Rapid ^{14}C events in tree rings due to solar and cosmic events.

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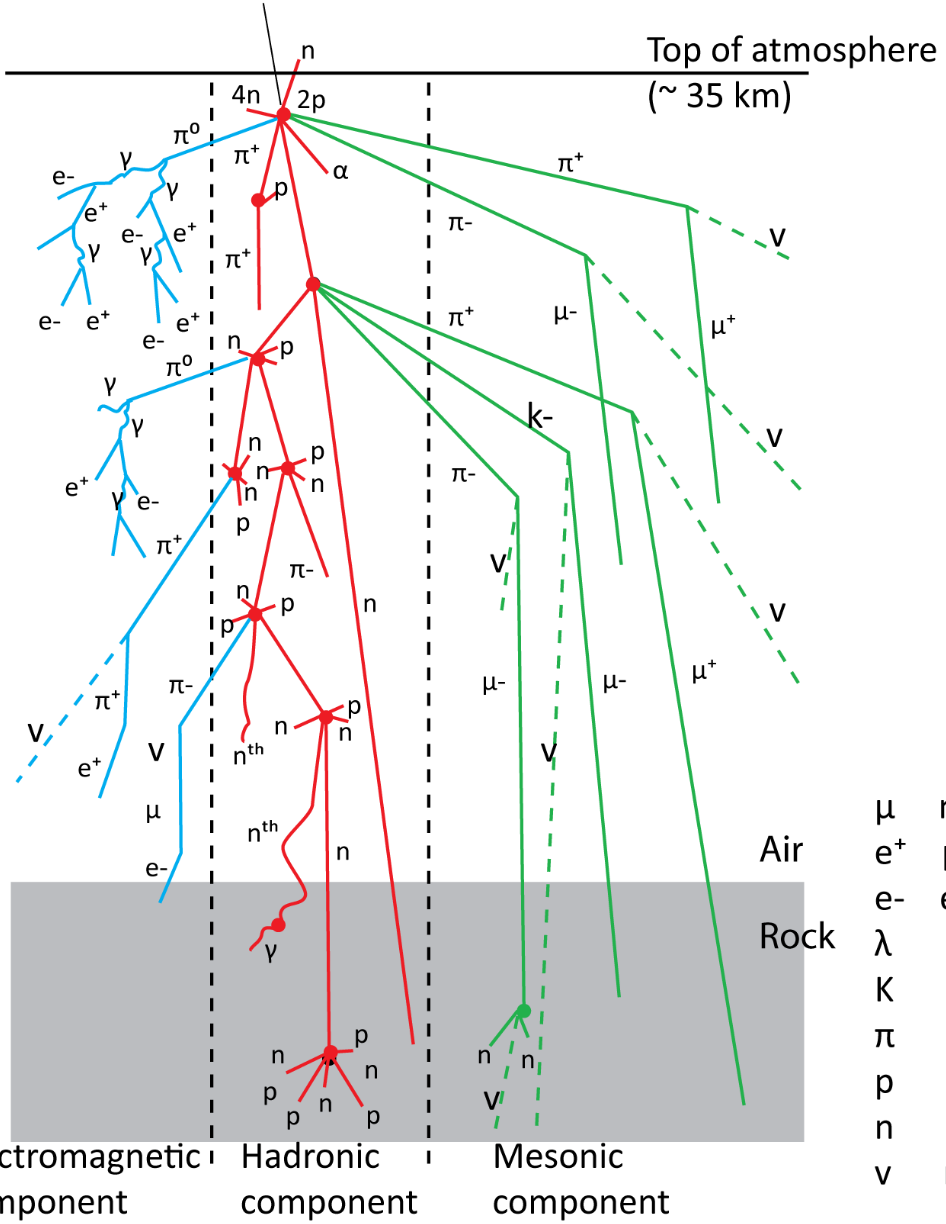
Sun and Climate Meeting, Flagstaff, AZ. October 2023

Secondary particle production in atmosphere and rock
After Gosse and Phillips, 2001



μ	muons
e⁺	positron
e-	electron
λ	photons (gamma rays)
K	kaons
π	pions
p	protons
n	neutrons
v	neutrino

www.AntarcticGlaciers.org

If we know the true age, we can calculate the original number of atoms incorporated

$N(t) = N_0 \exp(-\lambda t)$

At time of formation t_0 of the tree ring,
and we know the true age (t), then

$N_0 = N(t) \exp(+\lambda t)$.

Some numbers:
Preindustrial atmosphere: ~600Gt C
Preindustrial ^{14}C: ~600kg.
Annual production of ^{14}C: ~6kg

Important Definitions

It is useful to define Δ^{14}C, which tells us the value of ^{14}C at the time of formation of the material –

Positive Δ^{14}C = increase in production or 14/12 ratio.

Negative Δ^{14}C – decrease in production or 14/12 ratio.

$$\Delta^{14}\text{C} = 1000\,(Fe^{\boldsymbol{\lambda}(t)} - 1)$$

The value of F is the "fraction of modern carbon", i.e. F= $N/N_{0,}$ where N_0 is the value at 1950CE*, and
t = true age of the sample.

If t is given as CE or a negative for BCE, then t=(1950-t).

λ = true decay constant of ^{14}C, 1.21 x 10^{-4}

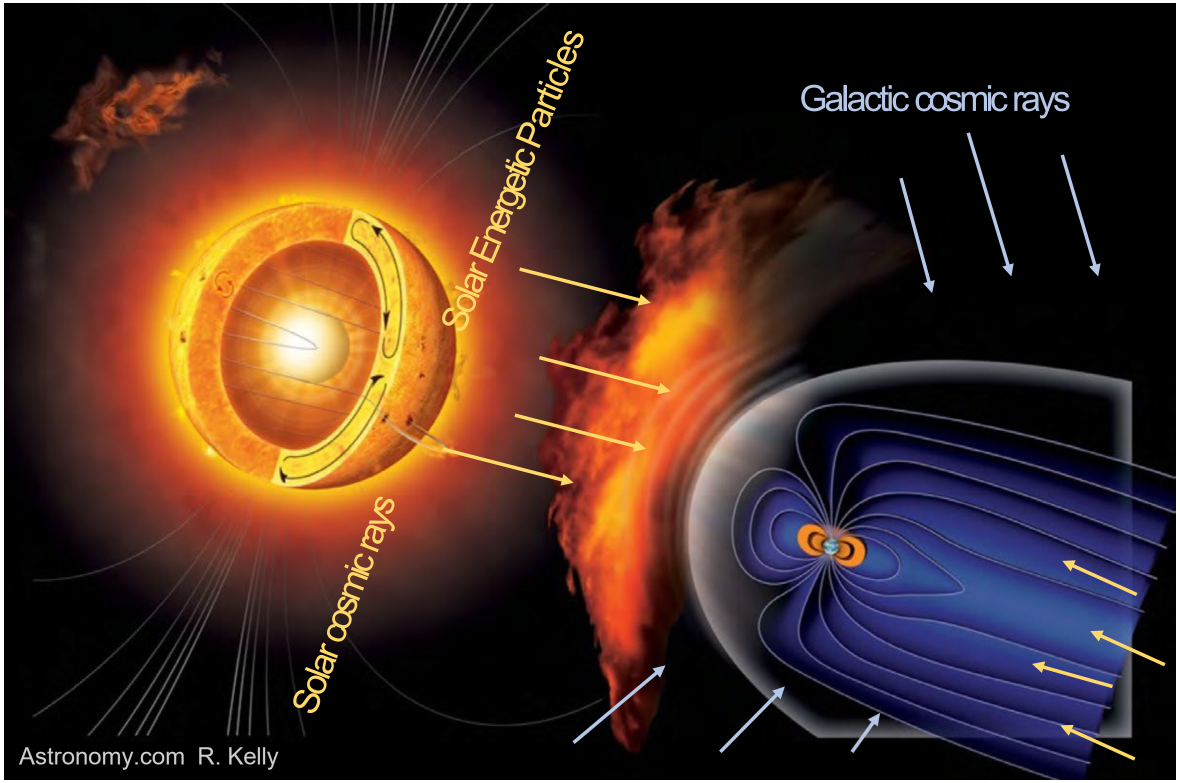
Cosmic Rays in Earth's Upper Atmosphere

Cosmogenic isotope ^{14}C - a tracer of cosmic ray flux

Atmosphere contains 814 kg of ^{14}C (relatively constant amount)

Annual ^{14}C production rate = 6.7 kg
<u>Global average</u> = 1.6–2.0 atoms/cm²/s

- Direct observations on intensity characteristics of Solar Proton energy influx (SPE or SEP) from the late 1930s and from space observation after 1997 (ACE).
- Indirect observations from historical network of Sunspot numbers start ca. 1640.



Astronomy.com R. Kelly

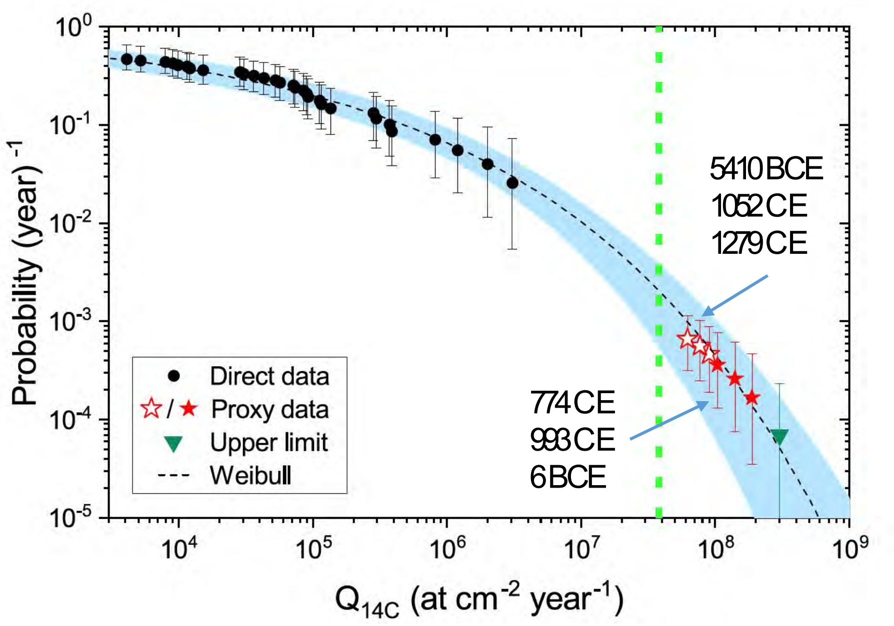


Great Cosmic Storms

..leave an imprint in the atmospheric radiocarbon record

SEP	12,350 BCE (1)
SEP	7176 BCE
GSM	5480 BCE
	5410 BCE
SEP	5259 BCE
	~~3372 BCE~~
GSM	813-15 BCE
SEP	664-660 BCE
SEP	993-994 CE
SEP	774-775 CE
	1021 CE
SEP or SN	1052-54 CE
	1262 CE
	1269 CE
SEP	1279 CE

- High-energy
- Short-lived
- Sporadic
- Low-probability



^{14}C spikes identified in annual tree-ring records.
SEP-solar energetic particle event.
GSM – Giant Solar Minimum
SN - Supernova

Integral probability density function for the annual production of radiocarbon Q14C due to solar energetic particles (SEPs), from *Usoskin et al 2021.*

New spike?
(1) Bard et al. (2023), Proc. Roy.Soc. Lond.A

Since 1950AD, an additional source of ^{14}C is from atmospheric nuclear testing.

This artificial “spike” gives us information
How rapid changes are reflected in the
Atmosphere.

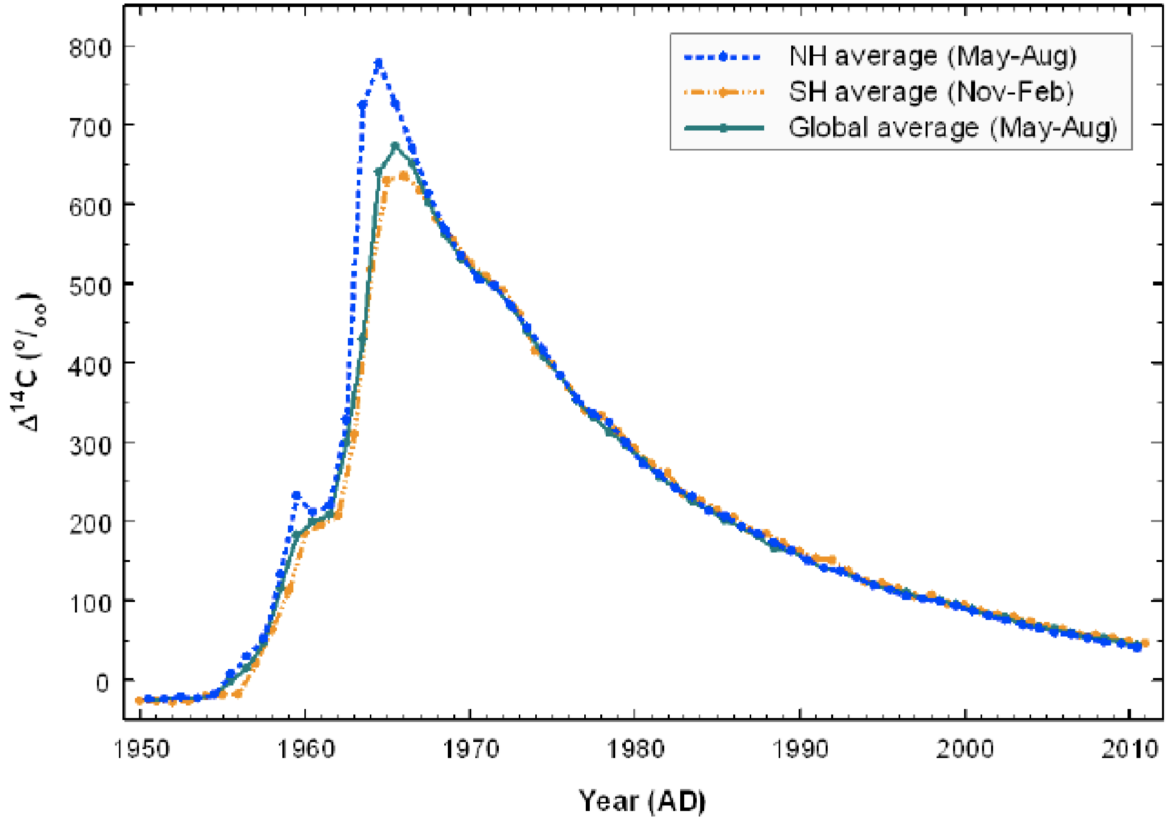


Figure 4 Compiled summer hemispheric and global ^{14}C curves. The compiled data sets are presented in Tables S2a–c.

Hua et al. 2022. Radiocarbon

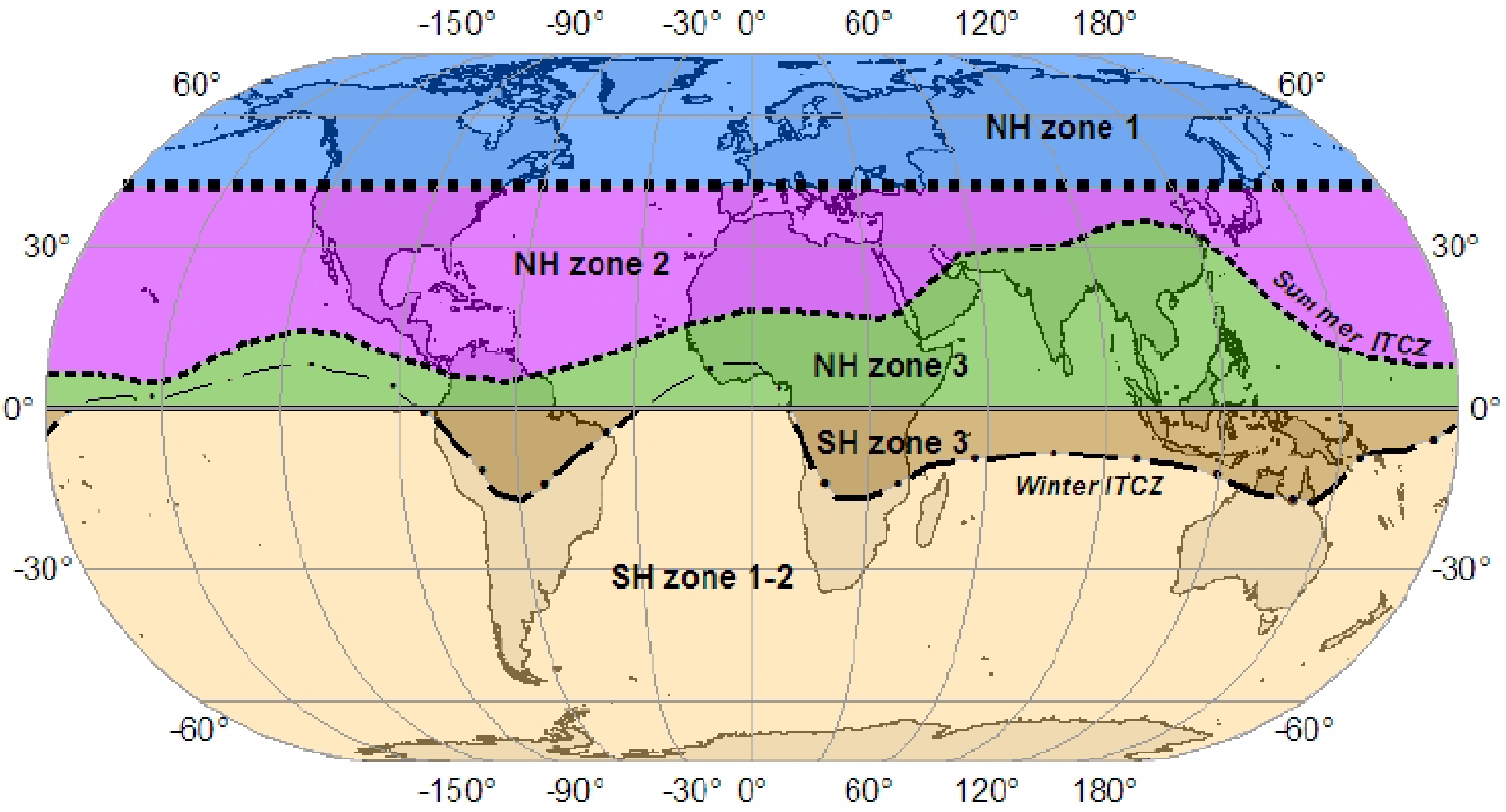


Figure 2 World map showing zonal atmospheric bomb ^{14}C. The mean positions of the summer and winter ITCZ are adapted from Linacre and Geerts (1997).

The spike of bomb ^{14}C tells us a lot about the atmosphere and its distribution (Hua et al. 2013)

Rapid events: Solar and other forcing?

- There are periods where there are rapid changes in the ^{14}C signal
- Solar-flare related events: 774-775CE, 993-994CE,

~660BCE, *5410BCE, 5259BCE and 7176BCE*

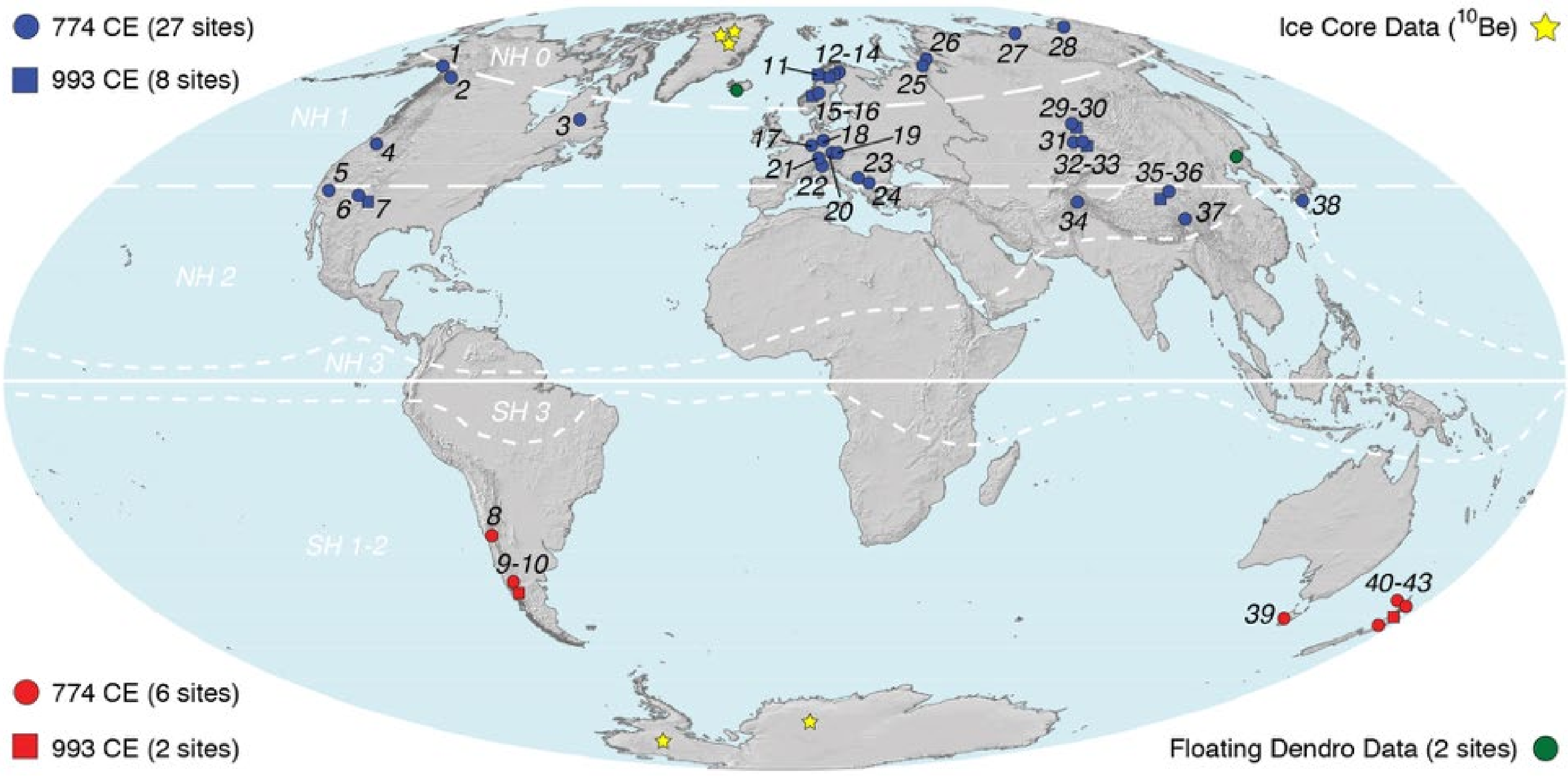
- Other solar phenomena: 810BCE, 5480BCE
- More events are likely.

Miyake et al. (2012) were the first
to recognize a very large event at 774CE
from ^{14}C in Japanese tree rings was likely
due to solar-flare effects.

Other possible effects:
Supernovae?
γ-ray bursts?
Carbon-cycle changes?

Fusa Miyake at Biosphere 2,
Oracle, Arizona in 2015.

774-775 and 993-994AD: Geographic distribution.



*(**from** Büntgen et al. 2018)*

Other effects on ^{14}C production:

During periods of solar minima, the solar magnetic field is decreased and more galactic cosmic rays reach the Earth, so $\Delta^{14}C$ will increase slowly (over decades).

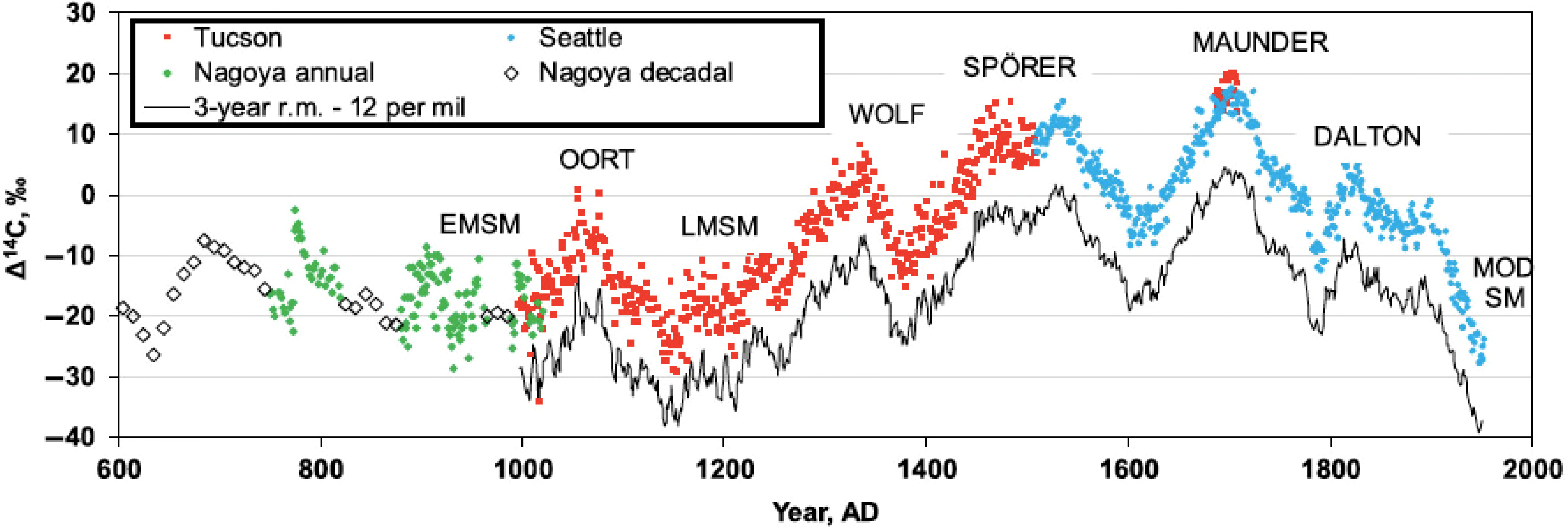
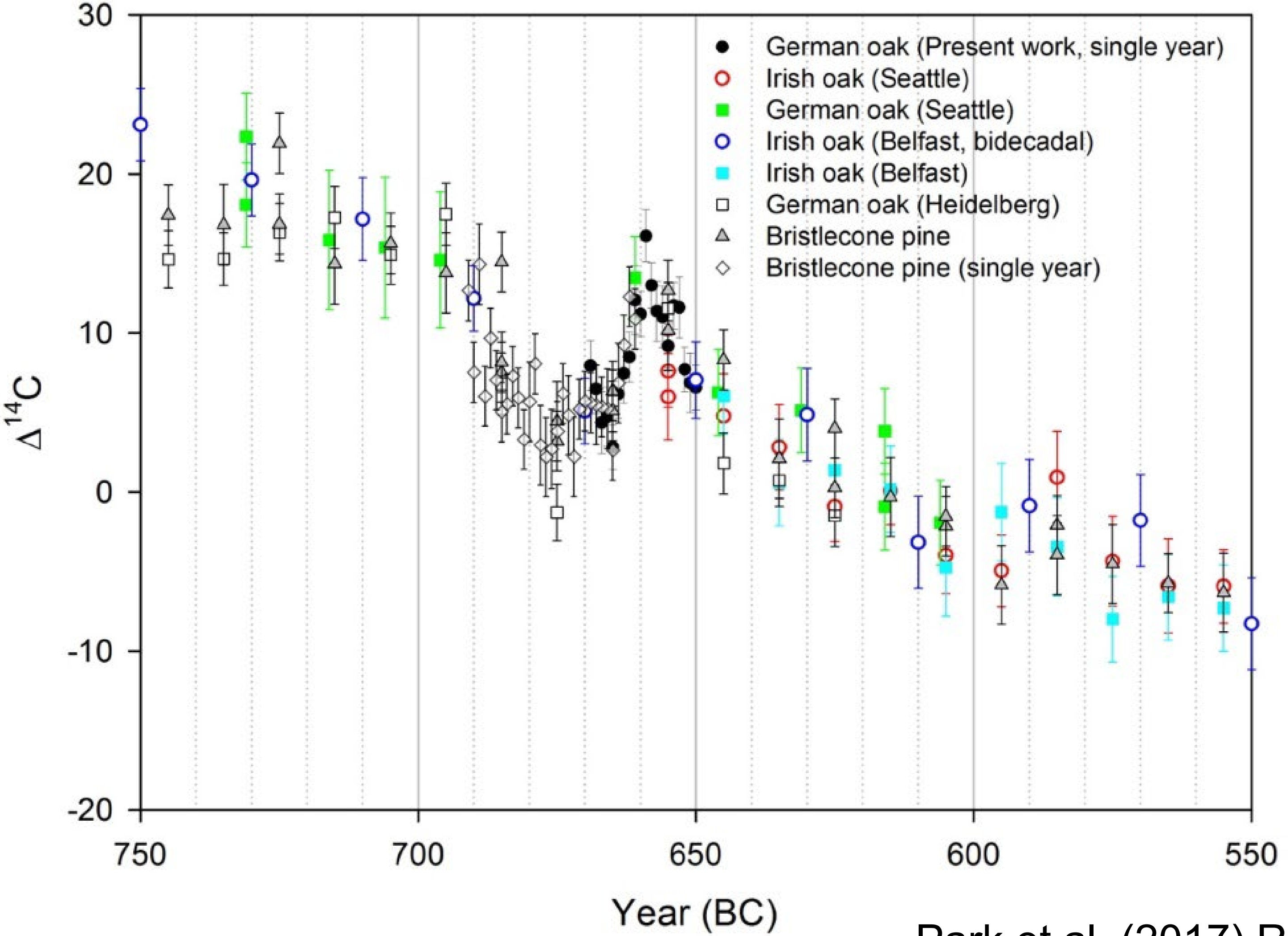


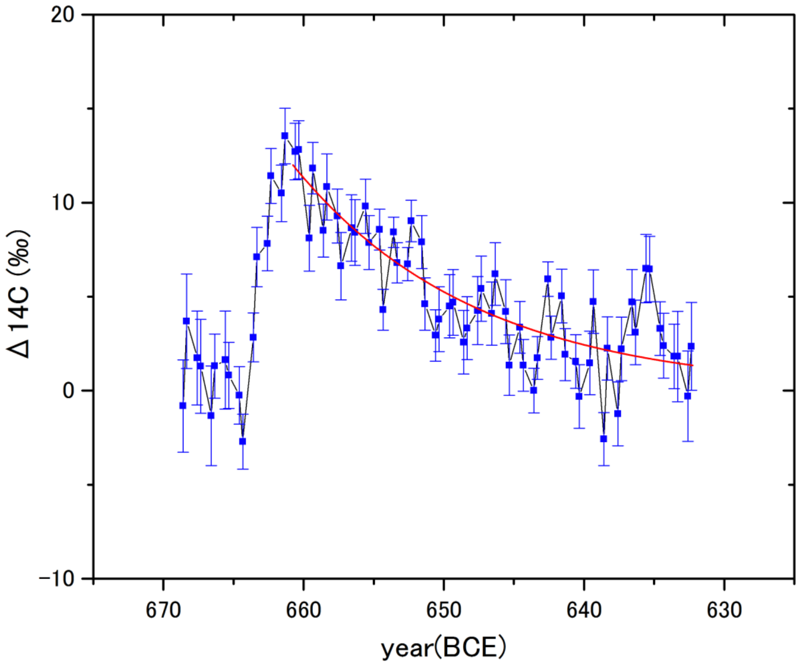
Figure 2 Annual and decadal $\Delta^{14}C$ time series for tree rings since AD 600 (Tucson laboratory: this study; Seattle laboratory: Stuiver et al. 1998; Nagoya laboratory; some data expressed as decadal means: Miyahara et al. 2004; Miyake et al. 2012, 2013a, 2013b), with a 3-yr running mean (displaced downwards by 12‰) for AD 998–1954. Named Grand Solar Minima and Maxima are shown. E(L)MSM = Early (Late) Medieval Solar Maximum, MOD SM = Modern Solar Maximum.

From Eastoe et al. 2019. Radiocarbon.

Park et al. (2017) 660BC "spike": Note the effect of these single-year data relative to the calibration curve



Park et al. (2017) Radiocarbon



Sakurai et al. (2020) measured a record In Choukai-Jindai cedar (*Cryptomeria japonica*) showing an excellent record.

Scientific Reports 10: 660 (2020)

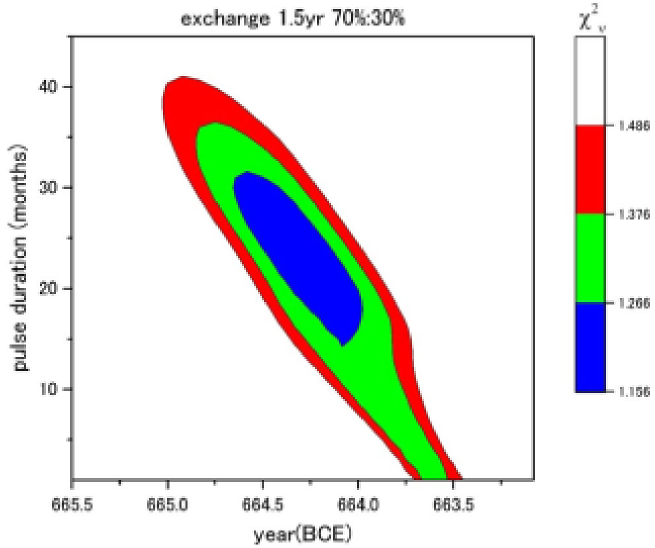
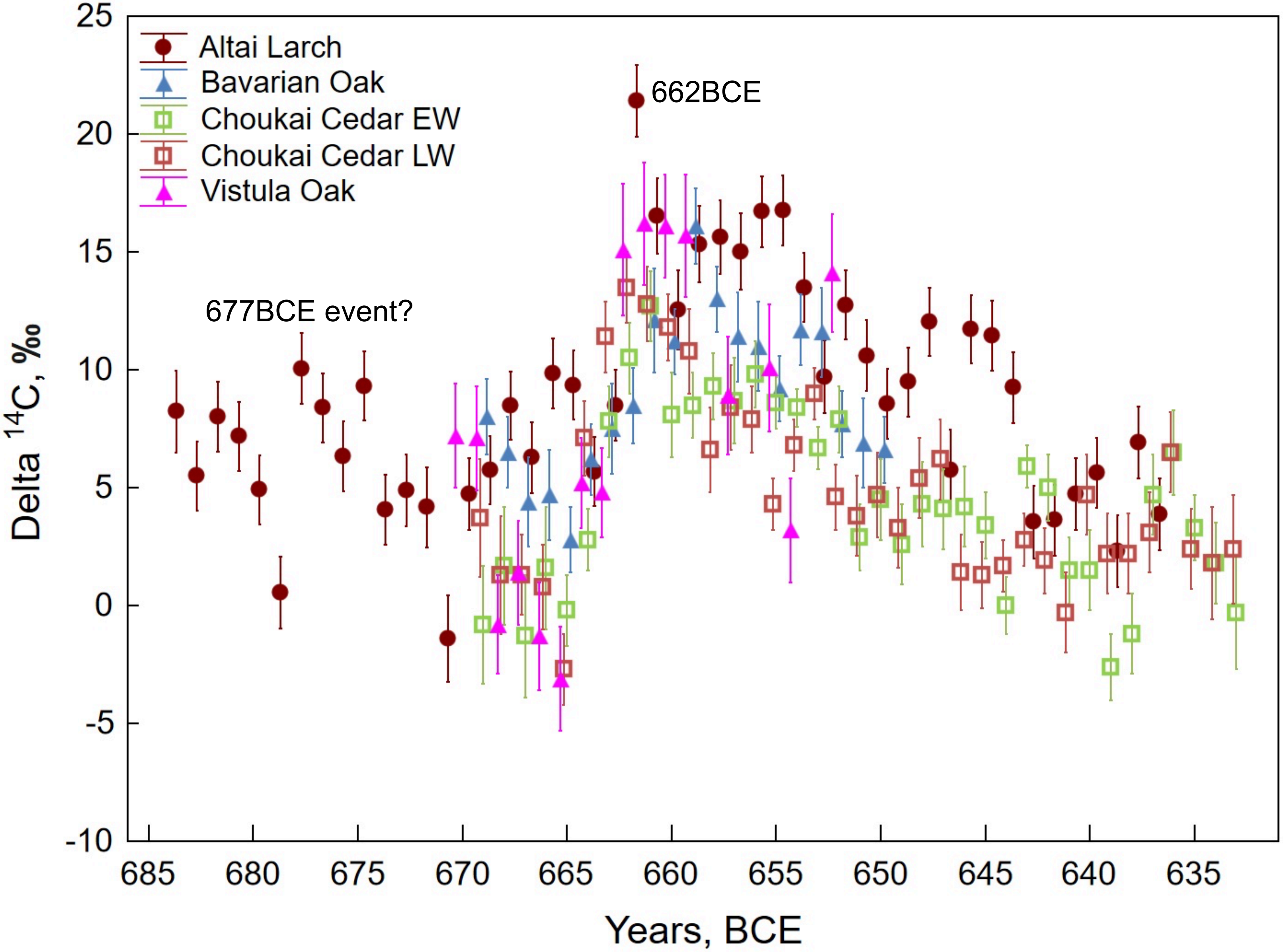
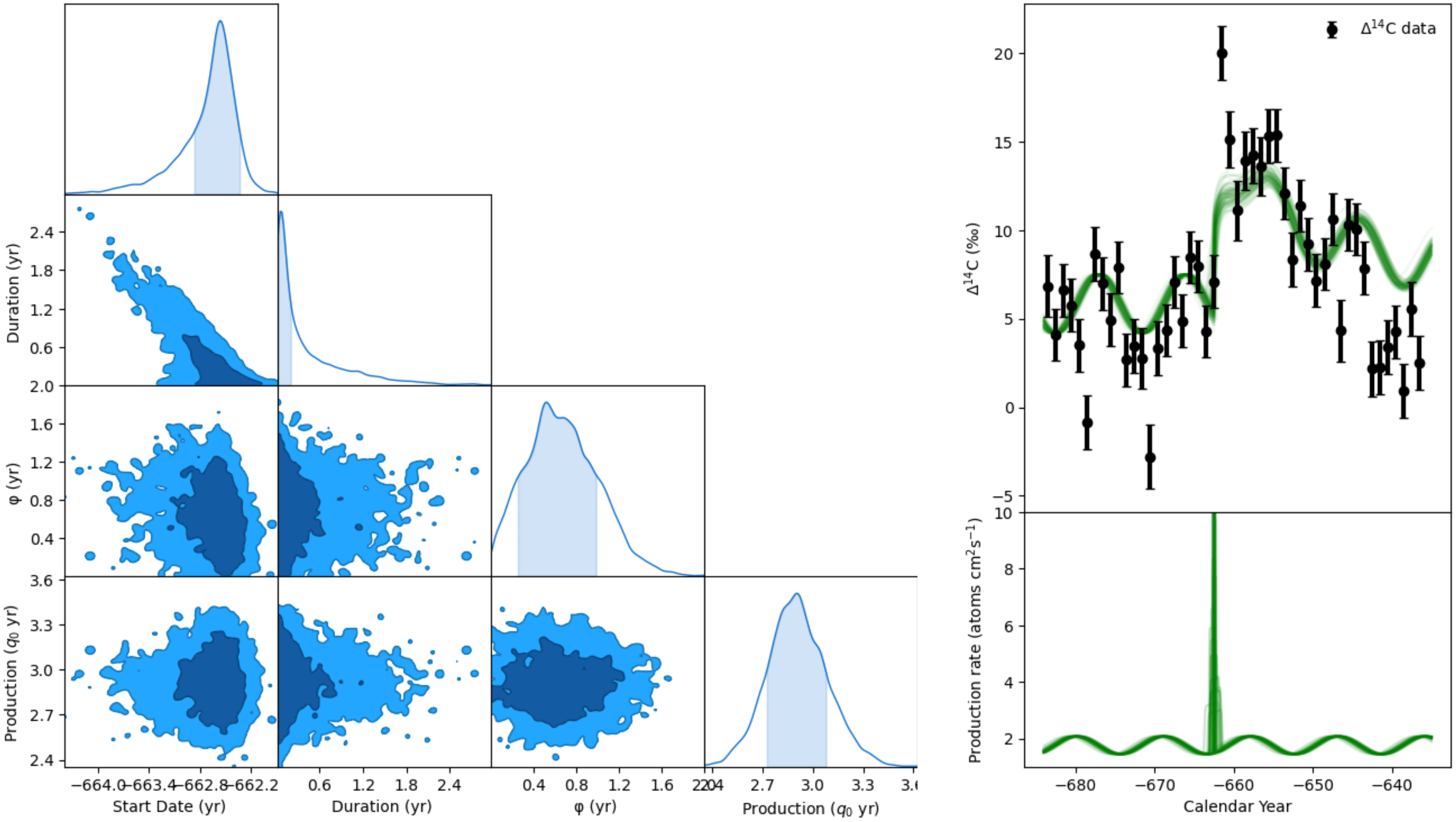


Figure 3. Contour map of reduced χ_ν^2 values as a function of pulse duration and pulse start date for the pulse height including the best-fitted single-pulsed event. The conditions of fitting calculation in the 11-box model are 1.5 years, and 70%: 30% for the exchange time and share rate of input ^{14}C production between the stratosphere and troposphere, respectively. Outside of the red region is rejected with 95% confidence level.

We obtained a new series for the period 684-634 BCE from wood collected from a kurgan in the Altai region (Siberia)



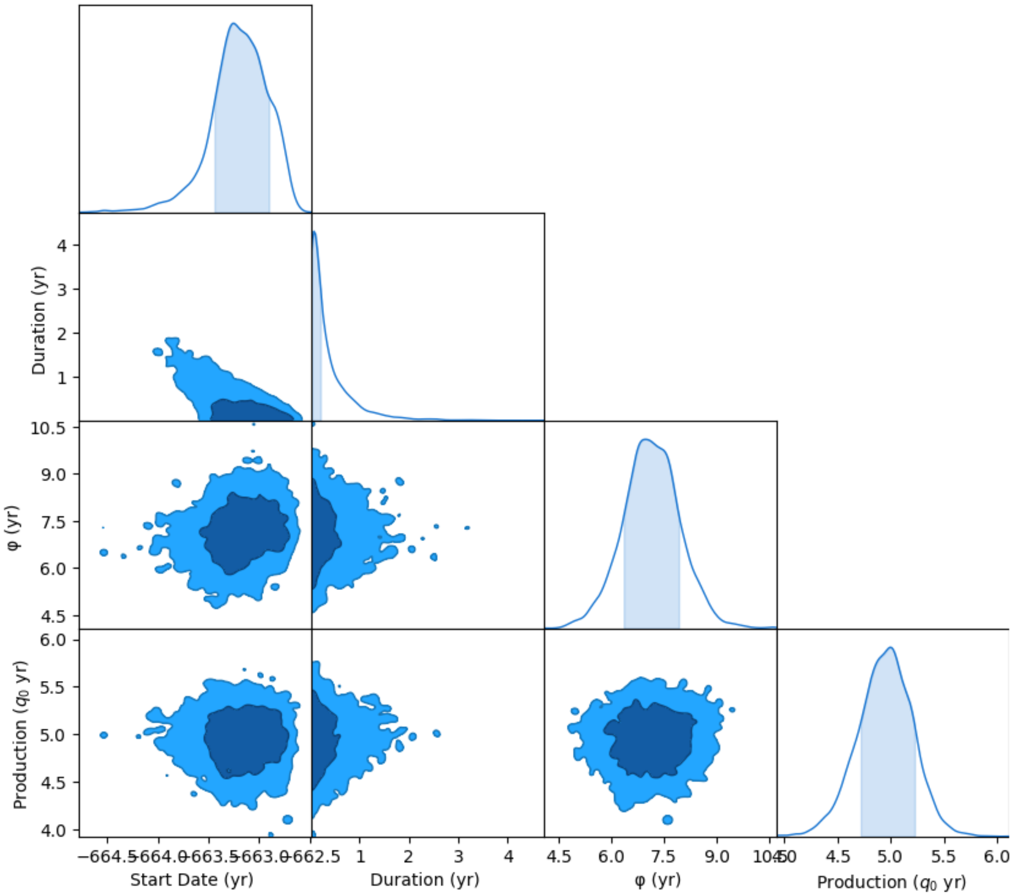
Results from Altai larch (684-634BCE) compared to other records.

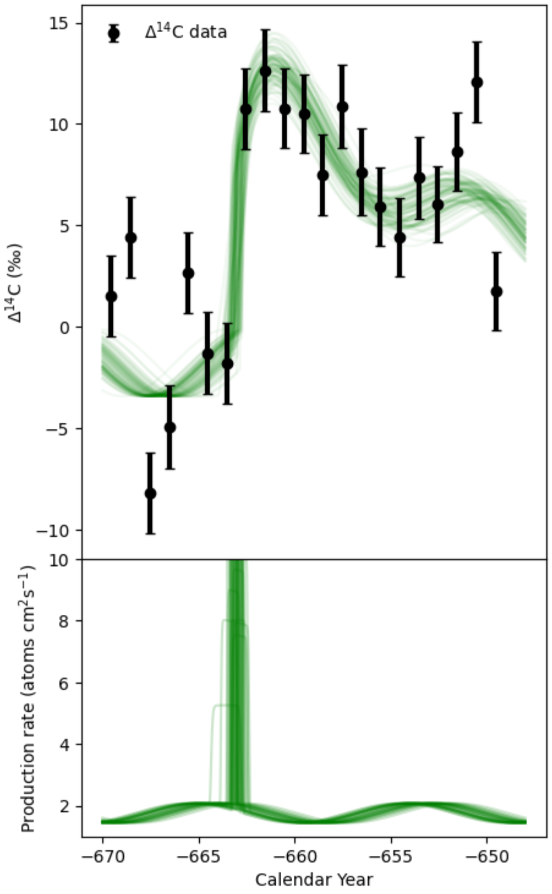


Analysis of Altai larch 664-662BCE excursion, using the Zhang et al. (2022) approach
And 22-box model of Buentgen et al. (2018)

Zhang et al. (2022), Proc. Roy. Soc. Lond. A. 478:20220497

Yamal, larch (*Larix sibirica*)





3 newest events reported

- New spike at 12350BCE (Bard et al, Proc. Roy. Soc. Lond. A, 2023), ~30 per mil.
- 5259BCE and 7176BCE (Brehm et al. 2022,Nature Comm.), ~20 per mil.

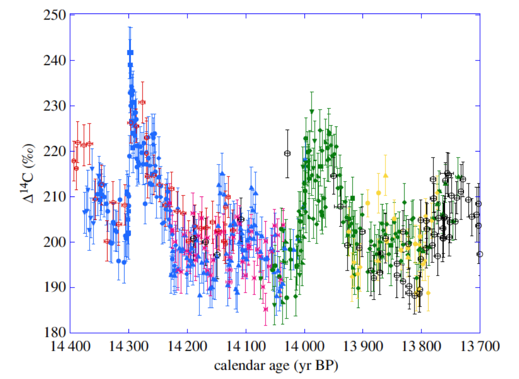
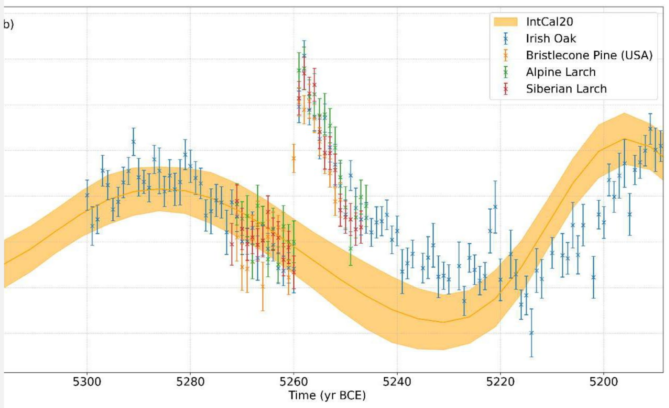
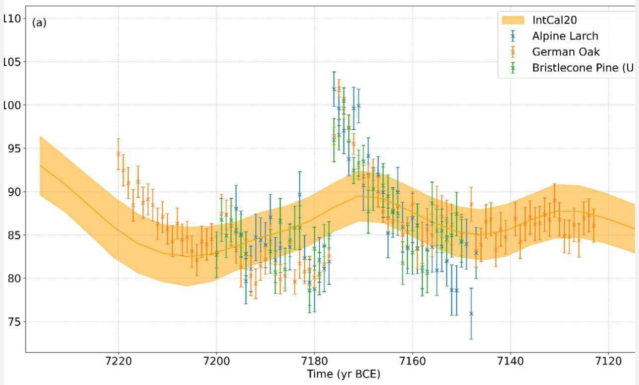
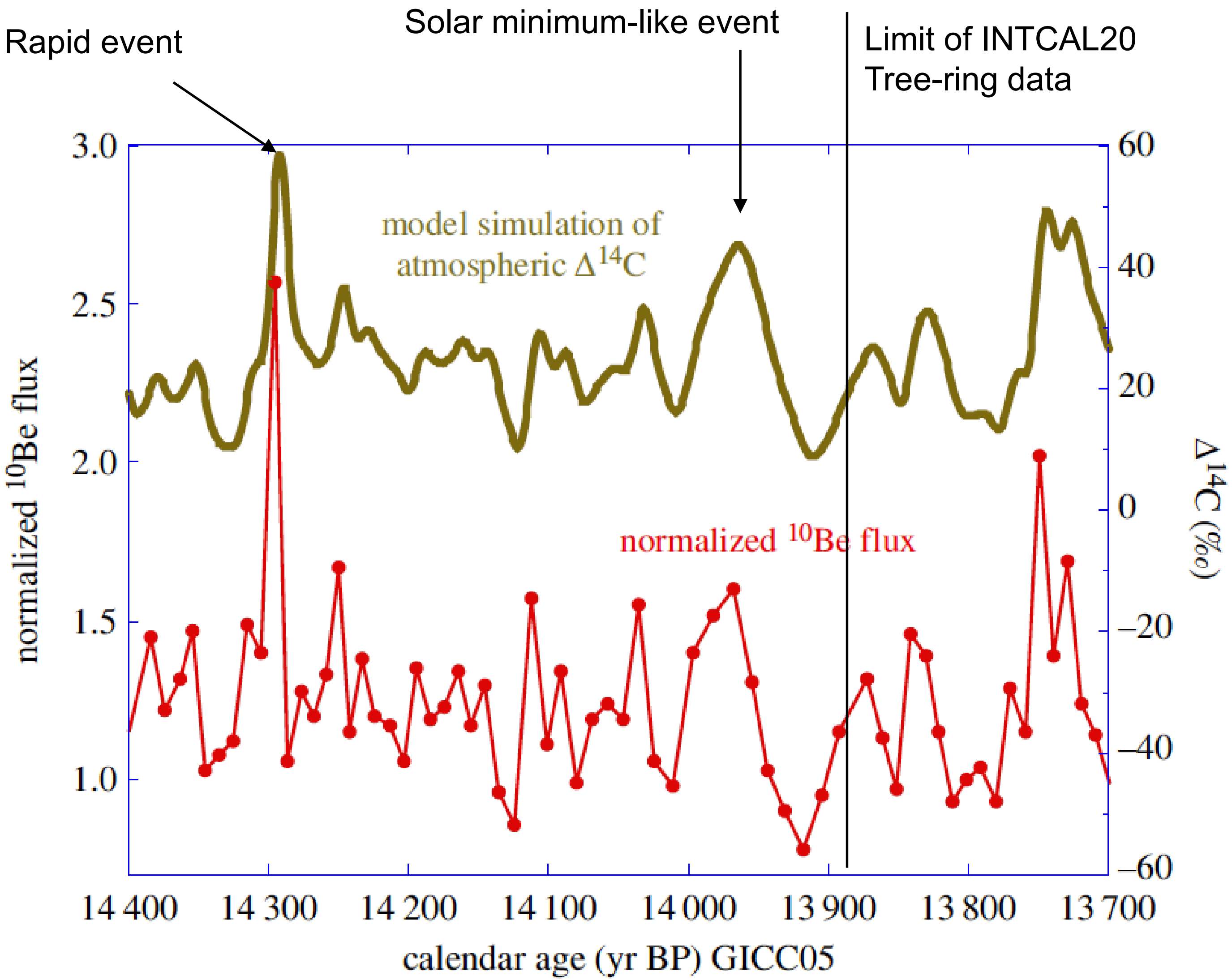


Figure 8. $\Delta^{14}C$ records corresponding to figure 6. The (*y*-axis) error bars for $\Delta^{14}C$ ages are shown at 1-σ. The data for Drouzet trees are shown for the DRM1 (blue), DRM2 (green) and DRM3 (yellow) sequences and for the P305u (red open dots) and A15 (pink crosses) Italian trees placed on the new chronology with our MCMC scheme for matching to the German pine absolutely dated chronology (black open dots). The number of annual rings measured in each sample is represented by the (*x*-axis) bars (e.g. ±0.5 yr for annual ring samples for most Drouzet analyses, ±5 yr for decadal measurements).





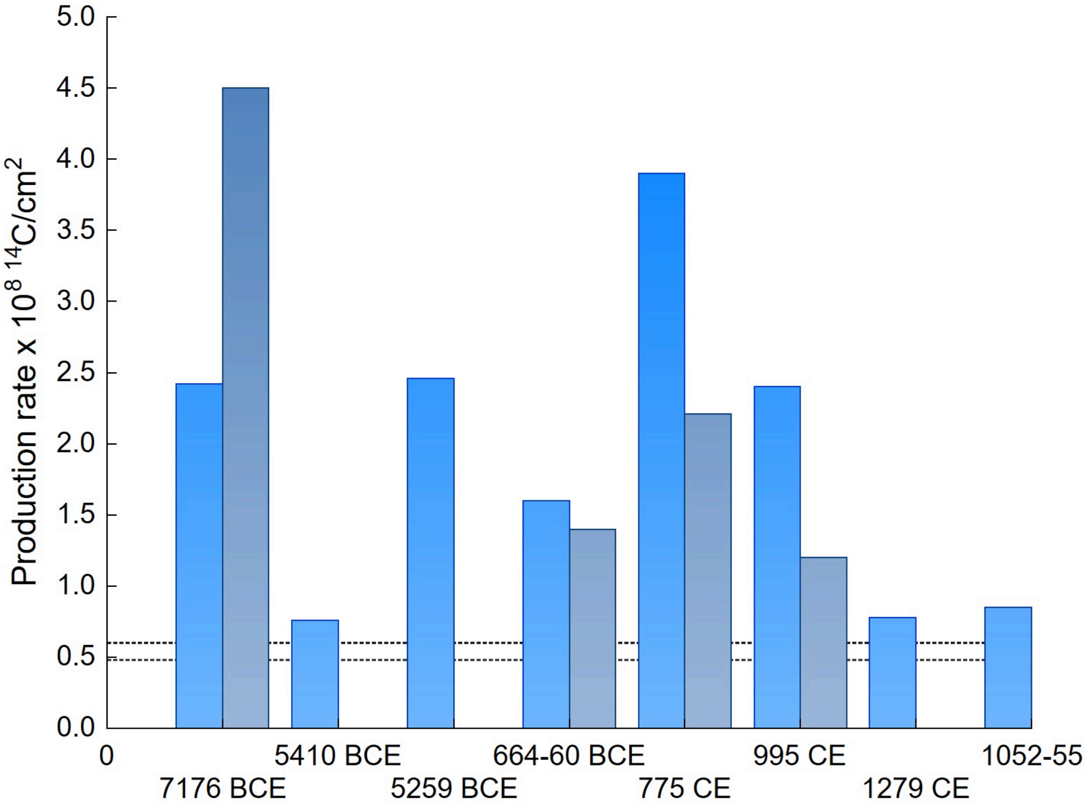


Bard et al. (2023) also compared the 12,350BCE (14,300 cal BP) event to ^{10}Be in ice cores.

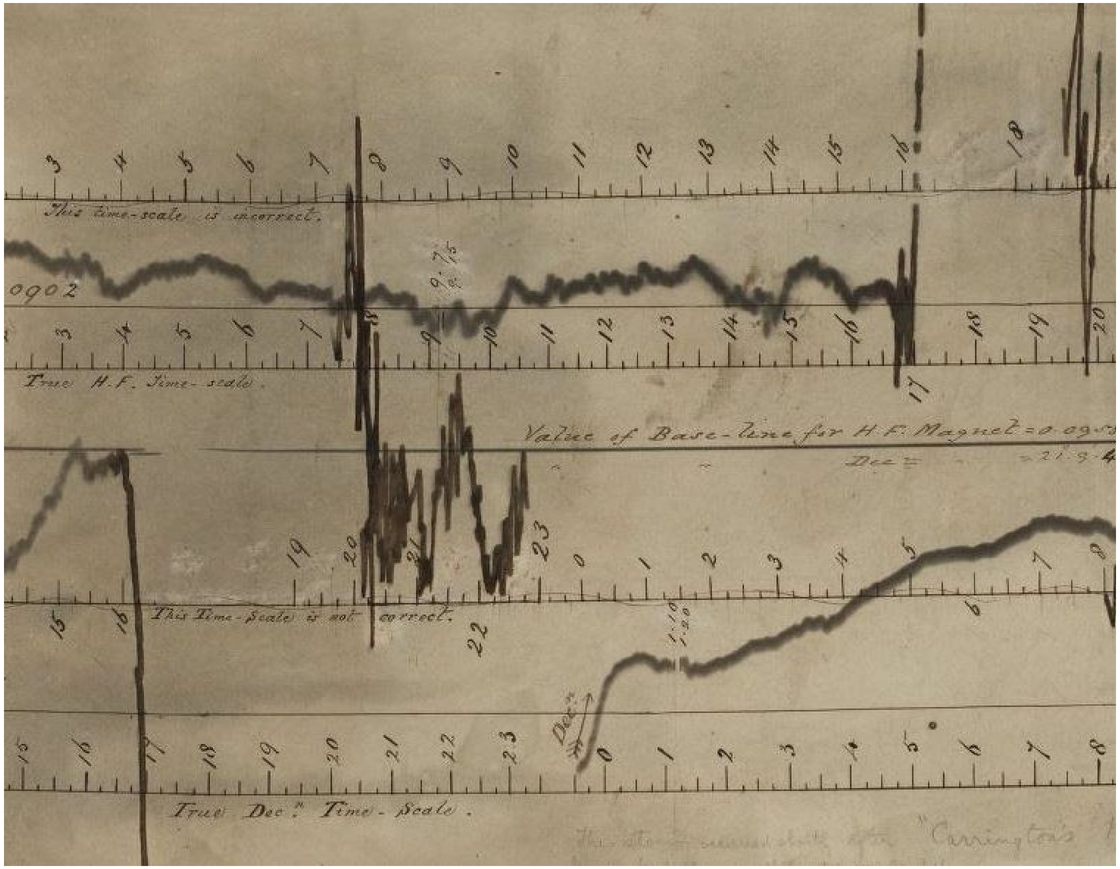
Estimated production rates (x 10^8 $^{14}C/cm^2$)

- The average annual production rate for ^{14}C from GCR is 0.48-0.60 x 10^8 p/cm^2

- Excess production rates needed to explain ^{14}C “spike” for different events
- 12,350 BCE event may be 50% larger than 775CE



Solar superstorm of 27 Aug to 7 Sep 1859 (Carrington Event)

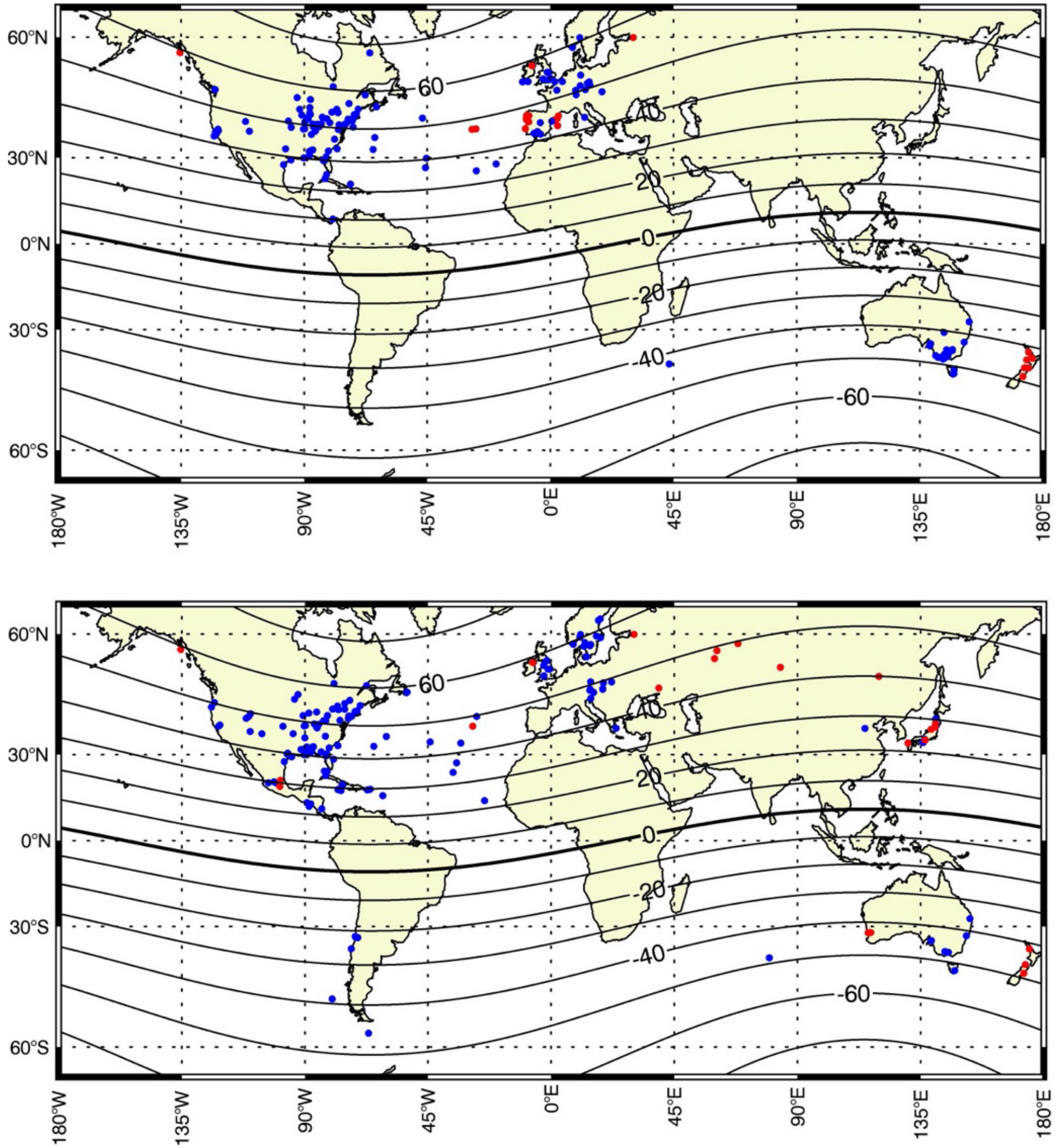


Horizontal intensity (upper) and declination (lower) observed at the Greenwich Observatory (London)

on 01 Sept 1859.

- “Modern estimates of Dst for the Carrington Event itself range from -800 nT to a staggering -1750 nT”

(science.nasa.gov)



Carrington Event (Sep 1859):
Aurora observed as far south
as Havana, Cuba and the Azores

Latitudinal observability of aurorae during the Carrington event (Hayakawa et al.)

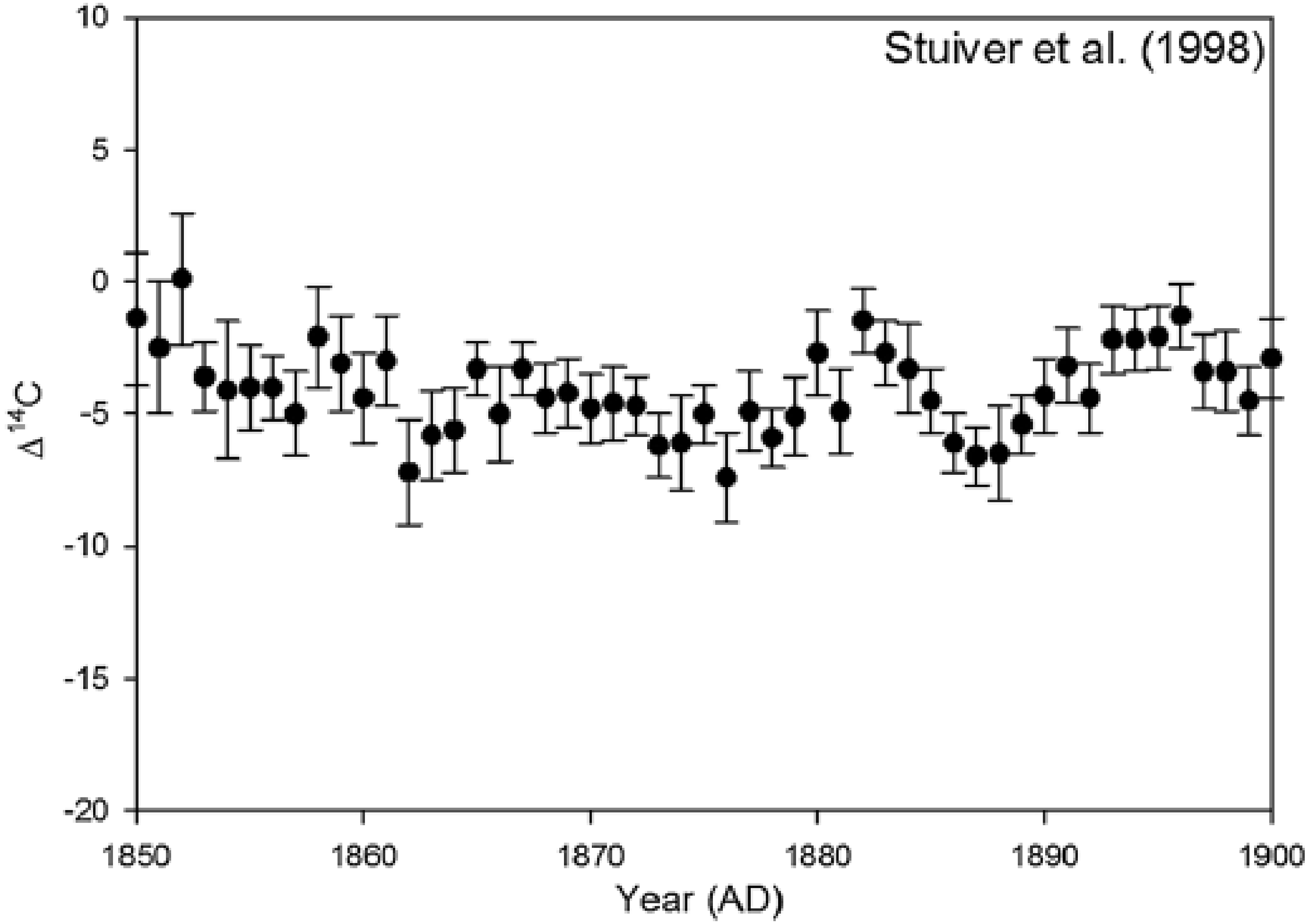


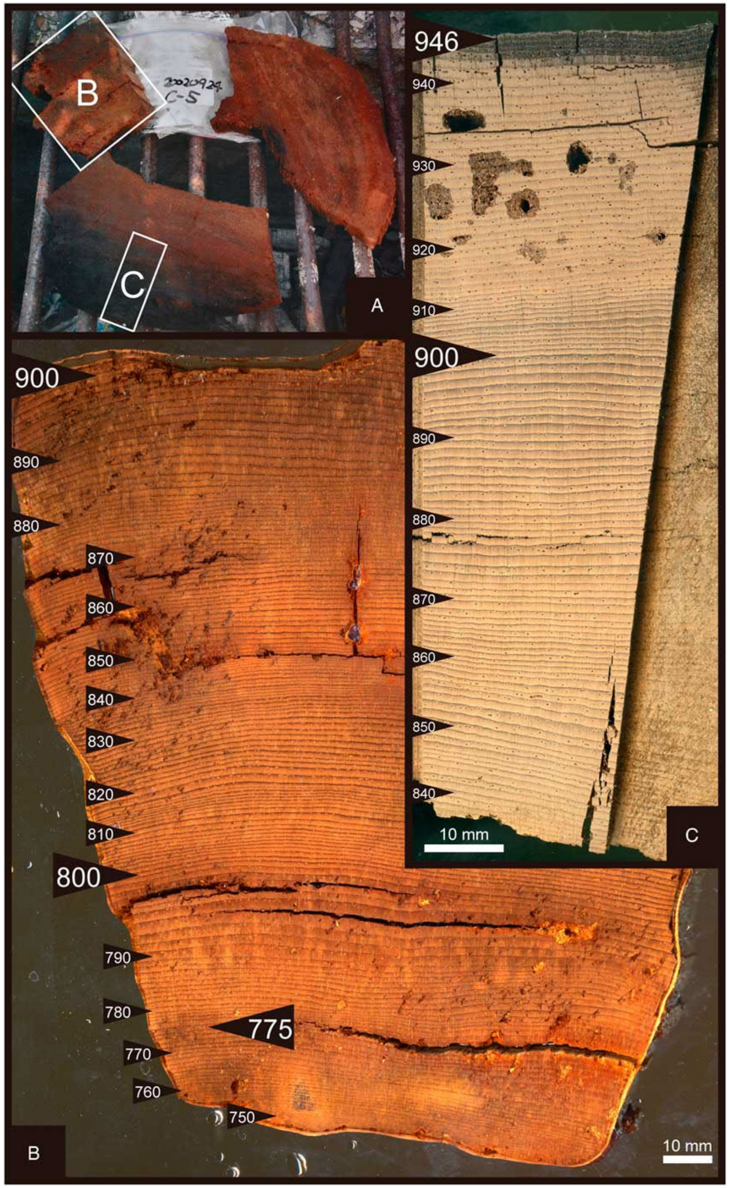
Figure 3. Record of $\Delta^{14}C$ (‰) between A.D. 1850 and A.D. 1900 from *Stuiver et al.* [1998].

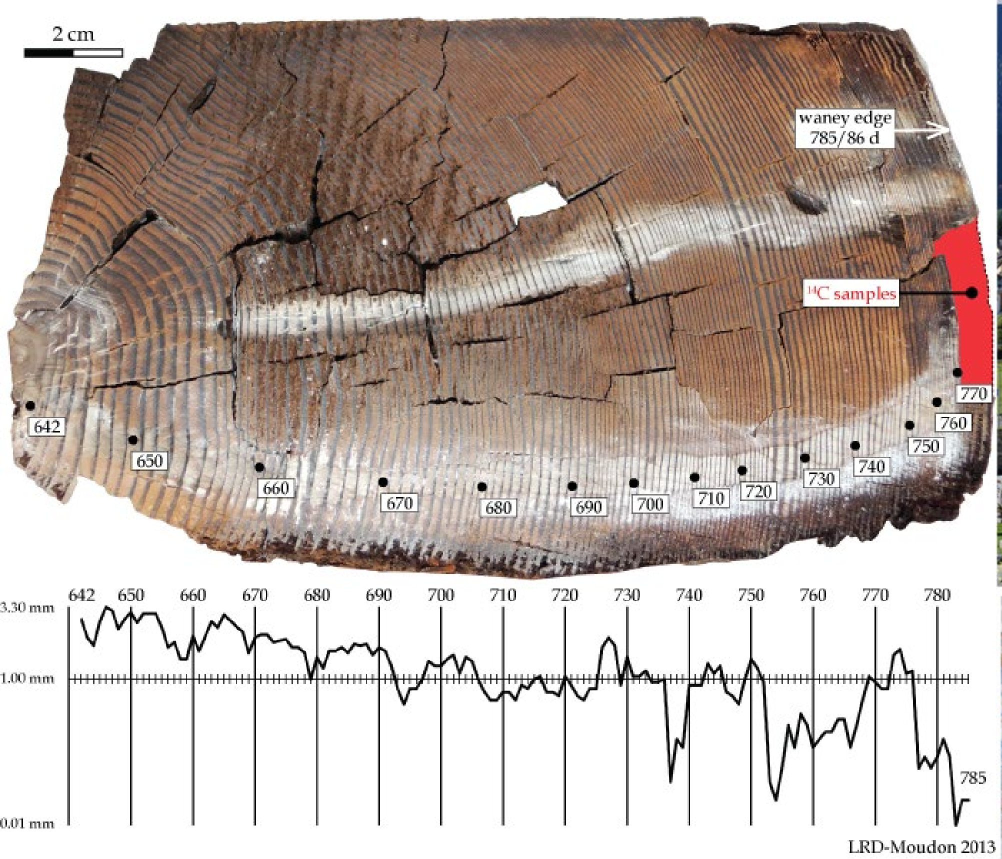
What about the Carrington event? Estimated F_{30} 1.9 x 10^{10} p/cm^2. Apparently, no significant effect on ^{14}C in the tree-ring record

Spikes in ^{14}C as markers for exact dating.

^{14}C rapid spikes can be used as markers for tree-ring sequences to one year.

Hakozaki et al. (2018), Radiocarbon 60(1): 261-268 used the log shown on the right to date the eruption of the Baitoshan (Changbaishan) volcano to 946AD.





LRD-Moudon 2013

Wacker et al. (2014) used wood from the Holy Cross Chapel (St. John Abbey, Mustair, CH) to date it precisely, since it included the 774AD event.

Radiocarbon 56(2): 573-579.

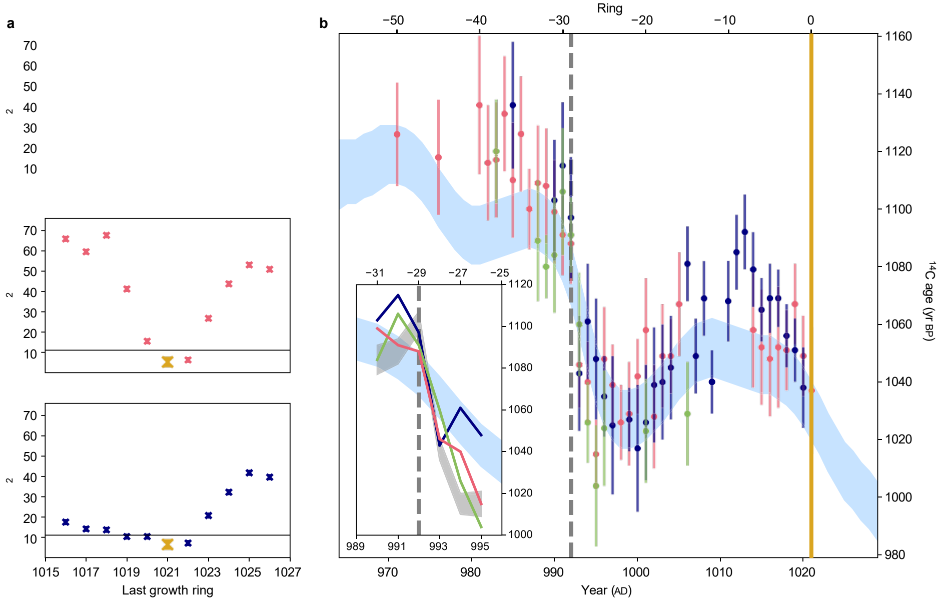
Archäologischer Dienst Graubünden, Bauhütte Müstair

Archäologischer Dienst Graubünden, Bauhütte Müstair

Date: 786AD. Abbey established about 780AD on the order of the Bishop of Chur.

993AD event
Included in a
wooden beam

Kuitems et al. (2022)
Nature 601: 388-391.



Article

Evidence for European presence in the Americas in AD 1021

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[redacted]

Check for updates

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Transatlantic contact took place centuries before the crossing of Columbus. Physical evidence for early European presence in the Americas can be found in Newfoundland, Canada[1,2]. However, it has thus far not been possible to determine when this activity took place[3–5]. Here we provide evidence that the Vikings were present in Newfoundland in AD 1021. We overcome the imprecision of previous age estimates by making use of the cosmic-ray-induced upsurge in atmospheric radiocarbon concentrations in AD 993 (ref. [6]). Our new date lays down a marker for European cognisance of the Americas, and represents the first known point at which humans

How can we refine the timing of events from different records?

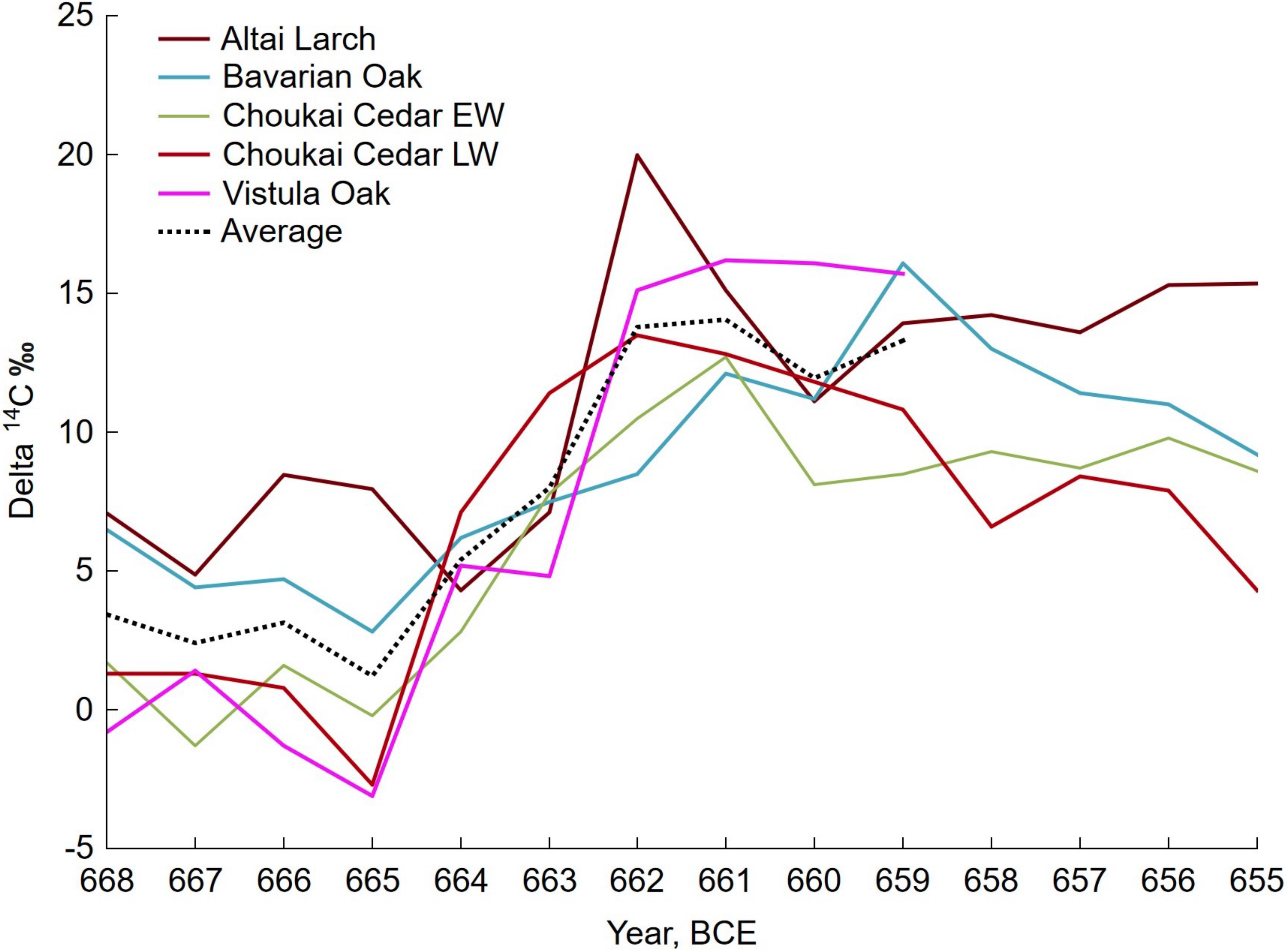
Various records of the same apparent event may be transposed in time due to different effects.

We have demonstrated the technique of **<u>“Dynamic Time Warping”</u>**
for the ”events” at 1052 CE (Brehm et al. 2021) and 1055CE (Terrasi et al. 2020)

λ

We try to minimize the variance between the different records to resolve timing questions.

Reference:
Panyushkina, I. et al. 2022. Scaling the 14C signal in multiple tree-ring series using dynamic time warping. Radiocarbon, online before print
https://doi.org/10.1017/RDC.2022.25



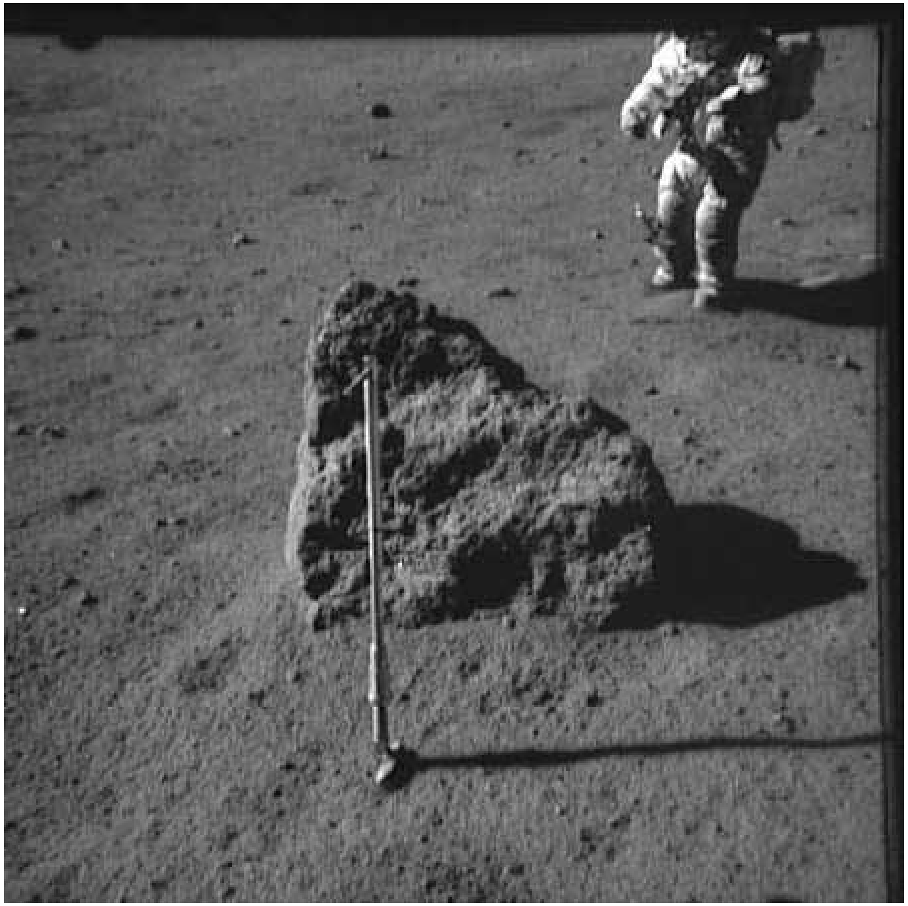
Altai Larch
Bavarian Oak
Choukai Cedar EW
Choukai Cedar LW
Vistula Oak
Average
25
20
15
10
5
0
-5
Delta ^{14}C ‰
668
667
666
665
664
663
662
661
660
659
658
657
656
655
Year, BCE

Can we use lunar data to constrain the total solar cosmic-ray fluence?

East-West Split Boulder (Tracy’s Rock) at Station 3 Apollo 16.

Is there other information to constrain the total fluence over time of solar proton events?

Lunar rock 68815. NASA photos.



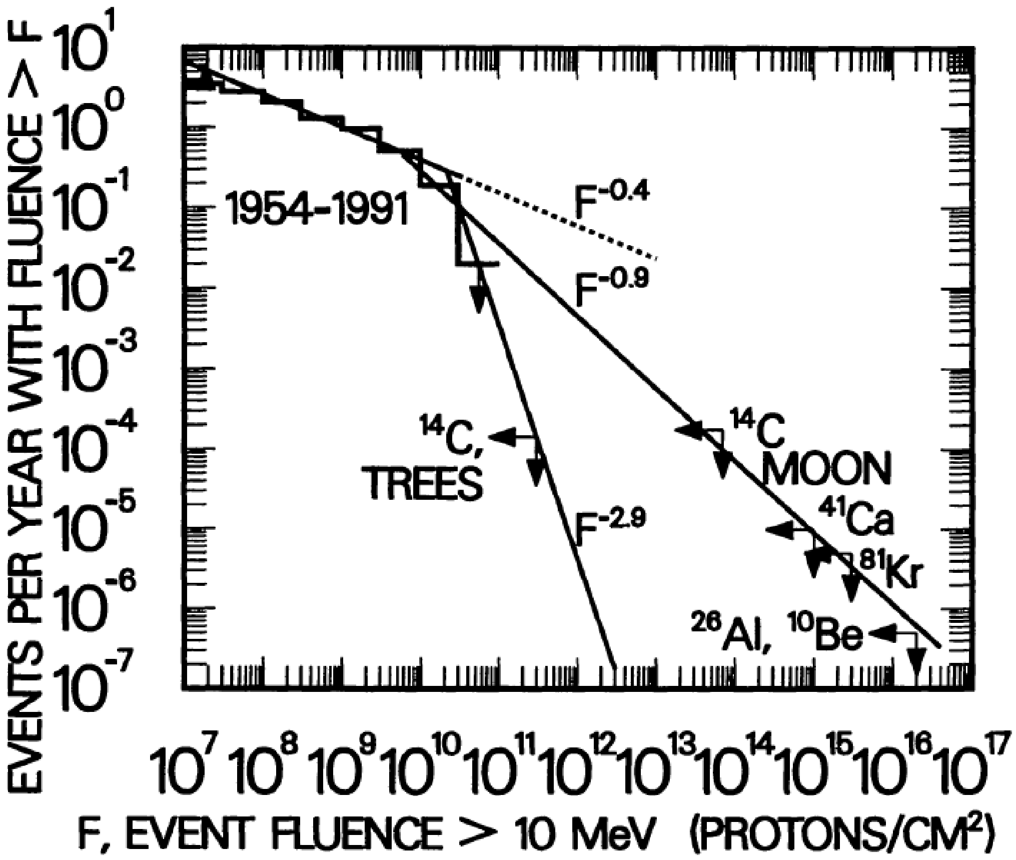


Figure 2. Probabilities of solar particle events with fluences above a given value occurring per year versus the fluence for both modern events and for limits determined from various fossil records

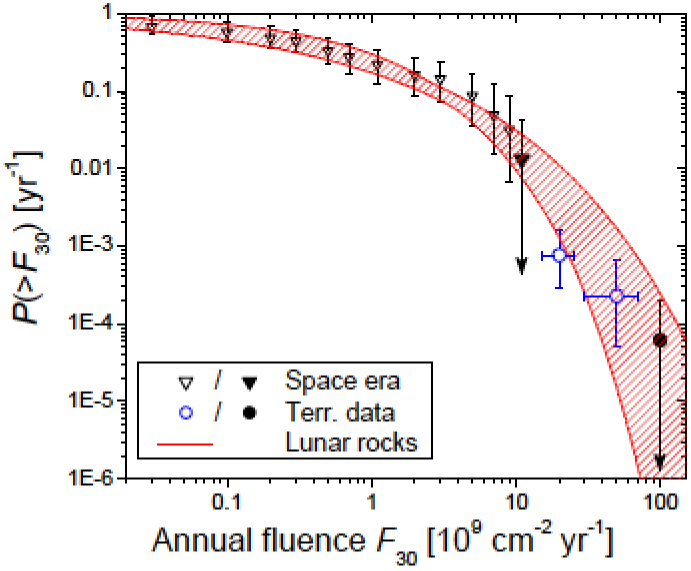
Solar Drivers of Interplanetary and Terrestrial Disturbances
ASP Conference Series, Volume 95, 1996
K. S. Balasubramaniam, Stephen L. Keil, and Raymond N. Smartt (eds.)

Constraints on Solar Particle Events from Comparisons of Recent Events and Million-Year Averages

Robert C. Reedy[1]
Group NIS-2, Mail Stop D436, Los Alamos National Laboratory, Los Alamos, NM 87545 USA

Poluianov et al. 2018

Astronomy and Astrophysics.
https://arxiv.org/pdf/1807.10153.pdf



Consequences: Solar Events

- We need to better understand the effects on ^{14}C production:
  - Solar flares and Coronal Mass Ejections
  - Supernovae – how large can they be?
  - Gamma-Ray Bursts
  - Geomagnetic field changes

- Evidence of large solar flare or similar events.
- If such an event occurred today, would cause massive electronic disruptions, eg. Zoom meetings.
- Important to our understanding of how rapid changes can occur in the carbon-14 system.

Acknowledgments

- We are grateful for the dedicated work of staff at the various institutions in Tucson, Debrecen and Nagoya.
- The research was supported by NASA LWS grant 80NSS21K1426, the European Union and the State of Hungary, co-financed by the European Regional Development Fund in grant GINOP-2.3.4-15-2020-00007 “INTERACT”.
- We also are grateful for support from Japanese funding agencies (to Dr. Miyake).