of which clearly pass the critical thresholds ($1/p \geq 100$ and IF ≥ 10). These *t* and $1/p$ values range from 6.12 to 15.49 and 4875 to > 1 million, respectively, with all the IF values being > 1000. However, the other two samples failed to pass the thresholds, with $1/p = 1$ and 2, and IF = 2 and 2, respectively, for P01 and P08. Therefore, 14 of the 16 pillar samples were robustly dated using our master chronology.

The two undated pillar samples (P01 and P08) were further subjected to dating using the local chronology, which was developed by averaging the 14 dated time-series. As shown in Fig. 5 and Table 2, notable peaks in *t*-values were observed for both samples, which passed the critical

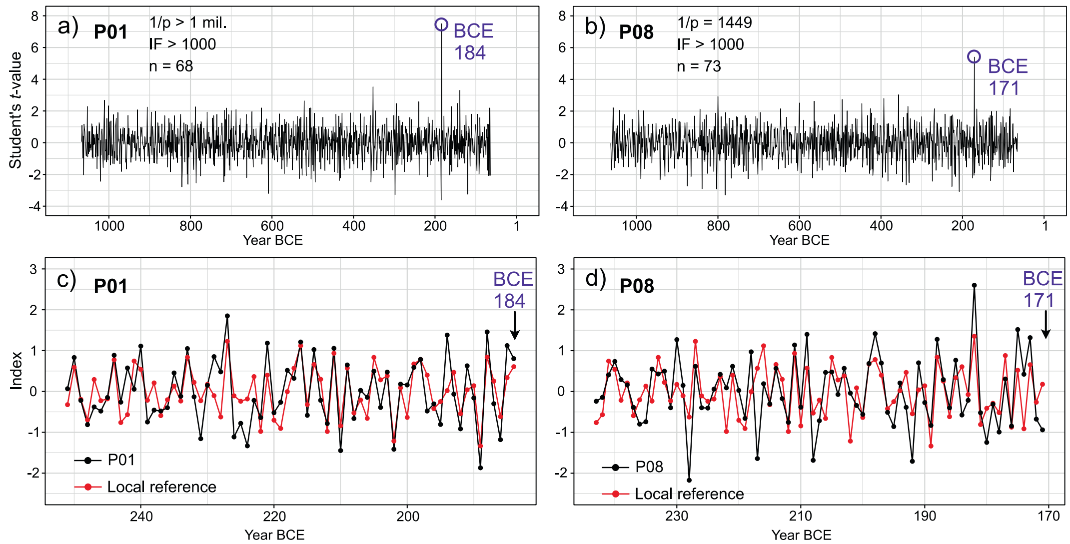

Fig. 5. (a–b) Distribution of Student's *t*-values for all possible dates through time, along with the dating results for two samples (P01 and P08) based on the 1071-year-long local chronology, which itself is based on the other 14 samples from the Ikegami–Sone site. (c–d) Plots of the dated oxygen isotope time-series (P01 and P08), and corresponding segments of the local chronology.

Table 2
Same as Table 1, but for the two samples that could not be robustly dated using the master chronology, which were dated based on the local chronology of the 14 other samples.

ID	Diameter (m)	Species	n	df	*r* value	*t* value	1/*p*	IF	Last ring	n+
P01	0.55	*C. obtusa*	68	50	0.727	7.49	>1 mil.	>1000	**–184**	11
P08	0.50	*C. obtusa*	73	56	0.585	5.40	1449	>1000	**–171**	2

thresholds. These *t* and 1/*p* values are 7.49 (P01) and 5.40 (P08), and > 1 million (P01) and 1449 (P08), respectively, with both having IF > 1000. In addition, nine samples including P01 and P08 for the period 363–65 BCE were cross-dated against each other without using the master chronology. All the cross-dating passed the critical thresholds, and the mean series derived from the nine series were finally cross-dated against the 4354-year-long master chronology (Table 3). Therefore, dating of these samples is considered to be robust.

As shown in Fig. 6, our annually resolved ^{14}C data for the two pillars (P04 and P20) for the period 667–656 BCE are closely correlated with those from northern Japan (Sakurai et al., 2020; Sano et al., 2023). The significant increase in ^{14}C concentration observed at 665–663 BCE is well reproduced in our measurements. Therefore, our tree-ring dates based on the pattern matching of the oxygen isotope data are independently verified by this ^{14}C spike. Of note, an earlier study using German oak samples initially identified a peak at 660 BCE with a rise time of 3–4 years (Park et al., 2017). The peak position and rise time of the ^{14}C spike event observed in Japan seem to differ slightly from those of the peak reported in Germany.

The age ranges of the 16 dated samples and the calendar ages of their outermost rings are shown in Fig. 7a. The pillar sample with complete sapwood rings (P12) was dated to 52 BCE, which is consistent with the date obtained from tree-ring widths (Mitsutani, 1997). The other 15 samples that do not include sapwood rings were dated within a range of 64–782 BCE. Eleven of 16 pillar samples cluster from 257 to 52 BCE (i.e., a 206-year range). Four samples define another cluster from 528 to 391 BCE (i.e., a 138-year range). The remaining sample has the oldest age of 782 BCE, with a 254-year gap to the other samples.

Table 3
Dating results for the nine samples cross-dated against each other, and their mean series ("Composite") cross-dated against the 4354-year-long master chronology.

Sample	Reference	n	df	*r* value	*t* value	1/*p*	IF
P18	P12	68	55	0.693	7.13	>1 mil.	>1000
P15	P12, 18	107	89	0.763	11.13	>1 mil.	>1000
P11	P12, 18, 15	61	50	0.585	5.09	1557	>1000
P06	P12, 18, 15, 11	93	67	0.654	7.08	>1 mil.	>1000
P03	P12, 18, 15, 11, 06	86	67	0.683	7.65	>1 mil.	>1000
P19	P12, 18, 15, 11, 06, 03	105	87	0.756	10.78	>1 mil.	>1000
P08	P12, 18, 15, 11, 06, 03, 19	73	56	0.570	5.19	2936	>1000
P01	P12, 18, 15, 11, 06, 03, 19, 08	68	49	0.714	7.14	>1 mil.	>1000
Composite	Master	299	266	0.678	15.04	>1 mil.	>1000

4. Discussion

The tree-ring analysis shows that the dates of the pillars used in the building vary from 782 to 52 BCE. One pillar (P12) includes complete sapwood rings, and thus the outermost ring dated to 52 BC corresponds to the year in which the tree died. However, the other 15 pillars do not include sapwood rings. A total of 112 modern samples of *Chamaecyparis obtusa* had 17–103 sapwood rings with a mean of 50.3 and standard deviation of 16.7 (Nara National Research Institute for Cultural Properties, 1990). Therefore, the dates when these trees died are expected to be at least a few decades later than our tree-ring dates. Despite this uncertainty, the 700-year age range obtained from our tree-ring dating was not expected, given these are pillars from a single building.

Tree-ring analysis of pile remains, with log diameters of up to 40 cm, from multiple buildings at a prehistoric site at Lake Ohrid in the

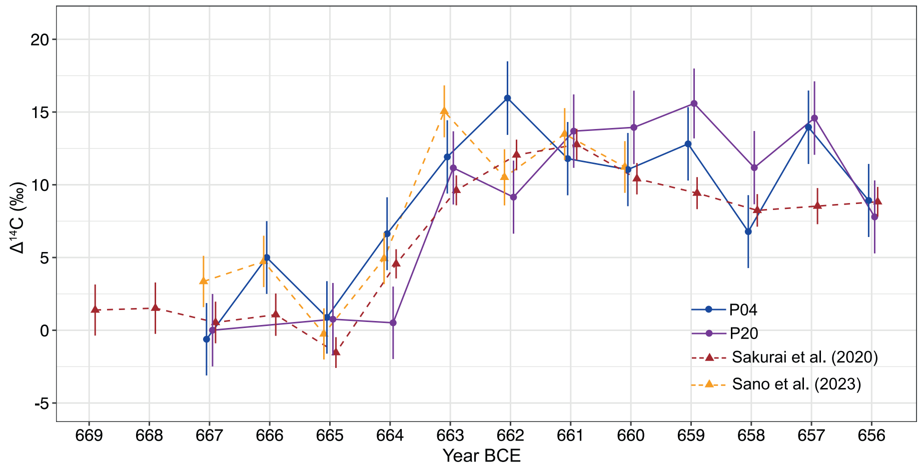

Fig. 6. Comparison of the annually resolved tree-ring $\Delta^{14}C$ time-series between our samples and those from northern Japan (Sakurai et al., 2020; Sano et al., 2023).

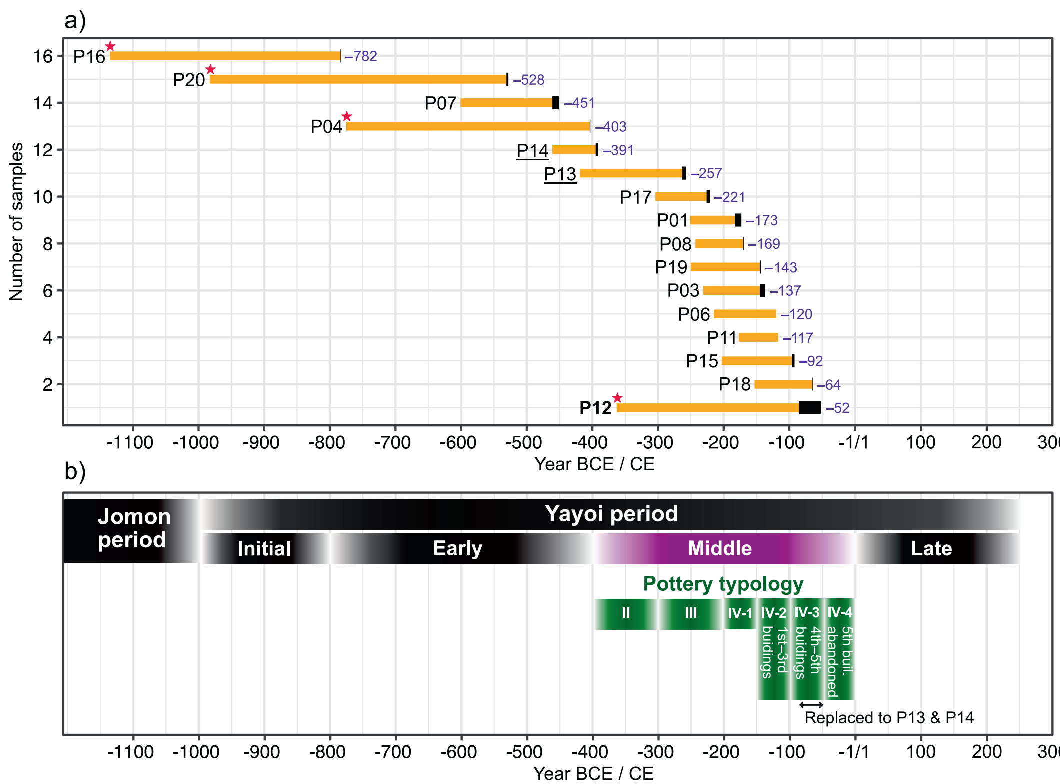

Fig. 7. (a) Age ranges of individual samples with corresponding ages of the outermost rings (yellow bars = oxygen isotope time-series; black bars = observed outermost rings, but not measured isotopically). Note that only four samples (P04, P12, P16, and P20), which are highlighted by red stars, contain nearly the entire range of rings recorded by the pillars. Only sample P12 includes complete sapwood rings. (b) Approximate chronological classification of the Yayoi Period derived from the ^{14}C calibrated pottery chronology, based on archaeological observations of the buildings. Note that the fifth building corresponds to the 'final building' of this study. Negative values for the calendar year represent BCE.

southwestern Balkans revealed at least five temporally independent settlement phases, with each occupation period having minimum time ranges of 17–87 years (Bolliger et al., 2023). The time ranges are much shorter than those evident from the tree-ring dates of the present study.

We now attempt to explain the 700-year age range of the pillars, focusing on three possibilities. Firstly, the outer wood of the tree trunks might have been carved out prior to constructing the building. In fact, some of the pillars show processing marks that indicate a hand axe was used to carve out the sapwood. Fallen trees would have been common in natural forests during the Yayoi Period. The wet and warm climate induced by the summer monsoon would have caused the wood to decay over time. For example, if an old cypress tree died several centuries before construction of the building, it is likely that the outer wood of the trunk would have been decomposed. The rotten outer trunk could have been easily removed to produce sturdy pillars for the building. In fact, some old trees containing > 800 rings are still alive in modern Japan, and are often toppled by typhoons, floods, and other natural disasters. In addition, the number of tree rings in the P04 pillar (403 BCE) varies significantly with the radial direction, implying that uneven rates of decomposition depended on the micro-environmental conditions of the fallen trunk (Supplementary Fig. 3). We also observed that the P07 pillar (451 BCE) does not contain its pith, indicating that a large trunk was vertically split into several parts before the round-shaped P07 pillar was carved out.

Secondly, the Yayoi people might have used buried wood that had been preserved by landslides. Intensified summer monsoon rainfall in the latter half of the 1st century BCE is recorded by tree-ring $\delta^{18}O$ and $\delta^{2}H$ data from central Japan (Nakatsuka et al., 2020). Therefore, these buried trees with different dates might have been exposed by the frequent floods at that time. Woods exposed by flooding might have been easier to use for construction because logging was not required. In fact, some of our samples used for the master chronology were derived from wood buried in riverbanks, suggesting that buried wood could have been used for the building.

Thirdly, the building could have been constructed using pillars that had been utilized elsewhere. Archaeological observations indicate that the building was rebuilt four times within a short period (*ca.* 100 years based on pottery typology) at the same site during the middle Yayoi Period (Fig. 7b). The final building, which is the subject of this study, was larger than the preceding buildings. Therefore, the observed pillar pits used for the preceding buildings were too small to hold the pillars of the final building, clearly indicating that reuse of pillars from the preceding buildings was not physically plausible. Reuse of wood from other artifacts or buildings located elsewhere is a plausible alternative, but there is no evidence to directly support this possibility.

The final (i.e., fifth) building was further investigated from an archaeological perspective. As shown in Fig. 7b, the building was partially repaired, which involved the replacement of two pillars (P13 and P14) without rebuilding, implying that its occupation period was longer than those of the preceding buildings. The diameters of the two replacement pillars (0.20 and 0.30 m for P14 and P13, respectively) were much smaller than those of the other pillars (0.50–0.65 m) that were used when the final building was initially constructed. Pottery shards excavated together with all the pillars have been categorized into a single type (IV-3) (Akiyama, 2006). Structures of the abandoned building were also associated with pottery shards identified as the following type (IV-4). These findings suggest that the final building was constructed and partially repaired during the IV-3 period (Fig. 7b).

The two replacement pillars P13 and P14 were dated to 257 and 391 BCE, respectively. Although the other 10 pillars were embedded earlier than the replacement pillars, they have younger ages of 173–52 BCE (Fig. 7a). In addition, the other four pillars are older than the replacement pillars, although the final building was only occupied during the IV-3 period. These results indicate the Yayoi people utilized dead trees/wood to construct and repair the final building. The P12 pillar, dated to 52 BCE, includes complete sapwood rings, which may be key to explaining the 700-year age difference. Specifically, the P12 pillar was logged shortly before the building was constructed, while the other pillars might have been collected from dead wood resources. Another tree-ring sample that was excavated with pottery shards (IV-3) in Kyoto was dated to 1 CE (Kyoto Prefecture, 2018), which is broadly consistent with the date of the P12 pillar. Collectively, the tree-ring dates and archaeological observations indicate that the final building was constructed in the latter half of the 1st century BCE. Our study indicates that the use of wood in the middle Yayoi Period did not just involve the logging of living trees. Continued efforts to date archaeological woods using tree-ring oxygen isotope records and archaeological observations of processing marks on the pillars will provide more insights into the use of wood in prehistoric Japan.

Author contributions

MSan, MH, TC, TN, and MSak planned and designed the research. MSan, MH, TC, and MSak collected the wood samples. MSan, ZL, and HM undertook the sample treatment and isotopic analysis. MSak conducted the ^{14}C analysis. TC, YY, and TA contributed to the archaeological observations and discussions. MSan conducted the statistical analysis and wrote the draft manuscript. All authors discussed the results and provided input to the manuscript.

CRediT authorship contribution statement

Masaki Sano: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Masataka Hakozaki:** Writing – review & editing, Resources, Investigation, Funding acquisition, Conceptualization. **Yusuke Yamashita:** Writing – review & editing, Investigation. **Zhen Li:** Writing – review & editing, Methodology, Investigation, Data curation. **Takeshi Nakatsuka:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Taro Chiba:** Writing – review & editing, Visualization, Resources, Investigation. **Takashi Arakawa:** Writing – review & editing, Investigation. **Minoru Sakamoto:** Writing – review & editing, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2025.105416.

Data availability

Data will be made available on request.

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