

Radiocarbon calibration – past, present and future

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Abstract

Calibration of the Radiocarbon timescale is traditionally based on tree-rings dated by dendrochronology. At present, the tree-ring curve dates back to about 9900 BC. Beyond this limit, marine datasets extend the present calibration curve INTCAL98 to about 15 600 years ago. Since 1998, a wealth of AMS measurements became available, covering the complete ^{14}C dating range. No calibration curve can presently be recommended for the older part of the dating range until discrepancies are resolved.

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1. Introduction

The need for calibration of the ^{14}C timescale has been recognized soon after the onset of the ^{14}C dating method [1]. Variations in the ^{14}C content of the atmosphere [2] cause the ^{14}C timescale to be different from the historical timescale [3]. Traditionally, the calibration of the Radiocarbon timescale is based on ^{14}C measurements for tree-rings dated by dendrochronology. Since dendrochronology provides absolute dates, true ^{14}C calibration curves can be obtained. Early calibration data-tables that were practically used in the archaeological community during the 1970s were constructed by Ralph and Michael [4]. These early curves and tables were based on US Sequoia and Bristlecone Pine trees. Several laboratories able to perform high precision ^{14}C measurements (2–5‰) started to dedicate much time to the measurement

of large quantities of wood, including intercomparison exercises (e.g. [5]). At the 12th Radiocarbon conference in Trondheim, it was decided to bring all calibration information together a special issue of Radiocarbon [6]. The first calibration issue contained a recommended calibration curve back to 2500 BC based on Irish, German and US dendrochronologies [7,8]. The Irish Oak dataset extended to 5210 BC [9]. Following the 14th Radiocarbon conference in Tucson, the second calibration issue of the journal Radiocarbon was produced [10] including a calibration curve back to 9440 BC. The third calibration issue was produced following the 16th Radiocarbon conference in Groningen [11], containing the presently recommended calibration curve INTCAL98. This curve ranges back to 13 635 BC.

Since 1998, a wealth of new calibration information became available from natural archives, other than tree-rings. These data cover the complete ^{14}C dating range of about 50 000 years. Many hundreds of ^{14}C measurements have been performed for these archives. This significantly

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illustrates the power of AMS, enabling high throughput measurements of intrinsically small samples. Nevertheless, a calibration curve comprising the complete ^{14}C dating range cannot yet be recommended. The new records show deviations from each other, which are particularly large – up to a few millennia – for the oldest part of the records. Therefore one has to be careful in applying the new measurements to other disciplines like prehistory. At present, the question of whether one can safely calibrate Upper Palaeolithic ^{14}C dates still has to be answered negatively.

2. INTCAL98

The calibration curve INTCAL98, presently recommended [11], is largely based on tree-ring data ranging from the present into the Preboreal, with an extension into the Late Glacial using marine archives. The tree-ring part of the INTCAL98 calibration curve has a decadal resolution

and ranges back to 9908 BC [12]. In addition, high temporal resolution marine datasets are included allowing extension of the curve to 13 635 BC (15 585 calBP). These marine datasets consist of Pacific corals dated by both ^{14}C and U-series isotopes, and by laminated sediments from the Cariaco basin [13]. Note that this part of INTCAL98 is marine derived, so that the appropriate reservoir correction has to be applied. This is taken as 400 and 500 years for times younger and older than 10 000 calBP, respectively [14]. In addition, the laminated chronology is not absolutely dated but has to be matched to the tree-rings; for the corals, the U-series dates are considered absolute. The INTCAL98 calibration dataset is shown in Fig. 1. Fig. 1 (top) shows the calibration curve as BP versus calBP, whereas Fig. 1 (bottom) shows the same data, plotted as $\Delta^{14}\text{C}$.

3. The new AMS data

For the Deglaciation and Glacial parts of the ^{14}C dating range, attempts were made to compare a large variety of ^{14}C with other dating methods. This includes samples dated by both ^{14}C and U-series isotopes, or by both ^{14}C and TL (thermoluminescence dating). A collection of existing data is shown in [15]. Although attempts have been made to construct a ‘calibration curve’ based on such data (e.g. [16]), both scatter and measurement errors are much too large for useful calibration purposes. In addition, the temporal resolution for such datasets is very low. The latter is also true for the set of paired ^{14}C /U-series dates for the Pacific corals [17], the measurements in itself being considered as valid calibration datapoints.

The first high temporal resolution calibration dataset measured by AMS that became available concerns a laminated sediment from Lake Suigetsu, Japan (LS) [18]. For this lake sediment, a 29,100 year long varve chronology is constructed. More than 330 ^{14}C measurements have been performed for terrestrial samples (mostly macrofossils, but also insects, branches and leaves) from the sediment. The varve chronology is not absolute but floating; the youngest part of the sediment overlaps with the oldest part of the tree-ring

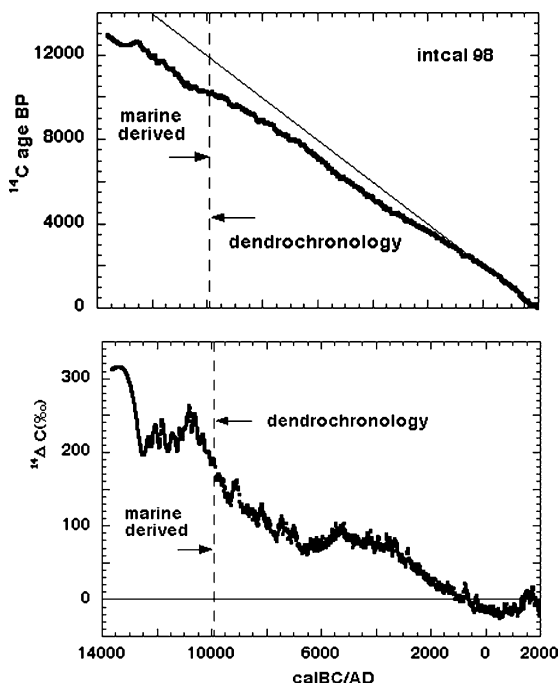


Fig. 1. INTCAL98 calibration dataset, showing the dendrological and marine derived part. Top: calibration curve (BP versus calBC/calAD). Bottom: same data, plotted as $\Delta^{14}\text{C}$ in ‰.

dataset and can therefore be matched using the ^{14}C measurements. Thus, the varve chronology is determined to range from 8830 to 37930 calBP. The (updated since 1998) datelist of ^{14}C measurements can be found in [19]. The calibration curve based on the ^{14}C measurements for the LS varve chronology is shown in Fig. 2 (top). The ^{14}C errors are 1σ standard deviations. The errors for the ‘absolute’ time axis are not shown. This error is due to miscounting of varves and is cumulative, and is estimated as not larger than 2000 varve years at the oldest part of the dataset.

The next high temporal resolution calibration dataset measured by AMS concerns a speleothem from the Bahamas (BS) [20]. For this archive, close to 300 paired $^{14}\text{C}/\text{U}$ -series dates have been measured. This dataset is not terrestrial, since for the carbonate a reservoir effect has to be taken into account. This is determined to be 1450 ± 470 (2σ) ^{14}C years and constant in time for this speleothem. The U-series dates are considered absolute, but

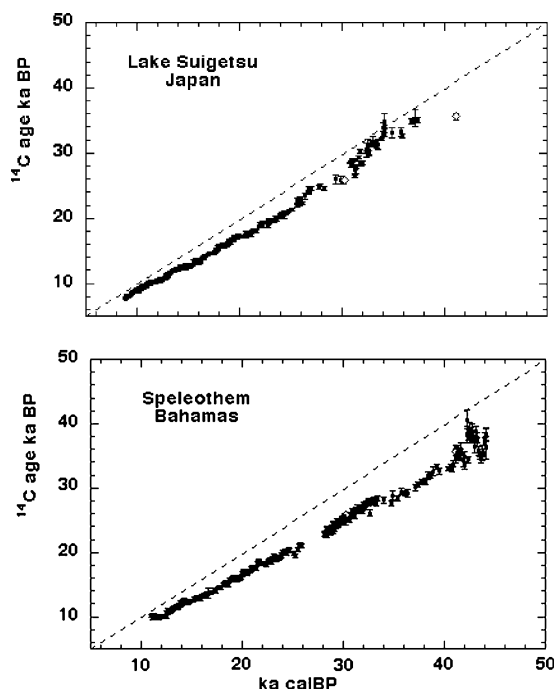


Fig. 2. Calibration (or comparison) curves for the laminated sediment from Lake Suigetsu, Japan (top) and for a Speleothem from the Bahamas (bottom). Two coral datapoints (at 30.2 and 41.1 ka calBP) are plotted for comparison (◆).

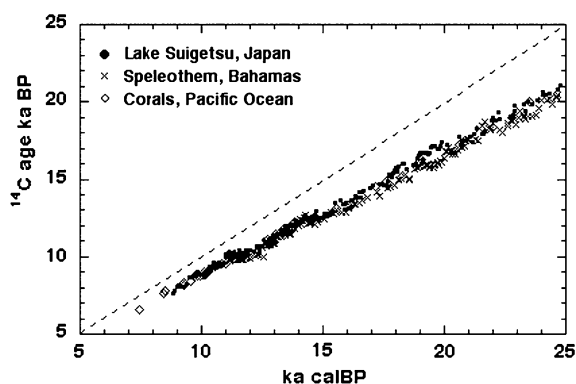


Fig. 3. Calibration (or comparison) curves for the laminated sediment from Lake Suigetsu, Japan (Fig. 2 (top), ●) and for a Speleothem from the Bahamas (Fig. 2 (bottom), ×). Only the deglaciation part is shown here in more detail. Coral datapoints are plotted for comparison (◇). For clarity reasons, the error bars are not plotted here.

there are measurement errors obviously. The BS dataset is shown in Fig. 2 (bottom). There is a gap in the record around 27 ka because the linear growth rate of the speleothem slowed considerably during this time interval, making sampling difficult.

Other high temporal resolution datasets that became available are derived from North Atlantic marine sediments. This concerns foraminifera, measured for ^{14}C by AMS [21,22]. Also for these marine data, the reservoir age has to be corrected for appropriately. This dataset is different in the sense that no ‘absolute’ time parameter is measured; instead it is derived from correlation of $\delta^{18}\text{O}$ events from the shells with those observed in the nearby GISP icecore [23].

The data in Fig. 2 are compared with the paired $^{14}\text{C}/\text{U}$ -series datapoints for corals [17]. This is not a high temporal resolution dataset (for that reason no calibration curve can be made, based on a few datapoints), but these measurements can be considered as a ‘reference dataset’. For visibility reasons, only the oldest two datapoints are plotted in Fig. 2, at 30.2 and 41.1 ka calBP. The others are plotted in Fig. 3 (to be discussed below).

4. Calibration, back to 50 ka?

As can be seen from Fig. 2, the agreement between the Lake Suigetsu (LS) and the Bahamian

Speleothem (BS) data is reasonable, or even good for the time back to about 25 ka calBP. The general trends of the curves, including wiggles and plateaux, agree. A detailed inspection, however (Fig. 3) shows that between both curves there seems to be a shift of about 500 calendar years, LS being younger. The cause of this shift is unknown. It cannot be due to varve counting error which is very small, but a section of missing varves cannot be excluded at this stage. The data can also be made to fit better at some sections by shifting the BS data to older ^{14}C age, perhaps due to non-constant reservoir age. The few coral datapoints seem to agree slightly better with LS.

Calibration of ^{14}C requires calibration curves that are absolute, or very close to absolute. In this sense, calibration of ^{14}C is not yet possible until the detailed differences are solved. One could make a 'calibration envelope' encompassing all data but this only yields limited information, just as for the 'stippled curve' that can be drawn through the coral datapoints [14]. Strictly speaking, this is not calibration. Nevertheless, we like to stress that overall the datasets are in good agreement with each other, considering the difficulties involved in obtaining them, and the uniqueness of the natural archives investigated.

For ages older than 25 ka calBP, the good-to-reasonable agreement between LS and BS disappears. The data are actually in total disagreement, for reasons as yet unknown. For a different perspective, the same data are plotted again in Fig. 4 as $\Delta^{14}\text{C}$, the relative ^{14}C content in permil, corrected for radioactive decay.

The LS record – Fig. 4 (top) – shows a peak in $\Delta^{14}\text{C}$ around 31 ka calBP, with an amplitude of ca. 200‰ on the general trend of the data. This could be a geomagnetic excursion like Mono Lake [24]. At older ages, the $\Delta^{14}\text{C}$ tends to go to zero which means there is no extra ^{14}C in the atmosphere compared with the present. Note that there are some additional datapoints measured back to 45 ka calBP [18]. These are measured for a section of the sediment which is not varve counted, and are not plotted here.

The BS data – Fig. 4 (bottom) – show that in general, the ^{14}C content remains higher than present between 30 and 45 ka calBP. The data

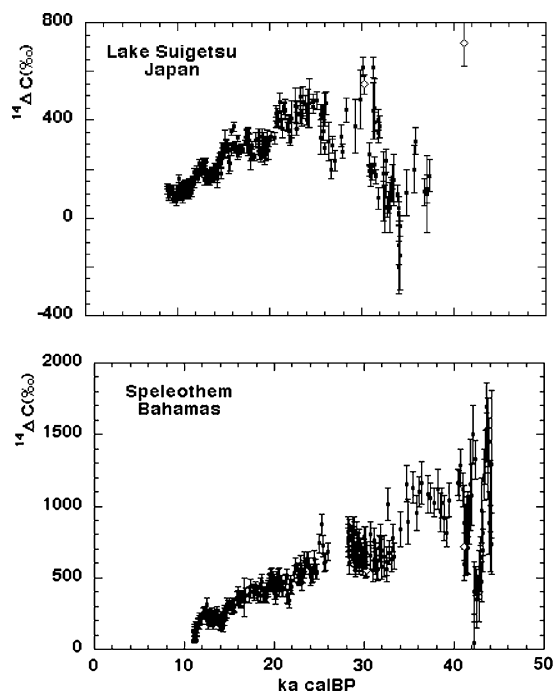


Fig. 4. Calibration data, plotted as $\Delta^{14}\text{C}$ in ‰ for the laminated sediment from Lake Suigetsu, Japan (Fig. 2, top) and for a Speleothem from the Bahamas (Fig. 2, bottom). Two coral datapoints (at 30.2 and 41.1 ka calBP) are plotted for comparison (◆).

show peaks or excursions, some with dramatic amplitudes: more than 1000‰, or the size of 20th century nuclear bomb explosions. Such large excursions cannot be explained by changes in the Earth's magnetic field intensity or the solar electromagnetic field alone. Switches in the mode of ocean circulation are required to enable the observed abrupt and high amplitude shifts [20].

It is obvious that there must be errors in one or both of the datasets since by definition, there can only be one ^{14}C calibration curve. A true calibration curve is a plot of the atmospheric ^{14}C content as a function of calendar time. For both the LS and the BS records, assumptions have to be made to derive such a plot from the measured data. For the (vertical) ^{14}C axis of the calibration function, LS qualifies as an atmospheric record because the samples are terrestrial materials. The BS data are not atmospheric, a reservoir age (dead carbon fraction) has to be determined and in addition

must be assumed constant through time. This correction for BS is determined as 1450 ± 470 (2σ) ^{14}C years [20]. For the (horizontal) calBP axis of the calibration function, both records are hampered. For LS, the varve chronology has counting errors (in a cumulative way) and missing varves cannot be excluded. In addition, the chronology is floating and thus has to be matched to the tree-ring part of the calibration curve. The varve error is estimated as 2000 years [18] at the older part of the record. For BS, the calBP dates are a result of a measurement by U-series isotopes which is geochemically complex.

We must conclude that no ^{14}C calibration curve for this timeframe can be constructed at present. The discrepancies must be resolved first, which probably requires a new and independent archive for confirmation of possible use of either LS or BS (or neither) record for calibration purposes. In order to prevent confusion, the term “comparison curve” has been proposed [15], and the U-series dates are expressed as ^{230}Th age rather than calBP [25]. And confusion there is: attempts to calibrate prehistoric ^{14}C dates from the Upper Palaeolithic is already taking place [26–28]. Constructing a calibration curve from both LS and BS records using some average value with a large error envelope seems not justified because it does not incorporate large ^{14}C fluctuations and ignores age reversals.

5. Beyond INTCAL98

Following INTCAL98, a new working group has been established to coordinate further ^{14}C calibration efforts. The goals of the working group are: (i) review datasets for calibration purposes, (ii) establish acceptance criteria for methods and archives, and (iii) make recommendation for the next ^{14}C calibration curve, probably INTCAL04. The working group had its first meeting in April 2002 in Belfast. A report of this meeting can be found in [29]. First, the dendrochronological part of calibration was reviewed. Minor corrections with respect to INTCAL98 were applied, the German oak and pine chronologies are now linked, and using pine trees from Switzerland the tree-ring data now

extend back to 12 058 calBP. Second, criteria have been established for the following archives: tree-rings, corals, carbonates (non-corals), laminated sediments and marine sediments. Note that many datasets available (as collected in [15]) do not meet these criteria. For a detailed discussion, see [29]. Third, the new AMS data (in particular LS and BS) have been extensively discussed. No calibration curve based on these datasets will be recommended at this stage.

6. Conclusion

For the ‘classical’ ^{14}C calibration archive, tree-rings, we have seen continuous progress since the publication of the first calibration tables and graphs. Since INTCAL98, the tree-ring calibration curve is now reaching well into the Younger Dryas. Beyond the tree-ring dataset, corals and marine varves provide data for a calibration curve (marine derived) back to 15 585 calBP. For these datasets, no new data became available since INTCAL98. All of this will be the backbone for the next calibration curve, probably INTCAL04, to be released by a specially established working group.

Since INTCAL98, a wealth of new data became available containing calibration information for practically the complete ^{14}C dating range, measured by AMS. Two “calibration curves” could possibly be constructed, one based on a laminated sediment from Lake Suigetsu (Japan), and one based on a speleothem from the Bahamas. The datasets show a reasonable to good agreement for the Deglaciation part. The difference is about 500 years, too large to construct a reliable calibration curve. For the full Glacial part, Both datasets are not compatible so that we presently cannot calibrate Upper Palaeolithic samples. We should consider this subject as ‘work in progress’. Clearly, more and independent measurements are needed to resolve the discrepancies. Ideally, an archive which is truly absolute and atmospheric/terrestrial, cross dated and continuous is needed. In practice this may be difficult to achieve; actually, only tree-rings qualify as a true calibration archive. Glacial trees with a significant number of rings are found

and analysed for ^{14}C , but such trees are individual and contain floating chronological information. Nevertheless, we observe that remarkable progress has been made the last few years. Truly unique records have been obtained, made possible only by the power of AMS.

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