# New radiocarbon tree-ring datasets used in the paper "The timing of the ca-660 BCE Miyake solar-proton event constrained to between 664 and 663 BCE"

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**Abstract**

Extreme solar energetic particle events, known as Miyake events, are rare phenomena observed by cosmogenic isotopes, with only six documented. The timing of the ca. 660 BCE Miyake event remains undefined until now. Here, we assign its occurrence to 664-663 BCE through new radiocarbon measurements in gymnosperm larch tree rings from arctic-alpine biomes (Yamal and Altai). Using a 22-box carbon cycle model and Bayesian statistics, we calculate the radiocarbon production rate during the event that is 3.2-4.8 times higher than the average solar modulation, and comparable to the 774-775 CE solar-proton event. The prolonged radiocarbon signature manifests a 12‰ rise over two years. The non-uniform signal in the tree rings is likely driven by the low rate of $CO_2$ gas exchange between the trees and the ambient atmosphere, and the high residence time of radiocarbon in the post-event stratosphere. We caution about using the event's pronounced signature for precise single-year-dating.

## Dataset description

The original radiocarbon data used in the study is available in the papers cited here [1, 2]. Two new radiocarbon datasets from Altai and Yamal regions developed purposely for this study are accessible from the Table 1 below. Figure 1 shows all radiocarbon data used in the study.

**Table 1.** Two datasets (Altai and Yamal) of high precision radiocarbon measurements from larch tree rings.

| Year BCE | Altai d14C | Altai sig_d14c | Yamal d14C | Yamal sig_d14c |
|---|---|---|---|---|
| 685 | 6.82 | 1.74 | | |
| 684 | 4.09 | 1.48 | | |
| 683 | 6.6 | 1.49 | | |
| 682 | 5.77 | 1.47 | | |
| 681 | 3.5 | 1.47 | | |
| 680 | -0.86 | 1.53 | | |
| 679 | 8.64 | 1.51 | | |
| 678 | 6.98 | 1.47 | | |
| 677 | 4.94 | 1.5 | | |
| 676 | 7.91 | 1.45 | | |
| 675 | 2.67 | 1.49 | | |
| 674 | 3.47 | 1.52 | | |
| 673 | 2.78 | 1.7 | | |
| 672 | -2.79 | 1.83 | | |
| 671 | 3.33 | 1.52 | 1.54 | 1.9 |
| 670 | 4.35 | 1.45 | 4.45 | 1.99 |
| 669 | 7.07 | 1.46 | -8.18 | 2.01 |
| 668 | 4.88 | 1.5 | -4.91 | 2.04 |
| 667 | 8.45 | 1.47 | 2.68 | 2 |
| 666 | 7.95 | 1.47 | -1.29 | 2.02 |
| 665 | 4.29 | 1.45 | -1.77 | 2 |
| 664 | 7.1 | 1.49 | 10.74 | 1.99 |
| 663 | 19.98 | 1.52 | 12.65 | 2 |
| 662 | 15.11 | 1.59 | 10.77 | 1.95 |
| 661 | 11.12 | 1.68 | 10.5 | 1.94 |
| 660 | 13.92 | 1.63 | 7.48 | 2 |
| 659 | 14.21 | 1.56 | 10.87 | 2.05 |
| 658 | 13.61 | 1.63 | 7.62 | 2.14 |
| 657 | 15.3 | 1.5 | 5.94 | 1.93 |
| 656 | 15.36 | 1.49 | 4.42 | 1.91 |
| 655 | 12.09 | 1.47 | 7.35 | 2 |
| 654 | 8.32 | 1.53 | 6.06 | 1.87 |
| 653 | 11.36 | 1.45 | 8.63 | 1.92 |
| 652 | 9.22 | 1.49 | 12.06 | 2 |
| 651 | 7.16 | 1.48 | 1.76 | 1.93 |
| 650 | 8.09 | 1.46 | | |

| | | |
|---|---|---|
| 649 | 10.64 | 1.45 |
| 648 | 4.34 | 1.74 |
| 647 | 10.33 | 1.46 |
| 646 | 10.05 | 1.47 |
| 645 | 7.86 | 1.49 |
| 644 | 2.16 | 1.55 |
| 643 | 2.25 | 1.5 |
| 642 | 3.37 | 1.52 |
| 641 | 4.26 | 1.49 |
| 640 | 0.94 | 1.53 |
| 639 | 5.53 | 1.52 |
| 638 | 2.49 | 1.52 |

**Tree rings and $^{14}C$ measurements**

In this study, radiocarbon production during the SEP ca. 660 BCE was simulated with five $^{14}C$ high-precision datasets from four locations in Eurasia. Two $^{14}C$ series were developed specifically for this paper and three others were previously published by Park et al. [1] and Sakurai et al. [2]. The geography of the locations and the variations of $\Delta^{14}C$ datasets are given in Figure 1, respectively. Individual rings of known age determined with cross-dating were separated with a scalpel, their cellulose was extracted, and carbon was graphitized following standard protocols of the AMS facilities where the $^{14}C$ content was measured. The specific procedures applied to develop each time series are briefly described below and referenced.

*Altai larch:* This 48-year $^{14}C$ series (685-638 BCE) was developed from *Larix sibirica* conifer rings of Scythian archeological timbers excavated at the Ulandryk IV cemetery [3]. The Ulandryk IV is located in the upper tree-line ecotone of the Chuysky Range, Altai Mountains, Russia. Specimen # 19116 was collected from Kurgan-1 and cross-dated with the Mongun Taiga tree-ring chronology [4]. The growth season in the Altai's extremely continental climate rounds a little over 3 months between late May and early September. The cellulose was pretreated with the acid-base-acid bleaching, and $^{14}C$ was measured at the ICER AMS facility of the Hertelendi Laboratory of Environmental Studies (HEKAL) in Debrecen, Hungary, following the standard protocols of this laboratory [5].

*Yamal larch*: This 21-year series spans from 671 to 651 BCE. The rings of *Larix sibirica* subfossil wood (specimen #1902) from fluvial deposits of the Yamal Peninsula, Russia, were dated with the Yamal multimillennial tree-ring chronology [6]. The site location is the taiga-tundra ecotone in cold semi-arid climate with less than 3-month growing season from June to August. The $^{14}C$ of the prepared rings was measured at ICER AMS Laboratory in Debrecen following the same procedure used for the Altai larch series.

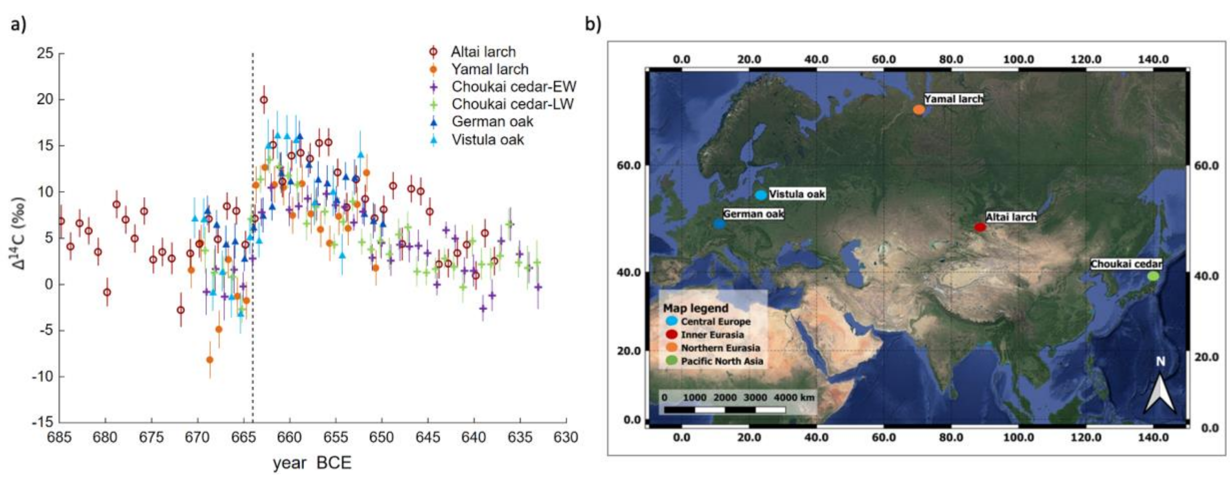
**$\Delta^{14}C$ calculation**

Radiocarbon analysis was performed on annually resolved time series of $\Delta^{14}C$ in astronomical year numbering (Astro years) then converted to BCE. $\Delta^{14}C$ is calculated as:

$$\Delta^{14}C = 1000(Fe^{\lambda t - 1}) \qquad (1.1)$$

where $\lambda$ is the true decay constant of $^{14}C$ ($1.209 \times 10^{-4}$) based on the half-life of 5730 yr, and $t$ is the known age of the ring sample by dendrochronology. The fraction of modern carbon, F, is defined as the $^{14}C/^{12}C$ ratio relative to the “modern” $^{14}C$ activity set to 1950 AD, which is defined as 0.95 of the $^{14}C/^{12}C$ ratio of the oxalic-I standard [7] or 0.7459 of the international oxalic-II standard (SRM-4990C), see Donahue et al. [8].

**Figure 1**. Variations of $\Delta^{14}C$ concentrations measured in tree rings at ca. 660 BCE ME (a) and map showing the locations of the tree rings (b). New time series and previously published ones are color-coded. Tree-ring data locations: red-Altai Mountains and orange- Yamal Peninsula from this study; green -Japan from Sakurai et al. [2]; and blue - Central Europe from Park et al. [1] and Rakowski et al. [9]. Rakowski et al. series [9] shown here is excluded from the production rate modeling due to short length and missing values. The vertical line represents the 664 BCE. Although the series show some differences in $\Delta^{14}C$ variations ca. 660 BCE ME, the spike signal is apparent as a ca. 15 ‰ increase over 2–3 years, which is sustained by high values for the next 2–3 years followed by a slow return to the average of ca. 5‰. The map was created in QGIS (3.8.0) using Google Earth imagery.




## References

1. Park, J., Southon, J., Fahrni, S., Creasman, P. P. & Mewaldt, R. Relationship between solar activity and $\Delta^{14}C$ peaks in AD 775, AD 994, and 660 BC. *Radiocarbon* **59** (4), 1147–1156 (2017).
2. Sakurai, H. et al. Prolonged production of $^{14}C$ during the ~660BCE solar proton event from Japanese tree rings. *Scientific Reports* **10**, 660 (2020).
3. Panyushkina, I.P., Sljusarenko, I.Y., Bikov, N.I. & Bogdanov, E. Floating larch tree-ring chronologies from archaeological timbers in the Russian Altai between 800 BC and 800 AD. *Radiocarbon* **49**(2), 693–702 (2007).

4. Myglan, V.C., Oydupaa, O.C. & Vaganov, E.A. Development of 2,367-year tree-ring chronology for the Altai-Sayan region (Mongun-Taiga mountain range). *Archeology, Ethnography and Anthropology of Eurasia* **3**, 51 (2012).
5. Molnár, M. et al. Status report of the new AMS $^{14}C$ sample preparation lab of the Hertelendi Laboratory of Environmental Studies (Debrecen, Hungary). *Radiocarbon* **55**, 665–676 (2013).
6. Hantemirov, R. M. et al. An 8768-year Yamal Tree-ring Chronology as a tool for paleoecological reconstructions. *Russ. J. Ecol.* **52**, 419–427 (2021).
7. Stuiver, M. & Polach, H.A. Discussion: Reporting of $^{14}C$ data. *Radiocarbon* **19**, 355–363 (10.1017/S0033822200003672, 1977).
8. Donahue, D.J., Linick, T.W. & Jull, A.J.T. Isotope ratio and background corrections for accelerator mass spectrometry radiocarbon measurements. *Radiocarbon* **32**(2), 135–42 (1990).
9. Rakowski, A. Z. et al. Radiocarbon concentration in sub-annual tree rings from Poland around 660 BCE. *Radiocarbon*, 1–10 (10.1017/RDC.2023.79, 2023).