Radiocarbon-based approach capable of subannual precision resolves the origins of the site of Por-Bajin

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Inadequate resolution is the principal limitation of radiocarbon dating. However, recent work has shown that exact-year precision is attainable if use can be made of past increases in atmospheric radiocarbon concentration or so-called Miyake events. Here, this nascent method is applied to an archaeological site of previously unknown age. We locate the distinctive radiocarbon signal of the year 775 common era (CE) in wood from the base of the Uyghur monument of Por-Bajin in Russia. Our analysis shows that the construction of Por-Bajin started in the summer of 777 CE, a foundation date that resolves decades of debate and allows the origin and purpose of the building to be established.

radiocarbon dating | exact-year precision | archaeology | Miyake event | Por-Bajin

Radiocarbon (^{14}C) is widely used to date organic material up to ∼50,000 y in age. The dating method is dependent upon the amount of ^{14}C incorporated by the organism during its life, which ultimately stems from the concentration of ^{14}C in the atmosphere. Atmospheric activities have long been known to vary by ∼1–2‰ (∼8–16 ^{14}C yrs) from 1 y to the next. However, recent ^{14}C measurements on series of known-age tree rings from dendrochronological archives have revealed that sudden increases have occurred in the past on, at least, two occasions. Specifically, an increase within 1 y of about 12‰ (which manifests as a decrease of ∼100 ^{14}C yrs) in 775 CE (1) and 9‰ (decrease of ∼70 ^{14}C yrs) in 994 CE (2). These increases, or "Miyake events," are presumed to be the result of intense bursts of cosmic radiation instigated by the sun (3–8). They have been identified in known-age tree rings of different species from all around the world (e.g., refs. 6, 7, 9–11).

Even with the use of advanced accelerator mass spectrometry (AMS) and probabilistic analyses, such as Bayesian modeling, decadal resolution has marked the zenith for traditional ^{14}C dating of (pre)historical contexts (12, 13). However, the discovery of these atmospheric ^{14}C anomalies, in principle, allows for results to be wiggle matched to the exact calendar year. Crucial to implementing this is finding a Miyake event within an annual sequence of samples, such as an archaeological structure containing tree rings (14). Because the ^{14}C signal of Miyake events is now well established, based on measurements of known-age wood, one should be able to find the same signal in samples of unknown age. If this were to be achieved in wood from an archaeological context, one could assign the exact years in which the rings were laid down. Then, essentially, one would only have to count the number of rings to the bark edge to know the felling year of the tree (14). Indeed, this technique has already been applied successfully to confirm the construction year of a Swiss chapel (15) and the eruption date of the volcano, Changbaishan (16). Dendrochronology, which potentially allows for the same precision, requires a large number of growth rings (typically >100 for individual isolated samples) and a local master chronology, but this new ^{14}C technique requires far fewer rings and can be applied to any tree species (with annual rings) anywhere in the world.

We apply the above-described method to date an archaeological site to the exact year using wood remains from the foundations of Por-Bajin, an enigmatic site in southern Siberia (Tuva, Russian Federation, 50 °36′54″N, 97 °23′5″E). Por-Bajin consists of a gigantic clay complex (∼35,000 m^2) built by the Uyghurs in the eighth century that completely covers an island in Lake Tere-Khol (∼1,300 m a.s.l.) (Fig. 1). It is situated close to the northern margins of the so-called Uyghur Khaganate, an empire that, at one point, encompassed the whole of modern-day Mongolia and parts of southern Siberia (17–20). The site has been known to archaeologists since the 17th century (18), and the first excavations took place around 1960 (21). An extensive multidisciplinary field campaign in 2007–2008 provided major insights about the building and its direct surroundings, such as building techniques (18), the extent of erosion, initial geometry of walls (22), damage caused by past fires and earthquakes (23, 24), and the fact the whole construction process took a very short time (25).

However, fundamental questions still remain. It is not clear when exactly Por-Bajin was built and what its precise function was. The complex may have been a palace or a monastery, and both defensive and ritual purposes have been suggested, but no compelling evidence for either option has yet been found (19). The permanence of the structure within a nomadic domain, the remoteness of its location (i.e., an island far from any contemporaneous

Significance

The problem with radiocarbon dating is that its resolution is only centennial or, at the very best, decadal. Thus, the method is incapable of resolving many historical problems. Here, we use recent developments in atmospheric science to date the construction of a renowned archaeological site to the exact year, in fact, to the exact season. Such precision opens up new possibilities for the broader study of human history. Achieving dates on an annual scale will offer the potential for new assessments to be made of considerable archaeological significance.

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Fig. 1. The site of Por-Bajin. The complex (215 × 162 m) has outer walls up to 12 m high and 12 m wide enclosing a number of courtyards and about 30 buildings (*19*). Photo: A. Panin.

settlements or trade routes), the lack of diagnostic artifacts, and the absence of an occupation layer have puzzled archaeologists. However, our best opportunity to resolve this issue is first to allocate the building to a specific ruler's reign. Due to its exactitude and precision, the method we apply here is capable of settling this long-standing debate about the origins and purpose of this intriguing complex.

Materials and Methods

Wooden beams were recovered from the base levels within the walls of Por-Bajin (*SI Appendix*, Figs. S1 and S2). Hence, they correspond to the very beginning of the building's construction. The foundation, including the beams, is subject to permafrost conditions, which allows for excellent preservation. In this study, we use parts of three of these wooden beams (larch, *Larix sibirica*, called PB-1, PB-2, and PB-5, see *SI Appendix*, Figs. S3–S5) for ^{14}C analysis. α-cellulose is extracted from individual tree-ring samples and dated by AMS at the Centre for Isotope Research (CIO), Groningen, following standard procedures (26). The measured ^{14}C concentrations of the tree-ring sample are matched to tailored single-year-resolution reference curves through the classic statistical method of χ^2 (15, 27) in order to estimate the felling date of the tree.

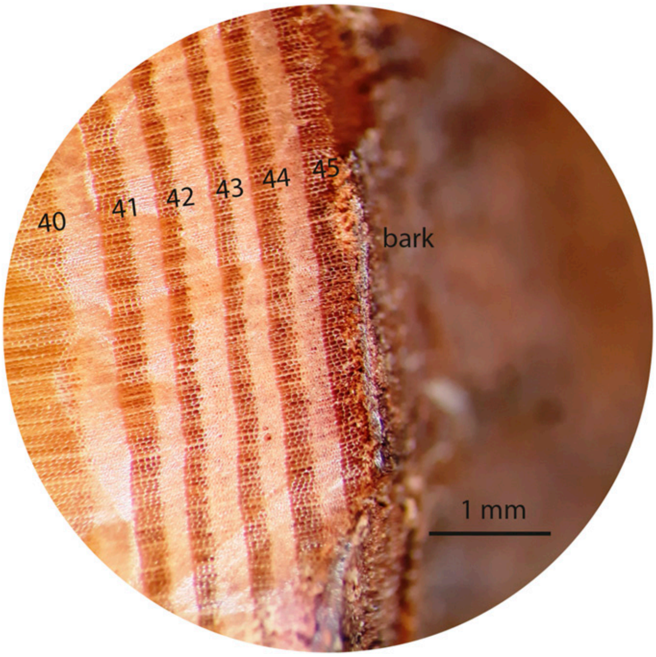

Fig. 2. A microscope image of the outermost tree rings from sample PB-2. Ring 45 is the last growth ring of the tree. In its 45th y, the tree only formed early wood (darker bands; lighter bands are late wood). Photo: P. Doeve.

Data Availability. All data and protocols are available in the main text or the *SI Appendix*.

Results and Discussion

A total of 26 radiocarbon measurements were carried out on a selection ($n = 20$) of mainly the outermost rings of each beam. The results are expressed in ^{14}C yr B.P. and measured at approximately ±2‰ uncertainty (∼16 y, 1σ). The reported uncertainties encompass counting statistics, normalization, and sample preparation calculated in accordance with standard data reduction procedures (27). Samples prepared and measured as replicates show excellent agreement. The full set of data is shown in *SI Appendix*, Table S1, and the outputs of χ^2 statistical comparisons of the replicates are shown in *SI Appendix*, Table S2.

An identifiable bark edge is an essential prerequisite for dating wooden remains to the exact year, irrespective of the kind of dating method involved. The bark edge is the last growth ring under the bark which is formed before felling. Due to the absence of this layer, beams PB-1 and PB-5 do not provide additional information about Por-Bajin's construction year (*SI Appendix*). By contrast, for beam PB-2, the identification of the bark was possible (Fig. 2). In addition, analysis of the cell formation in the last growth ring resulted in establishing the season

Table 1. Radiocarbon dates for the tree rings from PB-2

Laboratory reference	Ring number	^{14}C age (yr B.P.)	δ^{13}C (‰)
GrM-16173	30	1,299 ± 18	−24.33
GrM-12732	39	1,274 ± 14	−24.39
GrM-12736	39	1,278 ± 14	−24.27
GrM-12772	40	1,278 ± 16	−24.85
GrM-12734	41	1,286 ± 14	−25.02
GrM-12774	42	1,263 ± 18	−24.49
GrM-12735	43	1,202 ± 14	−24.44
GrM-12913	44	1,138 ± 16	−24.61
GrM-17491	43–45	1,162 ± 18	−25.33
GrM-17490	44–45	1,160 ± 18	−25.76

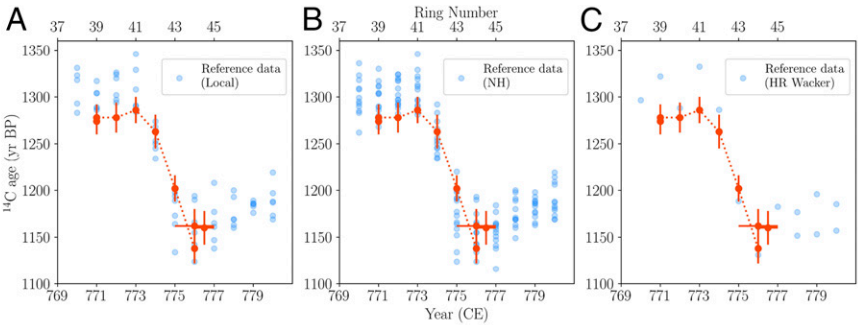

Fig. 3. ^{14}C data from PB-2 (red, ± 1σ) wiggle matched to the exact calendar year versus ^{14}C reference data (blue) from the local region (*A*); NH (*B*); and data of HR Wacker (*C*). The tree-ring numbers (upper x axis) are anchored to calendar years (lower x axis) based on a χ^2 test.

in which the tree was felled. The growth reaction of the tree to seasonal temperature changes underlies the interannual growth differences between early wood and late wood. After the growth season, the tree moves into a dormant phase due to subzero temperatures in southern Siberia. In the 45th ring, the last growth ring of PB-2, early wood is present, and late wood is absent. We conclude that this tree was cut down during or at the end of the summer and certainly prior to the winter months.

For PB-2, the ^{14}C and δ^{13}C values for the 30th ring and rings 39–45 are determined (Table 1). The last growth ring is too small for analysis so it is combined with the previous ring(s). As is evident from Table 1, there is a ~125 ^{14}C yr shift toward younger age between ring 42 and 44. To test if this divergence in ^{14}C yrs matches the signal of the 775 CE Miyake event, the ^{14}C data of PB-2 are wiggle matched to reference data (*SI Appendix*, Fig. S6) using the classical χ^2 method (15, 28). Three bespoke datasets are compiled to act as known-age references from previously published high-resolution ^{14}C data on dendrochronological archives traversing the period 770–780 CE (*SI Appendix*, Table S3 and see refs. 11, 15). The data sets comprise a local series from central Asia, a more general Northern Hemisphere (NH) record, and a further previously published reference set (HR Wacker, 15). In absolute terms, our suite of results matches the reference values of all three data sets very closely. However, in each case, the χ^2 test for goodness of fit is only met when tree-ring number 45 is set to the year 777 CE (Fig. 3 and *SI Appendix*, Fig. S6).

The data give new fundamental insights into the foundational age and function of Por-Bajin. The signal of the 775 CE Miyake event, successfully identified in tree-ring 43 of beam PB-2, unequivocally demonstrates that the tree from which it originates was cut in the summer of 777 CE. As larch grew abundantly in the close vicinity of the island on which Por-Bajin is built (29), there was no need to collect old trunks which would have been of poorer quality than living trees. Therefore, PB-2 was almost certainly felled for the purposes of this construction. This claim is substantiated by the fact the tree died in summer; the harsh winter conditions in the southern Siberian mountains would likely have prohibited construction work during winter.

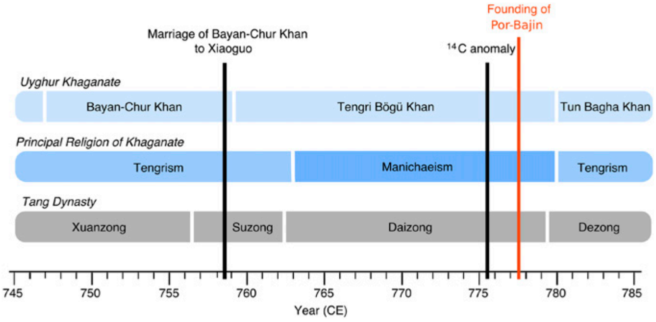

Fig. 4. Timeline showing the foundation date of Por-Bajin (summer 777 CE) in relation to rulers of the Uyghur Khaganate, its dominant religion, and rulers of the Tang Dynasty.

After the excavations in the 1960s, it was thought that Khagan Bayan-Chur (alias Moyun-Chur), who ruled from 747 to 759 CE (22), supervised the construction after his victory over local tribes in 750 CE. The building was then thought to be a fortress or palace. Khagan Bayan-Chur was married to the Chinese princess Nin-go, which would have explained the Chinese influence on Por-Bajin's architecture (17, 18). However, the previously accepted construction date of 750 CE was based on indirect data only (30). Archaeological excavations both in the 1950s and in 2007–2008 revealed that the site was almost completely abandoned after its construction, and the sparse archaeological finds afforded no opportunity to refine the construction date. However, the wiggle-matching ^{14}C data from decadal samples from beam PB-1 indicated that the original tree grew until the late eighth century (21). This younger date made it possible to exclude all hypotheses related to the Bayan-Chur Khan. However, it was still unclear to which of his successors it belonged.

Our exact-season result places the construction of Por-Bajin in the reign of Tengri Bögü Khan (Fig. 4). Bögü Khagan made Manichaeism the official religion of the Uyghur Khaganate, which—together with the lack of evidence for the complex's use—suggests that it was most likely a Manichaean monastery (21, 23). Furthermore, it may have been a place of worship for seasonal use only since no evidence of any kind of heating system has ever been found (18). In 779 CE, historical resources reveal Bögü Khagan was killed as the result of an anti-Manichaean rebellion (31). Since the construction works of Por-Bajin started only shortly before this rebellion, there would have been virtually no time to use it for its intended function, explaining the absence of an occupation layer. In light of this evidence, the hypotheses of the abandonment and the short construction period make sense.

Our study shows that this incipient approach to ^{14}C dating allows for the achievement of exact-year dates for archaeological sites. Such specificity offers the potential for new assessments to be made of considerable archaeological and geochronological significance.

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