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

Margot Kuitemsa, Andrei Panimb, Andrea Scifoa, Irina Arzhantsevad,e, Yury Kononovc, Petra Doevef, Andreas Neocleousg, and Michael Deeh

*Centre for Isotope Research, University of Groningen, 9747 AG Groningen, Netherlands; bLomonosov Moscow State University, 119991 Moscow, Russia; cInstitute of Geography, Russian Academy of Science, 119017 Moscow, Russia; dInstitute of Ethnology and Anthropology, Russian Academy of Science, 119334 Moscow, Russia; eInstitute for Oriental and Classical Studies, Faculty of Humanities, Higher School of Economics, 105066 Moscow, Russia; fLaboratory for Dendrochronology at BAAC Archaeology and Building History, 5222 BS ‘s-Hertogenbosch, Netherlands; and gDepartment of Computer Science, University of Cyprus, 2109 Aglantzia, Cyprus

Edited by James F. O’Connell, University of Utah, Salt Lake City, UT, and approved April 30, 2020 (received for review December 4, 2019)

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 (14C) is widely used to date organic material up to ~50,000 y in age. The dating method is dependent upon the amount of 14C incorporated by the organism during its life, which ultimately stems from the concentration of 14C in the atmosphere. Atmospheric activities have long been known to vary by ~1-2‰ (~8–16 14C yrs) from 1 y to the next. However, recent 14C 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 14C yrs) in 775 CE (1) and 9‰ (decrease of ~70 14C 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 14C dating of (prehistoric) contexts (12, 13). However, the discovery of these atmospheric 14C 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 site 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, Changaishan (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 14C 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 m2) 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.

Author contributions: M.K. and M.D. designed research; M.K., A.P., I.A., Y.K., and M.D. performed research; M.K., A.S., and M.D. contributed new reagents/analytic tools; M.K., A.S., P.D., A.N., and M.D. analyzed data; M.K. and M.D. wrote the paper; and A.P. provided material.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

This open access article is distributed under Creative Commons Attribution-NonCommercial-NoDerivatives License 4.0 (CC BY-NC-ND).

1To whom correspondence may be addressed. Email: m.kuitem@rug.nl.

This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.1921301117/-/DCSupplemental.

First published June 8, 2020.
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 14C 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 14C concentrations of the tree-ring sample are matched to tailored single-year-resolution reference curves through the classic statistical method of χ² (15, 27) in order to estimate the felling date of the tree.

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 14C 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 χ² 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 | 14C age (yr B.P.) | δ¹³C (%) |
|----------------------|-------------|------------------|----------|
| 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-12794            | 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   |

Kuitems et al. PNAS | June 23, 2020 | vol. 117 | no. 25 | 14039
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 $^{87}$Sr 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 $\sim 125$ $^{14}$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 $\chi^2$ 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 $\chi^2$ 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.

After the excavations in the 1960s, it was thought that Khagan Bayan-Chur (alias Moyun-Chur), who ruled from 747 to 759 CE (21, 23). Furthermore, it may have been a place of worship for 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 Bogü 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 exact-season result places the construction of Por-Bajin in the reign of Tengri Bogü Khan (Fig. 4). Bogü Khagan made Manichaeism the official religion of the Uyghur Khaganate, which—considering the absence 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 Bogü 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.

Acknowledgments. The authors acknowledge the contribution of J. van der Plicht, H. Härke, and the laboratory staff of the Centre for Isotope Research, Groningen. This work was funded by a European Research Council Research Project (Grant 714679). M.K., A.S., A.N., and M.D. were supported by this grant. Fieldwork in the Terekhol Basin (A.P.) and decadal-scale radiocarbon age estimation were supported by Russian Foundation for Basic Research Project 19-05-00863, and the initial preparation of dendrochronological samples (Y.K.) was supported by Institute of Geography, Russian Academy of Sciences State Target Project 0127-2019-0008.
1. F. Miyake, K. Nagaya, K. Masuda, T. Nakamura, A signature of cosmic-ray increase in AD 774-775 from tree rings in Japan. *Nature* 486, 240-242 (2012).
2. F. Miyake, K. Masuda, T. Nakamura, Another rapid event in the carbon-14 content of tree rings. *Nat. Commun.* 4, 1748 (2013).
3. A. K. Pavlov et al., Gamma-ray bursts and the production of cosmogenic radionuclides in the Earth’s atmosphere. *Astron. Lett.* 39, 571-577 (2013).
4. V. V. Hambaryan, R. Neuhäuser, A Galactic short gamma-ray burst as cause for the 14C peak in AD 7745. *Mon. Not. R. Astron. Soc.* 430, 32-36 (2013).
5. M. Dee, B. Pope, D. Miles, S. Manning, F. Miyake, Supernovae and single-year anomalies in the atmospheric radiocarbon record. *Radiocarbon* 59, 293-302 (2017).
6. I. G. Uosokin et al., The AD775 cosmic event revisited: The Sun is to blame. *Astron. Astrophys.* 552, L3 (2013).
7. A. Scifo et al., Radiocarbon production events and their potential relationship with the schwabe cycle. *Sci. Rep.* 9, 17056 (2019).
8. F. Tekheli et al., Multiradionuclide evidence for the solar origin of the cosmic-ray events of 774/5 and 993/4. *Nat. Commun.* 6, 8611 (2015).
9. A. T. Jull et al., Excursions in the 14C record at AD 774-775 in tree rings from Russia and America. *Geophys. Res. Lett.* 41, 3004-3010 (2014).
10. D. Güttler et al., Rapid increase in cosmogenic 14C in AD 775 measured in New Zealand kauri trees indicates short-lived increase in 14C production spanning both hemispheres. *Earth Planet. Sci. Lett.* 411, 290-297 (2015).
11. U. Büntgen et al., Tree rings reveal globally coherent signature of cosmogenic radiocarbon events in 774 and 993 CE. *Nat. Commun.* 9, 3605 (2018).
12. C. Bronk Ramsey et al., Radiocarbon-based chronology for dynastic Egypt. *Science* 328, 1554-1557 (2010).
13. S. W. Manning et al., Chronology for the agean late bronze age 1700-1400 B.C. *Science* 312, 565-569 (2006).
14. M. W. Dee, B. J. Pope, Anchoring historical sequences using a new source of astrophysical tie-points. *Proc. Math. Phys. Eng. Sci.* 472, 20160263 (2016).
15. L. Wacker et al., Radiocarbon dating to a single year by means of rapid atmospheric 14C changes. *Radiocarbon* 56, 573-579 (2014).
16. C. Oppenheimer et al., Multi-proxy dating of the “Millennium Eruption” of Changbaishan to late 946 CE. *Quat. Sci. Rev.* 158, 164-171 (2017).
17. H. Härke, Letter from Siberia: Fortress of solitude. *Archaeology Magazine* 63, 51-58 (2010).
18. I. Arzhantseva, H. Härke, A. Schubert, Por-Bajyn: Eine “Verbotene Stadt” des Uiguren-Reiches in Südsibirien [in German]. *Antike Welt* 3, 3-10 (2012).
19. I. Arzhantseva et al., Por-Bajyn: An enigmatic site of the Uighurs in Southern Siberia. *The European Archaeologist* 35, 6-11 (2011).
20. S. I. Vainstein, Ancient Por-Bajyn [in Russian]. *Sovetskaya Etnografiya* 6, 103-114 (1964).
21. A. V. Panin, I. A. Arzhantseva, M. A. Bronnikova, O. N. Uspenskaya, Yu. N. Fuzeina, “Interpretation of the Early Medieval Por-Bajyn site (Tuva Republic) in the light of earth science research results” in Trudy IV (XX) Vserossijskogo Arheologicheskogo Siedza v Kazan [in Russian]. (Otechestvo Publisher, Kazan, 2014), pp. 331-334.
22. G. L. Alifimov, G. V. Nosyrev, A. V. Panin, I. A. Arzhantseva, G. Oleaga, The application of cliff degradation models for estimation of the initial height of rammed-earth walls (Por-Bajyn Fortress, Southern Siberia, Russia). *Archaeometry* 55, 958-973 (2013).
23. A. V. Panin, I. A. Arzhantseva, Mysteries of Por-Bajyn [in Russian]. *Zhivotopisnaya Rossiya* 6, 14-19 (2010).
24. A. V. Panin, New data on the late Holocene Seismicity of the Southwestern edge of the Baikal Rift zone. *Dokl. Earth Sci.* 438, 563-568 (2011).
25. I. A. Arzhantseva et al., “Por-Bazhyn, pamyatnik drevnej istorii Tuva (Por-Bajyn, a monument to the ancient history of Tuva)” in Uryanhaj. Tyva depter: Antologiya nauchnov o praviteľskoj mysli [in Russian], S. K. Shoigu, Ed. (Stivo Publ., Moscow, 2008), vol. 7, pp. 886-898.
26. M. W. Dee et al., Radiocarbon dating at Groningen: New and updated chemical pretreatment procedures. *Radiocarbon* 62, 63–74 (2020).
27. M. Stuiver, H. A. Polach, Discussion reporting of 14C data. *Radiocarbon* 19, 355-363 (1977).
28. C. Bronk Ramsey, J. van der Plicht, B. Weninger, “Wiggle matching” radiocarbon dates. *Radiocarbon* 43, 381-389 (2001).
29. O. K. Borisova, A. V. Panin, Multicentennial climatic changes in the Terekhol Basin, Southern Siberia, during the Late Holocene. *Geogr., environ., Sustainability* 12, 148-161 (2019).
30. S. G. Klyashtornyi, Qasar-Qurug: Western headquarters of the uighur khagans and the problem of Por-Bazhyn identification. *Archaeol. Ethnol. Anthropol. Eurasia* 40, 94-98 (2012).
31. M. S. Asimov, C. E. Bosworth, Eds., *History of Civilizations of Central Asia. The Age of Achievement, AD 750 to the End of the Fifteenth Century; Pt. I: The Historical, Social and Economic Setting* (Unesco Publishing, Paris, 1998), Vol. IV.