

# Towards an Absolute Chronology of the Last Glacial

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**ABSTRACT:** *Based on geomagnetic extrapolations (Laj et al., 1996), quite recently Van Andel (1998) constructed the first continuous glacial radiocarbon calibration curve. The reliability of this calibration curve was challenged by Van der Plicht (1999), who also warned in general against glacial calibration, due to prevailing limitations in the corresponding geophysical data, ice core synchronisms, and terrestrial chronologies. It was suggested that prehistorians should refrain from glacial radiocarbon calibration, until a number of questions concerning the time-scales of the Greenland GRIP and GISP2 ice cores and the Japanese Lake Suigetsu varve chronology (Kitagawa and Van der Plicht, 1998a; 1998b) have been resolved.*

*We argue that the relevant glacial <sup>14</sup>C-calibration data have sufficient precision, both on an absolute time-scale and in relation to the ice-core chronologies, to support widespread construction of age-calibrated <sup>14</sup>C-chronologies in the Quaternary sciences.*

**KEYWORDS:** Last Glacial, Radiocarbon Age-Conversion, Palaeoclimate Archives, Marine Records, Ice Cores

Research on radiocarbon age calibration has a long and complicated history. Over the past 30 years there have been innumerable extensions, revisions, and corrections of the underlying Holocene tree-ring chronologies, and equally numerous improvements in the equipment and techniques necessary for the highly accurate and reproducible <sup>14</sup>C measurements required in archaeology. In brief, the history of Holocene radiocarbon calibration is a history of revisions, and the recently published data set INTCAL98 (Stuiver and Van der Plicht, 1998) represents the most advanced of these.

Today archaeological and geological chronologies of the Last Glacial cycle are largely based on radiocarbon data, for which precise age conversion is possible in the Holocene (Stuiver and Van der Plicht, 1998) and is just as necessary in the glacial.

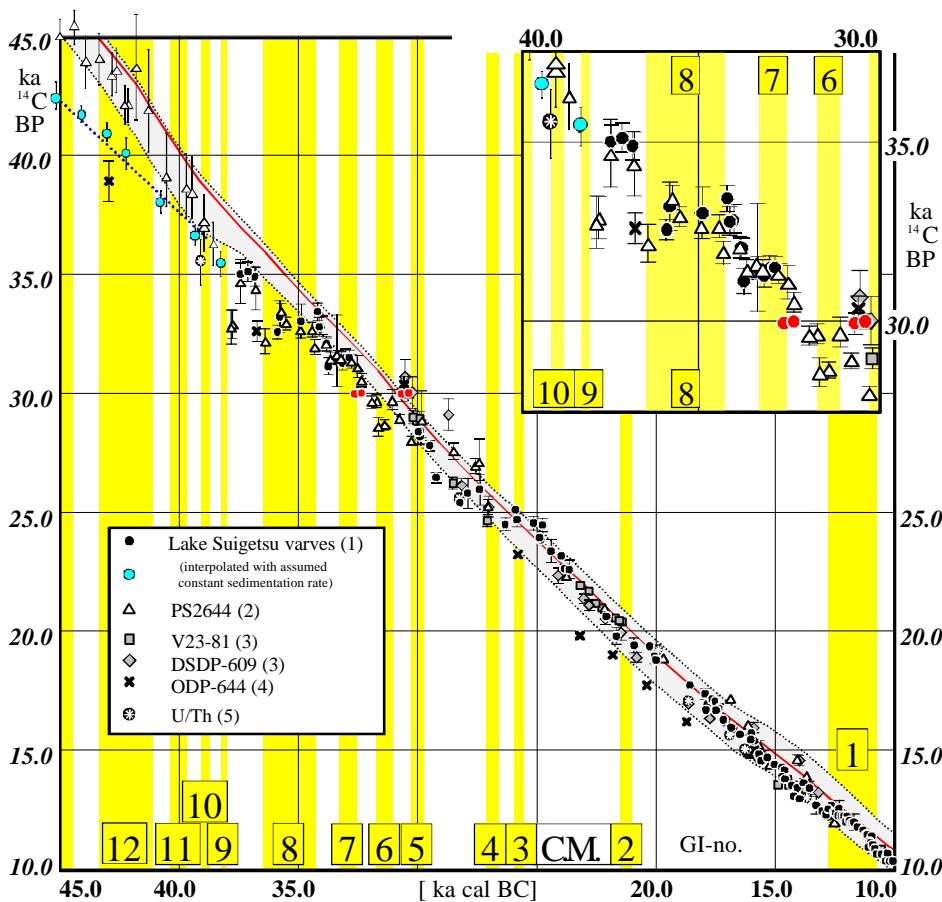
Alongside questions concerning calendric (absolute age) models, understanding the causes for past variations of the atmospheric <sup>14</sup>C level, and relating the Glacial <sup>14</sup>C-calibration curve to palaeoclimate signatures presents a new challenge to scientists involved in Quaternary research. Reliable synchronizations of deep-sea records with the high-resolution Greenland GRIP and GISP2 ice core time-scales (e.g. Bond *et al.*, 1993; Voelker *et al.*, 1998) have not merely made it possible to construct an extended Last Glacial calibration curve covering the last 50 ka, but also adequately link <sup>14</sup>C levels derived from marine foraminifera to climate change, as recorded with highest resolution in the GRIP and GISP2 cores (Jöris and Weninger, 1998; Voelker *et al.*, 1998). These archives show an essentially identical relative sequence of stadials (GS) and interstadials (GI) (Björck *et al.*, 1997; *cf.* Johnsen *et al.*, 1992). However, the underlying age-models show differences steadily increasing with core depth, amounting to many thousands of years during the period covered by the radiocarbon method. Accordingly, <sup>14</sup>C data derived from the marine cores and transferred to the GRIP and GISP2 ice-core time-scales must reveal alternative glacial calibration graphs. The discrepancies between the two ice core time-scales are often overlooked.

Independent age control of the radiocarbon time-scale is given by couplets of U/Th and <sup>14</sup>C measurements on coral samples (Edwards, 1993; Bard *et al.*, 1993, 1998). For the entire period of the Last Glacial covered by radiocarbon, the GISP2-based marine <sup>14</sup>C calibration graph established by synchronisms with deep-sea records is in good agreement with the available U/Th-<sup>14</sup>C-coral data (Jöris and Weninger, 1998). For the Late Glacial period of GS-1 and GI-1 we, instead, prefer the GRIP chronology which seems to us more reliable (Jöris and Weninger, 2000).

Additional arguments for the reliability of the long-term trend of the GISP2 chronology are that the counting of annual ice layers is established further back for the GISP2 core than for GRIP, and that the oldest part of GISP2 is synchronized with the Antarctic Vostok chronology (Meese *et al.*, 1994; Sowers *et al.*, 1993; Petit *et al.*, 1999), which is itself calibrated with the orbitally tuned, stacked deep-sea SPECMAP chronological framework (Martinson *et al.*, 1987; Sowers *et al.*, 1993). An important marker to control the validity of the combined U/Th-GISP2-Vostok-SPECMAP time-scale is the Toba eruption some 71 ka ago at the very end of GI-20 (Chesner *et al.*, 1991; Leuschner and Sirocko, *in press*; Westgate *et al.*, 1998; Zielinski *et al.*, 1996).

Records potentially useful for the construction of a Glacial <sup>14</sup>C calibration curve are high-resolution deep-sea records and long continuous terrestrial sequences of laminated limnic sediments. Whereas <sup>14</sup>C data derived from marine records require corrections for specific reservoir values, <sup>14</sup>C data from terrestrial sequences do not, but here difficulties may exist in the continuity of the record and in sample taphonomy.

Among other deep-sea records, the North Atlantic core PS2644 shows the highest resolution of the  $^{14}\text{C}$  scale in relation to sample depth, and appropriate links to the GISP2 ice core ages have been established (Voelker *et al.*, 1998). In PS2644 past variations in  $^{14}\text{C}$ -levels show up with a pattern almost identical to that recorded in other marine proxies, as well as in the U/Th- $^{14}\text{C}$  coral couplets. The combined data show satisfactory agreement with the smoother, geomagnetic glacial calibration curve proposed by Van Andel (1998), back to 50 ka calBC (**Fig. 1**).



**Fig. 1** Time-window 45.0 - 10.0 ka calBC, showing paired  $^{14}\text{C}$  and calendric ages for different data sets. Sequence of GIs (GI-no.: grey underlay) following Björck *et al.*, 1997. C.M. = Cold Maximum. Grey shaded band shows geomagnetic calibration curve (Lay *et al.*, 1996) as used in Van Andel's (1998) approach (with mean values: solid line; note asymmetric error). Data points (with  $\pm 1\sigma$  error bars for errors  $> \pm 200$  BP) derive from: Lake Suigetsu varves, marine sediments (North Atlantic cores PS2644, V23-81, DSDP-609, ODP-644; all  $^{14}\text{C}$ -ages are from planktonic foraminifera), and corals (U/Th- $^{14}\text{C}$ -data). **Inlay**: enlargement of the time-window 40.0 - 30.0 ka calBC, showing the overall agreement between PS2644 and Suigetsu data, with the later (basel part) shifted 1,930 calyrs to older ages (split Suigetsu data shown twice), and with depth-age interpolated Suigetsu data  $> 38.0$  ka calBC. Dotted line represents linear extrapolation through the combined data set of the last 40 ka. (1) Kitagawa and Van der Plicht, 1998a; 1998b; (2) Voelker *et al.*, 1998; (3) Bond *et al.*, 1993; (4) Fronval *et al.*, 1995; (5) Bard *et al.*, 1993; 1998. Time-scales for (3)+(4) following Jörns and Weninger, 1998.

This glacial calibration curve receives further support by AMS-dates on terrestrial

macrofossils from the Japanese Lake Suigetsu (Kitagawa *et al.*, 1995; Kitagawa and Van der Plicht, 1998a; 1998b; Van der Plicht, 1999). The total error in Suigetsu varve counting is estimated to 1.5% (Kitagawa and Van der Plicht, 1998a), which adds up to some 437 yrs at the base of the almost 30 ka long  $^{14}\text{C}$  dated part of the sequence. Alternatively, a  $\Delta^{14}\text{C}$ -record for Suigetsu with an accumulative dating error amounting to 2,000 calyrs is discussed (Kitagawa and Van der Plicht, 1998b). Varve counts older than ca. 20,000 calBP, which are based on a single core, are considered to be "minimum ages" (Van der Plicht, 1999), but these estimates do not allow for errors in the varve sequence due to abrupt sedimentational discontinuities.

The Suigetsu record shows  $^{14}\text{C}$  levels similar to those identified in the marine cores and also shown by the U/Th- $^{14}\text{C}$ -couplets back to ca. 30 ka calBC. Shortly before this point the Suigetsu  $\Delta^{14}\text{C}$ -record reaches an extreme value that Van der Plicht (1999) associates with changes in the Earth's geomagnetic field. Such an event is of highest importance for synchronization of the different records, and consequently Van der Plicht (1999) discusses its timing in some detail and compares the Suigetsu  $\Delta^{14}\text{C}$ -event with a variety of new geomagnetic data. This discussion does not refer to potential discontinuities in the Suigetsu record that would change the underlying age model and, following this, the very appearance (i.e. amplitude and shape) of the Suigetsu  $\Delta^{14}\text{C}$ -event.

In core PS2644 a geomagnetic excursion is measured not only as a  $\Delta^{14}\text{C}$ -peak relative to the GISP2-chronology, placing this event between GI-7 and GI-5, at ca. 31 ka calBC, but also directly by NRM (natural remanent magnetization). A second event in the same core dates to ca. 39.5 ka calBC, between GI-11 and GI-9 (Voelker *et al.*, 1998).

For radiocarbon ages older than 30 ka BP, both records PS2644 and Suigetsu show identical patterns of past  $^{14}\text{C}$ -levels, except that the underlying time-scales differ systematically by 2,000 years, with Suigetsu giving younger ages. This implies a varve sedimentation gap in Lake Suigetsu around 30 ka calBC, which could be corrected by a downward shift of the basal Suigetsu section by some 1,930 calyrs (Jörns and Weninger, 1999a-b).

The close-up view (**Fig. 1, inlay**) demonstrates the quality of agreement between the age-corrected Suigetsu and the PS2644 data. The combined glacial calibration data allow for a more precise calculation of the  $\Delta^{14}\text{C}$ -impulses associated with the potential Lake Mono and Laschamp geomagnetic events, respectively.

To summarize, a coherent chronology is obtained for the Last Glacial by linking a wide variety of palaeoclimate signatures, and referencing these to a combined U-Th/GISP2/Vostok/SPECMAP time-scale, using radiocarbon calibration as a sensitive tool.

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