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Calibration of the ^{14}C time scale: towards the complete dating range

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Abstract

Radiocarbon calibration based on dendro-chronology and U-series dated corals yield a calibration curve (INTCAL98) well into the Late Glacial, back to ca. 15,600 calendar years ago. Beyond this limit, various calibration curves are produced, mainly based on laminated sediments and various carbonates dated by U-series isotopes. Such calibration curves now cover the complete ^{14}C dating range of about 45,000 years, but are not consistent with each other. Each calibration method (other than dendro-chronology) has its own assumptions and pitfalls. Thus far, the calibration curve obtained from Lake Suigetsu laminated sediments is the only terrestrial (atmospheric) one.

Keywords: Radiocarbon, calibration, dating, cosmogenic isotopes, laminated sediments

Introduction

The naturally occurring isotope ^{14}C (Radiocarbon) is continuously produced in the earth's atmosphere by cosmic radiation. Radiocarbon is radioactive and decays with a half life of 5730 ± 40 years (Godwin, 1962). A stationary state of production, distribution between the main carbon reservoirs (atmosphere, ocean and biosphere) and decay results in a more or less constant ^{14}C concentration in atmospheric CO_2 (Mook and Waterbolk, 1985; Mook and Streurman, 1983).

However, it is known for some time that the ^{14}C concentration of atmospheric CO_2 has not always been the same in the past. In tree rings, natural variations of the atmospheric $^{14}CO_2$ abundance were discovered on a time scale of one decade to a few centuries (De Vries, 1958). Later it was discovered that these variations can be attributed to variations in solar activity (Stuiver, 1965), which in turn influence the production of ^{14}C in the atmosphere. Also changes of the geomagnetic field strength influence the production of ^{14}C in the atmosphere (Bucha, 1970). This is understood because both solar activity and geomagnetic field strength determine the amount of cosmic radiation impinging on the earth. In addition the atmospheric $^{14}CO_2$ concentration also depends on exchange between the atmosphere and ocean.

Because of these variations in the natural ^{14}C concentration, the ^{14}C clock runs at a varying pace, different from real clocks: ^{14}C time is not equivalent to historical time. Therefore, the ^{14}C timescale is *defined* and has to be *calibrated* to establish the relationship between ^{14}C time and historical time.

By definition, the ^{14}C timescale is expressed in BP (Before Present), where 'Present' is the 'standard year' 1950 AD (Mook and Van der Plicht, 1999). Radiocarbon measurements are always measured with respect to a standard (Oxalic Acid with a radioactivity of 0.226 Bq/gC) which corresponds to 1950. By convention, this definition includes correction for isotopic fractionation (to $^{13}\delta$ = -25‰) and uses the original value for the ^{14}C halflife (5568 years), used in the early days of the ^{14}C dating method (Libby, 1955). We note that this definition applies to both the conventional method (radiometry) and AMS (mass spectrometry).

Calibration involves measuring samples by both the ^{14}C method (in BP) and another method. Ideally this other method has to be independent from ^{14}C, yielding absolute dates (in AD/BC), and the samples have to be terrestrial (atmospheric).

The ideal samples for calibration are tree rings, because they can be dated absolutely by means of dendrochronology. Following the early work of Suess et al. (Suess, 1978), the ^{14}C community has issued special issues of the journal Radiocarbon with calibration curves based on dendrochronology (Stuiver and Kra, 1986; Stuiver et al., 1993). The latest and presently recommended calibration curve is INTCAL98 (Stuiver and Van der Plicht, 1998). The dendro-chronological part of INTCAL98 covers practically the complete Holocene.

Because of the irregular shape of the calibration curve, the translation of a ^{14}C age (in BP) into a calendar age is not straightforward. Special calibration software has been developed, producing calibrated age ranges with 1σ or 2σ confidence intervals (Bronk Ramsey, 1998; Van der Plicht, 1993; Stuiver and Reimer, 1993). Calibrated ages are reported in calBC or calAD (Mook 1986). In addition, calBP is used, where calBP = 1950 – calAD or calBP = 1949 + calBC, (calBP means calibrated or calendar years before 1950).

Beyond the Holocene boundary, dendrochronology does not exist. For the purpose of calibrating the ^{14}C time scale, therefore one has to use other methods. A variety of such methods is employed, each with their own assumptions, limits and pitfalls. The 'absolute' timescale is usually the result of a measurement and thus it is not truly absolute; the ^{14}C timescale is often obtained from non-terrestrial sample materials, making assumptions for possible reservoir effects necessary. A variety of ^{14}C 'calibration curves' are produced, extending back to cover the complete ^{14}C dating range of ca.45,000 years. These are compared and discussed in another special issue of the journal Radiocarbon (Van der Plicht, 2000). For times back to ca. 20,000 calBP consensus likely will be reached soon; for the older ages, the various curves strongly deviate from each other. Nevertheless, important information on ^{14}C variations in the past – and thus on calibration of the ^{14}C timescale – can be deduced from the available data. Altogether, for ^{14}C calibration remarkable progress has been made the last few years, in particular made possible by employing AMS.

Calibration methods

Calibration information is based on paired measurements of ^{14}C vs. another independent dating method. We can make the following inventory:

- **a)** tree rings measured by both ^{14}C and dendrochronology (absolute) *in principle, only this is true calibration because of the 'absolute' character*
- **b)** tree rings measured by both ^{14}C and dendrochronology (floating) *floating chronology has to be matched to absolute chronology*
- **c)** corals dated by both ^{14}C and U-decay series *marine reservoir effect for ^{14}C; U-series not necessarily absolute*
- **d)** laminated ('varved') sediments which contain ^{14}C datable material *floating chronology; varve counting can be problematic*
- **e)** speleothems dated by both ^{14}C and U-decay series *reservoir effects for ^{14}C; U-series not absolute; growth interruptions?*
- **f)** Radiocarbon vs. Thermoluminescence (TL) *large errors; TL not organic*
- **g)** Radiocarbon vs. dating methods such as $^{40/39}$Ar, ESR, OSL, AAR *large errors; limited practical use*
- **h)** reconstructions *comparison of events in ^{14}C stratigraphy with those in ice cores, etc.*

This inventory consists of 8 categories, with a one-line summarizing remark in italics, stating assumptions, validity, etc., for each particular method. Each of these categories will be discussed in detail below.

INTCAL98

The presently recommended calibration curve INTCAL98 (Stuiver et al. 1998) is constructed from records from the above categories a, b and c. The following remarks can be made concerning the selection of these records:

Ad **a**) Strictly speaking, only this part is a true calibration curve since dendrochronology is the only dating method which is absolute. This part of the calibration curve is the product of high-resolution ^{14}C measurements on mainly German oak, Irish oak, US Bristlecone pine and US Douglas fir. These measurements have been performed during the last decennia by several laboratories (Belfast, Heidelberg, Pretoria, Seattle, Tucson and Groningen), using high precision conventional dating and mutual cross-checking. The absolute tree ring chronology yields a calibration curve, now reaching back to 8329 calBC (Kromer and Spurk, 1998; Stuiver et al., 1998).

Ad **b**) A 1900 year long floating chronology for German pine trees is matched (using the ^{14}C measurements) to the absolute tree ring chronology, extending the calibration record back to 9908 calBC (Kromer and Spurk, 1998). The uncertainty of the match is ca. 20 calendar years.

Ad **c**) For the time frame beyond the tree-ring limit, corals can be used for calibration purposes. The record consists of paired measurements ^{14}C vs. U-series dating (Bard et al., 1998; Burr et al., 1998). Contrary to tree rings which are atmospheric, the coral record is marine so the calibration curve beyond the tree ring limit is 'marine derived'.

One has to be aware of the following constraints using these data:

1) Concerning ^{14}C dating: Because the coral part of the curve is marine, there is a 'reservoir effect' correction. For INTCAL98, this reservoir age is taken as 400 and 500 years for times younger and older than 10,000 calBP, respectively. These are very reasonable numbers, but it remains an assumption. Furthermore, reservoir ages are now known to be significantly larger during Late Glacial and Glacial times, at least in the Southwest Pacific (Sikes et al., 2000). As another additional possible complication, rapid atmospheric ^{14}C fluctuations are damped by the ocean.
2) Concerning U/Th dating: the U-series dates are a result of a measurement, which is different from dendrochronology which is simply based on tree-ring counting. For U-series dating, the sample needs to be part of a closed system, i.e., no U or Th isotopes should exchange with the environment since fossilization. For corals, this is a valid assumption in general. Thus, these measurements are considered reliable and understood, but are by definition not absolute.

All together, INTCAL98 was and is the calibration curve recommended for general use until further notice. The INTCAL98 curve covers the time from the present back to 13635 calBC (15585 calBP), and is based on the records a) b) and c) as listed in the above inventory.

As an exception to the rule, marine varved sediments from the Cariaco Basin (Hughen et al. 1998a, 1998b) are included in INTCAL98 because it strengthened the tree ring / coral link considerably at the time. The assumptions here are 1) the marine reservoir correction for ^{14}C, and 2) the accuracy of varve counting.

The INTCAL98 calibration curve is shown in Fig.1: the dendro-chronological part (both absolute and floating) in red, and the marine derived part in blue. The calibration dataset is decadal, i.e., it has a

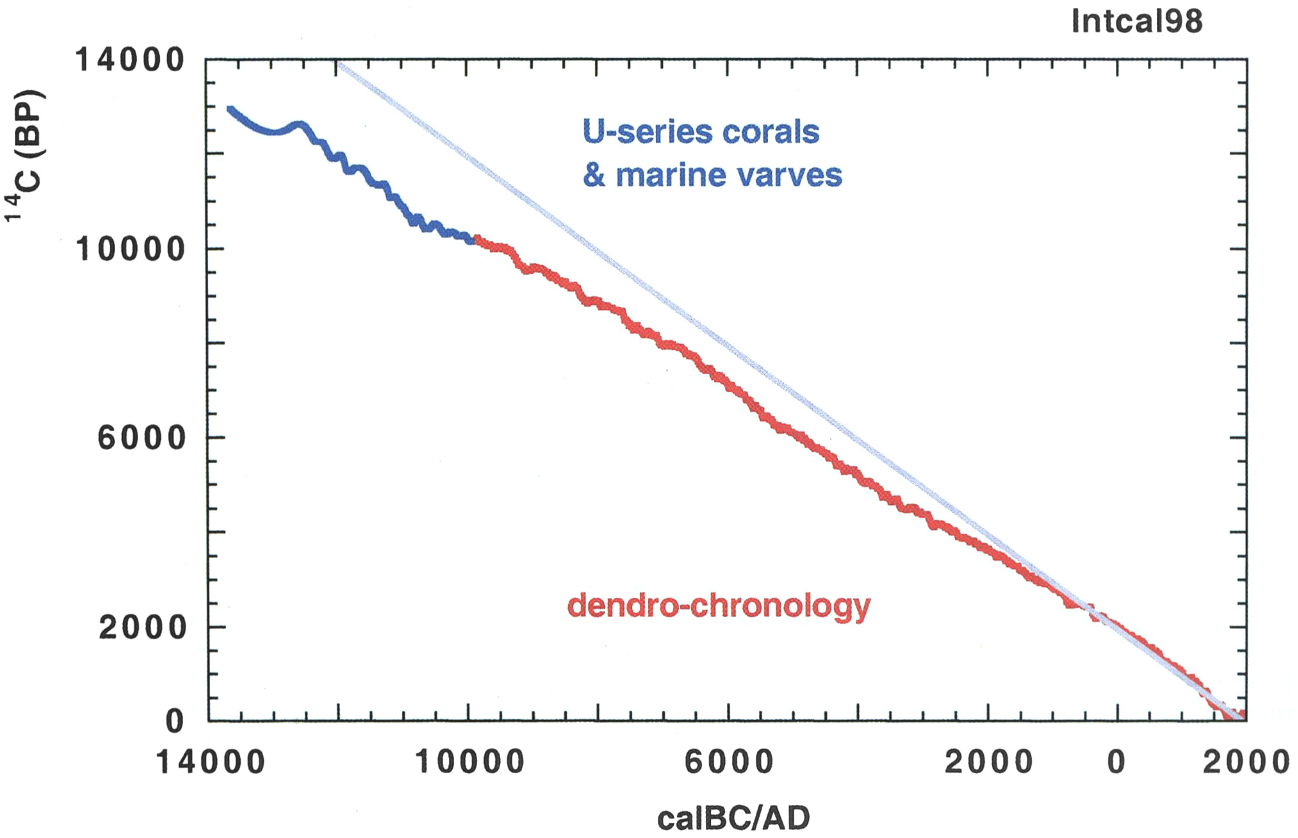

Fig. 1. The ^{14}C calibration curve INTCAL98 (Stuiver et al., 1998), based on dendrochronologically dated wood (red) and corals dated by both ^{14}C and U-series (blue).

resolution of 10 calendar years. The uncertainties plotted are 1σ.

The coral calibration data points cover mainly the Late Glacial Period, with additional (low-time resolution) data to the Last Glacial Maximum (LGM) and 2 isolated data points at ca. 30,000 and 41,000 cal BP (Bard et al., 1998). This resolution, however, is too low in order to describe the part beyond 15585 cal BP as a 'calibration curve'. In addition, there are conflicting records for this time range, as will be discussed in the next paragraph. Because of these conflicts, no records based on d-h from the above inventory have been used for INTCAL98 (except the data from the Cariaco Basin, as mentioned above).

Beyond INTCAL98

Beyond INTCAL98, calibration information for the ^{14}C timescale is based on records from the categories d)-h) from the above inventory. All of these categories have their own problems, as will be discussed below.

Ad **d**) Laminated sediments yielding varve chronologies are only absolute when they extend to the present and when the laminations are truly annual. However, all varve chronologies are floating (none extends to the present) and thus have to be matched to the calibration curve; counting of laminations is quite often problematic. Revisions had to be made often in the past (see e.g. Wohlfarth 1996). Annual layer identification can be a personal affair, and there can be hiatuses in the sediment. Individual chronologies are not internally checked like treerings, where missing or double rings can be identified by cross-dating. In addition, reservoir effects have to be reconciled for marine or lacustrine sediments.

Ad **e**) Calibration work based on dating speleothems depends on assumptions for both methods. For ^{14}C there is the reservoir effect: the initial conditions of fossil carbon has to be known, and this reservoir correction is assumed to be constant throughout time. For U/Th, the initial ^{230}Th present during speleothem growth has to be known (Beck et al., 2000). Furthermore there can be periods of reduced growth (Vogel and Kronfeld, 1997). In general, U-series dating of speleothems is not as reliable as dating of marine corals by the same method.

Ad **f**) The practical use of TL for calibration purposes is limited because of the large error bars for this method. In addition, TL does not work for organic material, so comparison with ^{14}C is only possible by association (e.g., pottery dated with TL, vs. charcoal dated with ^{14}C). No calibration curves can be constructed, but many data points in BP vs. calBP plots exist. For the complete ^{14}C dating range, useful ^{14}C/TL comparisons have been made (Barbetti 1980) in an attempt to reconstruct the geomagnetic field strength during the past (Barbetti and Flude, 1979).

Ad **g**) Comparing ^{14}C dates with results based on these techniques (ESR: Electron Spin Resonance dating, OSL: Optically Stimulated Luminescence dating and AAR: dating by Amino Acid Racemization and $^{40/39}$Ar dating) have been used only incidental, and the use is limited for the same reason as TL (large errors; association based). These are only mentioned here to give a complete overview.

Ad **h**) Radiocarbon 'calibration curves' can be reconstructed by linking series of ^{14}C measurements to archives such as ice cores and pollen sequences. Voelker et al. (2000) use ^{14}C and ^{18}O from marine sediment foraminifera. The ^{18}O shows Dansgaard/Oeschger cycles which could be linked to the same signals in the nearby GISP2 ice core, so that the GISP2 timescale can be used as a 'calibrated timescale' for the ^{14}C measurements.

Sediments with a ^{14}C time/depth relation have also been used to reconstruct 'calibration curves'. This can be done when (absolute) time markers are identified, like clear boundaries between pollen zones. As an early example for the Late Glacial/Early Holocene, see Zbinden et al. (1989).

A survey of comparison measurements based on the methods e, f, and g from the above inventory shows large variations – up to many millennia for the Glacial part (> ≈ 20,000 cal BP). It is illustrative to plot paired ^{14}C / 'other method' (BP vs. calBP) for all data available to date. For reasons of clarity, the data are compared with the 'equiline' (calBP = 1950 – calAD). Fig.2 shows ^{14}C versus TL in green as published over the years in a variety of studies (Barbetti, 1980; Mellars, 2000; Richter et al., 2000; Huxtable and Aitken, 1977; Prescott and Smith, 1993; Bell, 1991; Zhu et al., 1999; Readhead, 1988; Roberts et al., 1990). Single data points for OSL (Abeyratne et al., 1997), ESR (Mellars, 2000), AAR (Farrand, 1994) and $^{39/40}$Ar (Geyh and Schlüchter, 1998) are shown here as well.

The data showing ^{14}C versus U/Th taken from: a). a literature survey plotted in red (Bischoff et al., 1994; Chappell and Veeh, 1978; Geyh and Schlüchter, 1998; Holmgren et al., 1994; Lin et al., 1996; Lin et al., 1998; Lomitschka and Mangini, 1999; Vogel and Kronfeld, 1997; Goslar et al., 2000a, Schramm et al., 2000; Yokoyama et al., 2000) and b) the 'reference data set' of coral calibration data plotted in blue (Bard et al., 1998).

Measurements with quoted errors > 2500 years (1σ) are omitted. The only conclusion one can draw from this compilation is that (apart from the coral da-

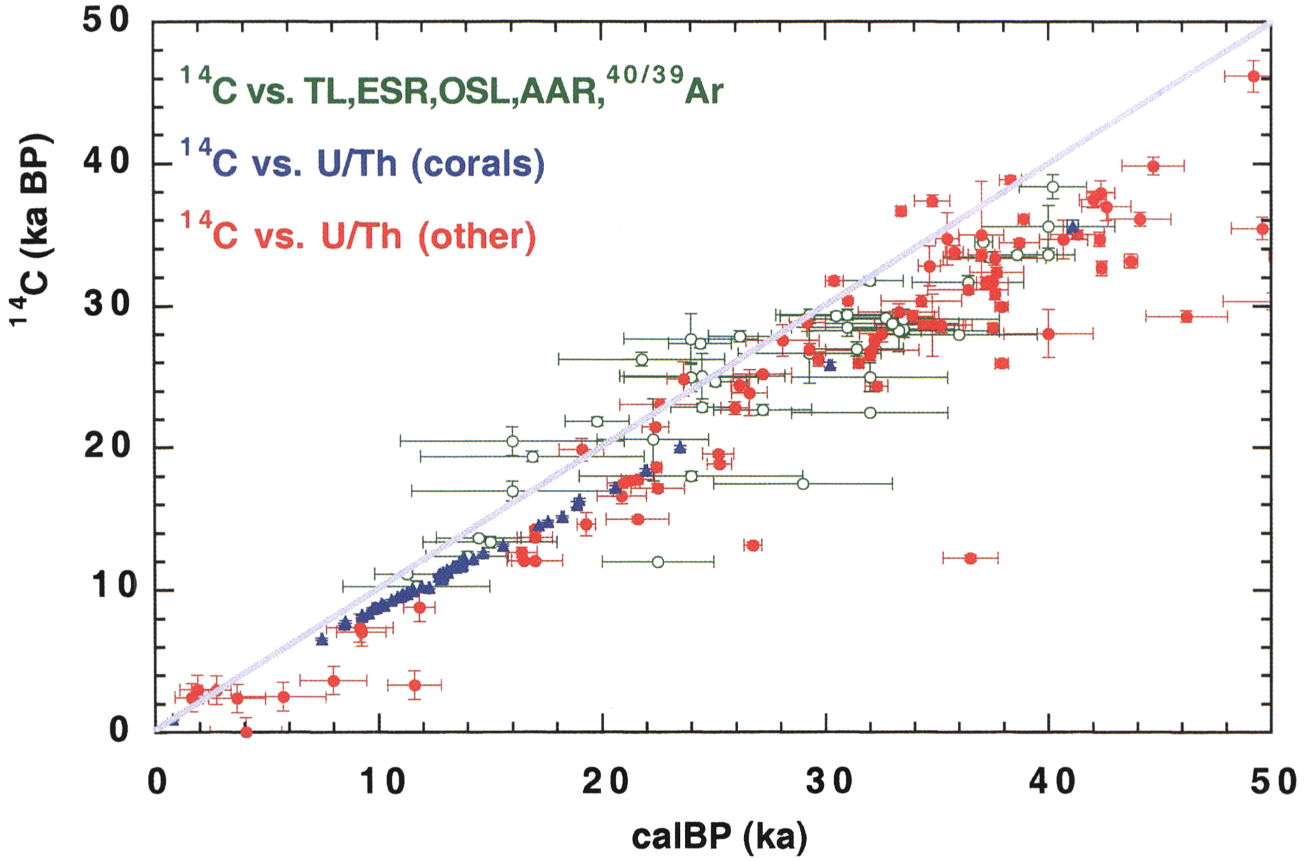

Fig. 2. Comparison of ^{14}C versus other dating methods. Green: various techniques, red: U-series dating, blue: U-series dating of corals (Bard et al., 1998). All errors correspond to 1σ.

ta set) the records deviate to strongly from each other to yield anything like a calibration curve. Clearly, the assumptions underlying each particular method (as discussed above) have to be further investigated. In any case, calibration cannot be done by interpolating between a few coral data points (Bard et al., 1998).

Laminated sediments

The first varve chronologies used for ^{14}C calibration purposes where the Swedish varves (Tauber, 1970) and varves from Lake of the Clouds in Minnesota, USA (Stuiver, 1970). At that time, dendrochronologically based ^{14}C calibration curves were limited in time scale, and the varved records gave unique information on Late Glacial atmospheric ^{14}C variations (Stuiver et al., 1986). The ^{14}C measurements were conventional, and not very detailed. After the introduction of AMS it became possible to obtain detailed varve chronologies by measuring material from individual laminations – such as pollen, seeds, leaves and insects. Over the years, new or revised varve/^{14}C chronologies were obtained for Sweden (Wohlfarth, 1996), Holzmaar/ Germany (Hajdas et al., 1995), Soppensee/Switserland (Hajdas et al., 1993), Lake Gosciaz/Poland (Goslar, 2000b) and Meerfelder Maar/Germany (Brauer et al., 2000).

Calibration information based on these varved records from Europe does extend beyond the dendrochronology limit, but never further than ca. 13,000 calBP (Wohlfarth, 1996; Björck et al., 1996; Goslar et al., 2000b).

A recently established chronology from Lake Suigetsu in Japan, however, shows laminations for the past 100,000 years, which are likely to be annual (Kitagawa and Van der Plicht, 1998, 2000).

The sediments from a 75 m long continuous core are characterized by dark-coloured clay with white layers due to spring season diatom blooms. Thus far, more than 300 terrestrial macrofossil samples (leaves, insect remains, branches) were measured by the Groningen AMS facility.

Until now, the varve numbers have been counted in the 10.42-30.45 m deep section interval. This Lake Suigetsu floating varve chronology consists of 29,100 varves. The features in our data overlapping the tree ring calibration agree very well, even for 'wiggles' in the ^{14}C calibration curves. Using this match we defined the absolute time scale, which then covers the absolute age range from 8830 to 37,930 calBP. The combined ^{14}C and varve chronologies from Lake Suigetsu can be used to calibrate the ^{14}C time scale beyond the range of the absolute tree-ring calibration.

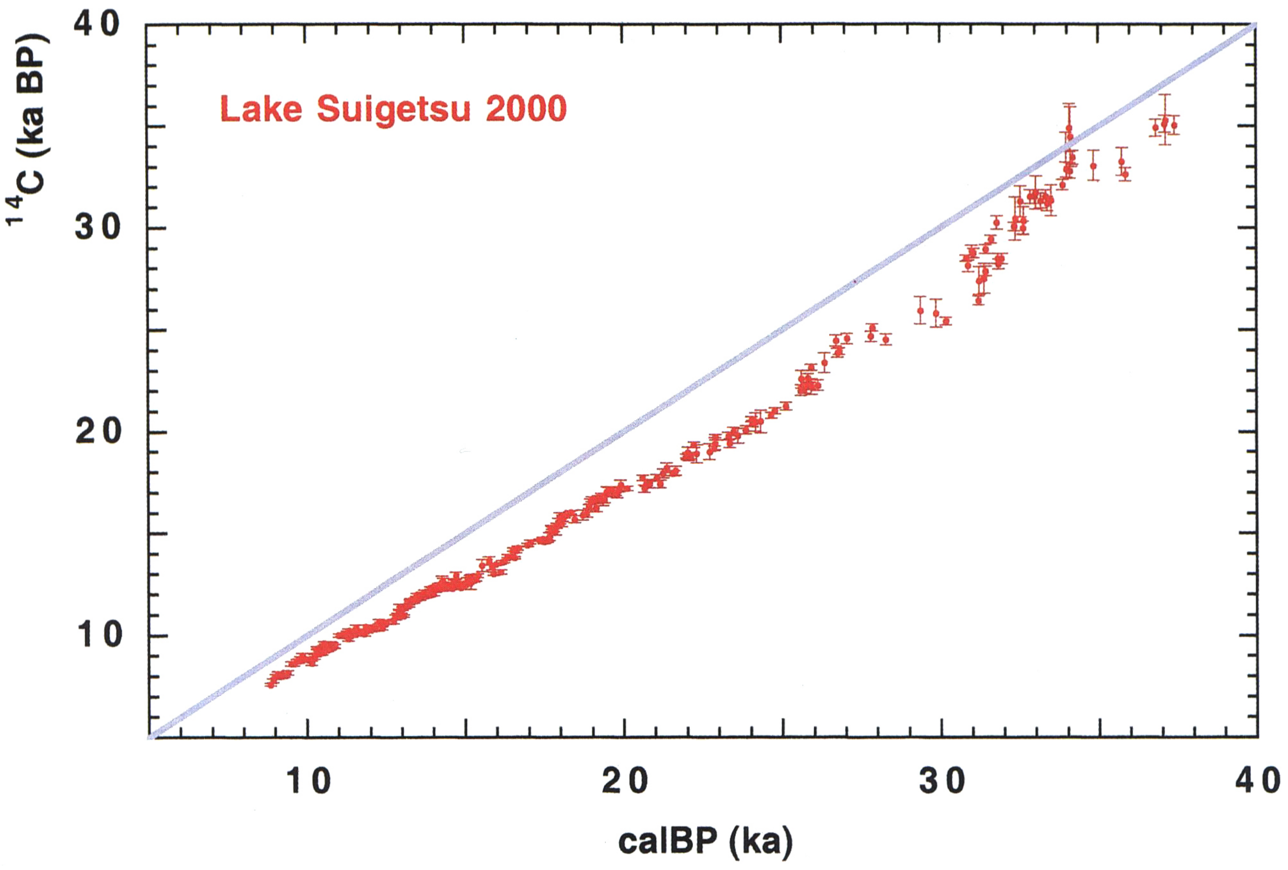

Fig. 3. The ^{14}C calibration curve from Lake Suigetsu, Japan (Kitagawa and Van der Plicht, 2000), based on more than 300 AMS measurements of organic material from the laminated sediment.

Figure 3 shows an atmospheric ^{14}C calibration curve for almost the complete ^{14}C dating range (< 45,000 cal BP).

Note that the accumulated counting error in the varved chronology is estimated as 2000 calendar years for the older part of the record (Kitagawa and Van der Plicht, 1998). Therefore, as with all such datasets, one has to be careful using the term 'calibration curve', because the varved chronology is not (yet) established as 'absolute' (Van der Plicht, 1999). The older ages should be considered as 'minimum ages'.

The latest review of the data sets can be found in the varve/comparison special issue of Radiocarbon (Van der Plicht, 2000). The varved sediments were not included in INTCAL98 because of conflicting records; the European varve chronologies have been revised many times in the past, and the Japanese varve chronology needs to be confirmed since there are conflicts with other records (discussed in the next paragraph).

Discussion of the oldest part of the ^{14}C time scale

Fig. 4 shows a comparison plot in terms of Δ^{14}C, which is the atmospheric $^{14}CO_2$ content, in per mil deviation from the standard and corrected for radioactive decay (Mook and Van der Plicht, 1999).

In green, the dendrochronological part of INTCAL98 (Stuiver et al. 1998) is plotted, in red, the coral dataset of Bard et al. (1998), and in blue, the updated dataset for the Lake Suigetsu varves (Kitagawa and Van der Plicht, 2000).

The 'band' (between the 2 black solid lines) shows the range of atmospheric Δ^{14}C values calculated from palaeomagnetic stack measurements (Guyodo and Valet, 1996). Note that the 2 black solid lines correspond to 2σ errors. Similar Δ^{14}C yields result from calculations of cosmogenic radionuclide production, derived from stacked ^{10}Be deposition rates (Frank, 2000).

The long-term trend in Δ^{14}C agrees well with reconstruction of cosmogenic isotope production rate deduced by the ^{10}Be deposition and geomagnetic field intensity reconstruction (Bard, 1997). For this time span, we observe two pronounced peaks in Δ^{14}C at 23,000 and 31,000 cal BP. These apparent Δ^{14}C increases correspond to an increase in the concentration of another cosmogenic isotope, ^{10}Be, observed in ice cores and marine sediments.

The peak at 31,000 cal BP is about 300 per mil in Δ^{14}C after removing the long-term geomagnetic

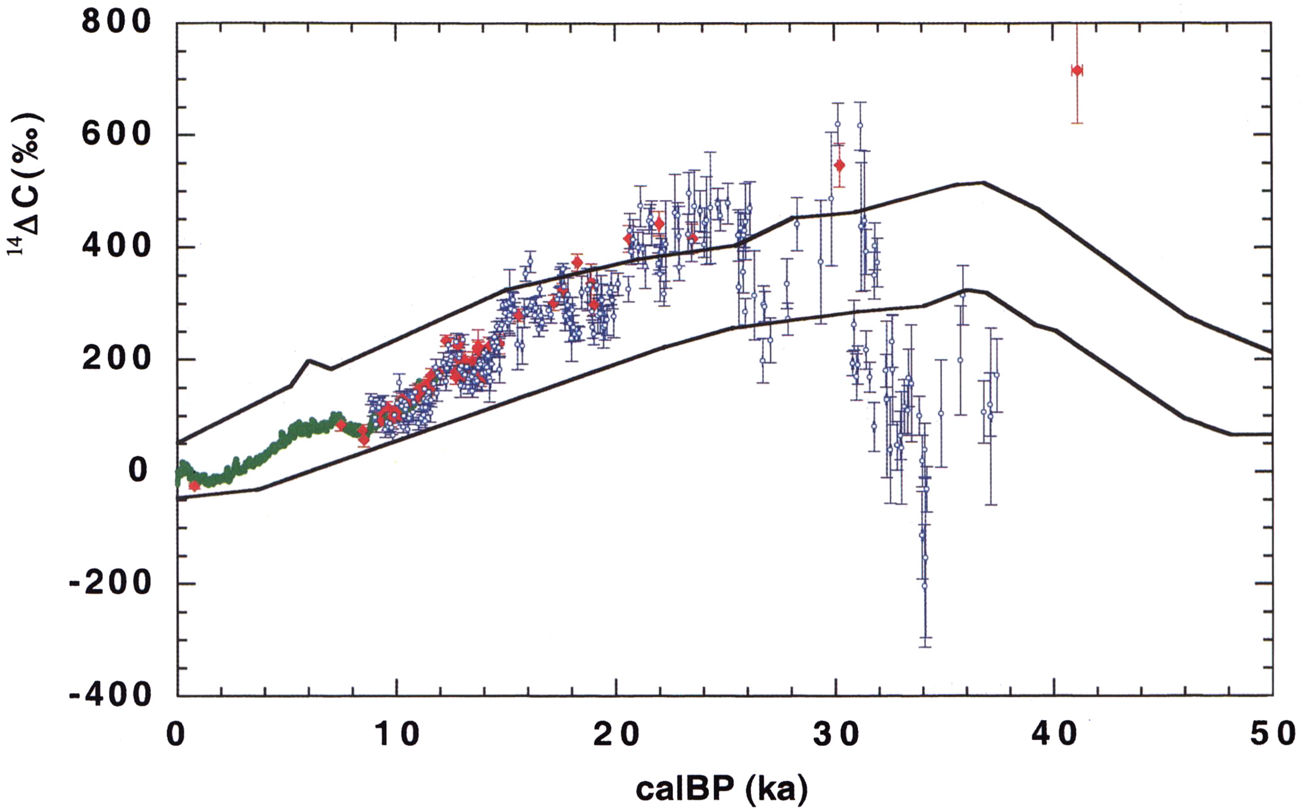

Fig. 4. Atmospheric ^{14}C content ($\Delta^{14}C$, ‰) for the complete dating range of 50,000 years, derived from paleomagnetism (Guyodo and Valet, 1996; 2σ range, indicated by black lines), INTCAL98 (green, tree-ring part only; Stuiver et al., 1998), U/Th for corals (red, 1σ error; Bard et al., 1998) and Lake Suigetsu (blue, 1σ error; Kitagawa and Van der Plicht, 2000).

trend. For ^{10}Be, a factor of 2 is observed in Antarctic ice cores at 35,000 cal BP (Raisbeck et al., 1987). Such increase during 2 millennia corresponds to a ^{14}C increase by a factor 1.3, equivalent to 300 per mil, which is exactly what is observed in the data from Lake Suigetsu.

The time gap between the ^{14}C and ^{10}Be enhancements can be explained by errors in both varve and ice core chronologies.

Beyond 30,000 calBP, fluctuations in $\Delta^{14}C$ are shown in conflict with the general geomagnetic trend. The large peak at 31,000 calBP is attributed to a magnetic excursion (Kitagawa and Van der Plicht 1998a). Such excursions (known as Mono Lake and/or Laschamp) have also been observed in other cosmogenic isotope records: ^{10}Be in the ice cores Vostok (at 35,000 cal BP, Raisbeck et al., 1987) and GRIP (at 41,000 cal BP, Yiou et al., 1997), ^{10}Be in marine sediments from the Mediterranean Sea (at 37,000 cal BP, Castagnoli et al., 1995), the Gulf of California (at 32,000 cal BP, McHargue et al., 1995) and the Caribbean Sea (at 37,000 cal BP, Aldahan and Possnert, 1998), and ^{36}Cl in the GRIP ice core (at 38,000 cal BP, Baumgartner et al., 1998; at 32.000 cal BP, Wagner et al., 2000).

Recently, the Mono Lake and Laschamp excursions were observed at 34,000 and 41,000 calBP, respectively, in a marine sediment from the Icelandic Sea (Voelker et al., 2000). Also this record comprises a ^{14}C 'calibration dataset' by comparing GISP2 and sea-core events: method h from the above inventory.
Also new records show cosmogenic peaks, at different times and sometimes with extremely large amplitudes (Beck et al., 2000). The latter data are measured for a stalagmite from the Bahamas, dated by both ^{14}C and U-series isotopes – method e from the above inventory. Taking the U-series dates as absolute, assuming a continuous growth and for ^{14}C a (constant) reservoir age of 1500 years, peaks up to 1600 â are observed in the derived $\Delta^{14}C$ signal. These are higher than the so called bomb-peaks resulting from atmospheric nuclear weapons testing during the 1950s and 1960s.
Obviously there is a lot of room for discussion here concerning the 'absolute' time scale calBP, and caution concerning the influence of this time scale on peaks in the $\Delta^{14}C$ signal is necessary: deviations from the true calendar age may have strong effects on calculated $\Delta^{14}C$ values.

The latest development concerns a detailed ^{14}C stratigraphic investigation of Palaeolithic sites throughout the Eurasian plain, from Western Europe to Central Asia. Terrestrial cold and warm signatures (permafrost resp. soil formation) can be correlated with climate signals from ice cores (Heinrich-events and Dansgaard/Oeschger cycles). Concerning the chronologies, it appears that ^{14}C-dated events correspond with the GISP2 time scale, when calibrated with the calibration curve from Lake Suigetsu. A full report will be published in the near future (Haesaerts et al., in preparation).

Discussion of the Deglaciation period

For the Late Glacial period, the Japanese varve data agree very well with the marine calibrations obtained by combined U/Th and ^{14}C dating of corals (Bard et al., 1998; Burr et al., 1998). These data also agree with the varved sediments from Lake Gosciaz (Goslar et al., 2000b), and with marine varves from the Cariaco Basin (Hughen et al., 1998a,b). The detailed Δ^{14}C record for the last ca. 20,000 years shows millennium-scale fluctuations, superimposed on a long term increasing trend, resulting from a decreasing geomagnetic intensity and consistent with ^{10}Be records (Bard, 1997).

For the time period younger than 10,000 calBP, the reservoir effect R for the corals is taken as 400 ^{14}C years in INTCAL98; for the part older than 10,000 calBP, R=500 ^{14}C years. There is a good agreement between INTCAL98, Lake Suigetsu and Lake Gosciaz back to 12,500 calBP. Beyond 12,500 calBP, a systematic offset between Lake Suigetsu and INTCAL98 was observed (Stuiver et al., 1998), which was one of the reasons for not incorporating part of the Japanese varve record in INTCAL98. These three data sets (INTCAL98, Lake Suigetsu and Lake Gosciaz in blue, red and green, respectively) are plotted in Fig. 5. Now it appears that the same offset also exists for Lake Gosciaz. So, either there is an underestimation of varve counts (also equal in size) in both Lake Suigetsu and Lake Gosciaz, or the value for R in this part of INTCAL98 should be revised to about 400 years. This hypothesis is supported by new data from the Cariaco Basin, extending the time scale for this data set by several more millennia (Southon et al., 2000). Back to about 20,000 calBP, there is now emerging a remarkable agreement between Lake Suigetsu and the Cariaco Basin.

Conclusion

Radiocarbon calibration for the complete dating range of ca. 50,000 years remains to be qualified as 'work in progress'. It is obvious that this is in particular true for the period > 20,000 calBP, where records deviate from each other; in particular for the oldest part of the ^{14}C dating range. Several 'calibration curves' could be constructed, differing up to many

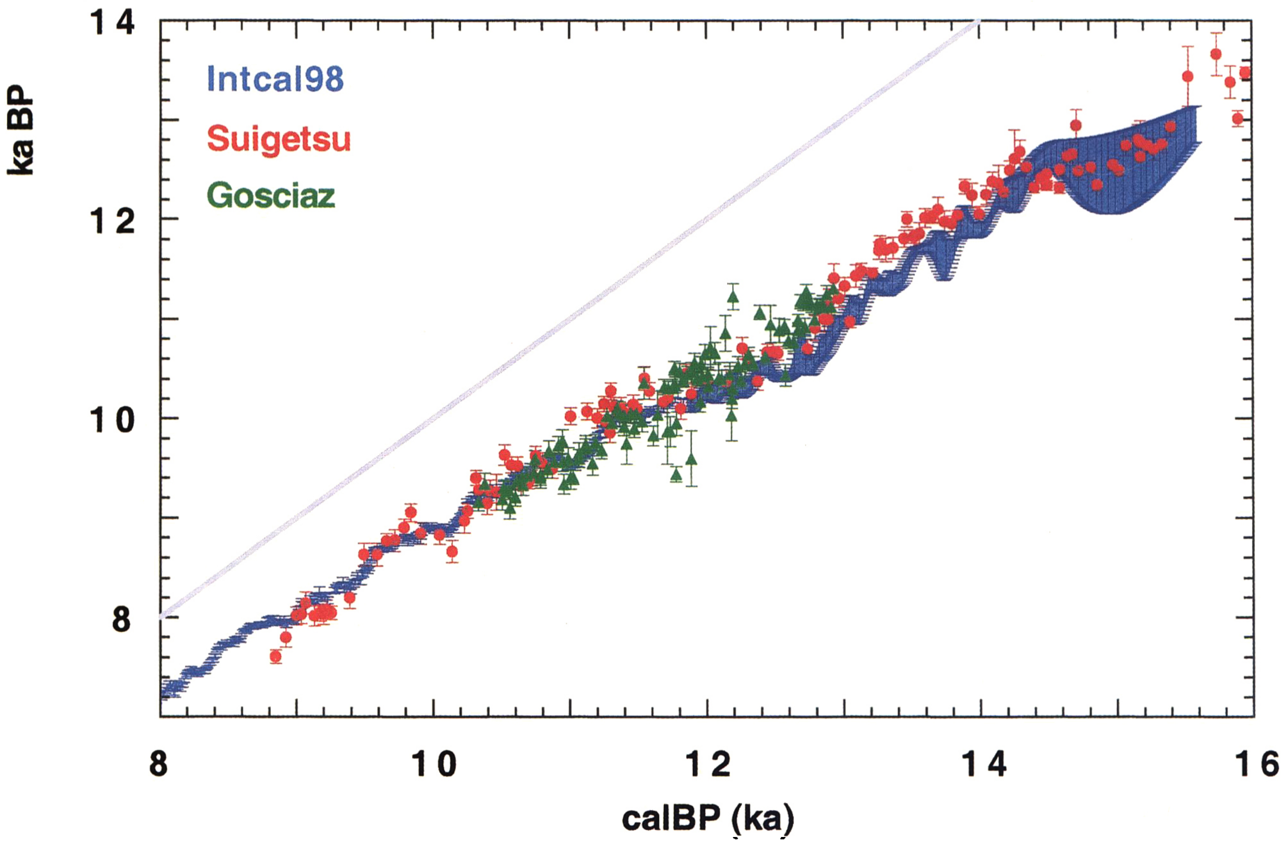

Fig. 5. Radiocarbon calibration records for the period 8-16,000 years ago: INTCAL98 (blue; Stuiver et al., 1998) compared with varved sediments from Poland (Lake Gosciaz, green; Goslar et al., 2000b) and Japan (Lake Suigetsu, red; Kitagawa and Van der Plicht, 2000).

millennia at ca. 45,000 years ago. Nevertheless there is a wealth of important information on ^{14}C variations in the past available in these records. The dates from the laminated sediment of Lake Suigetsu, at present, form the only terrestrial data set. But considering the large discrepancies with other data sets, it needs to be confirmed. An independent terrestrial, high resolution $\Delta^{14}C$ record is needed before all observed events can be explained.

The curve INTCAL98 carries the status 'recommended' by the international Radiocarbon community (Stuiver and Van der Plicht, 1998). This calibration curve is based on dendrochronology for the largest part, with extension to 15585 calBP based on paired ^{14}C/U-series dates obtained from corals.

The INTCAL98 curve remains recommended, but relatively small adjustments ($\approx$100 ^{14}C years) for the marine part are likely.

Beyond INTCAL98, a calibration curve for times to 20,000 cal BP is emerging based on both Lake Suigetsu (Kitagawa and Van der Plicht, 2000) and the Cariaco Basin (Southon et al., 2000), supported by some datapoints from the U-series dated corals that already existed (Bard et al., 1998) and the Polish varves (Goslar et al., 2000b). Efforts are already underway to prepare decisions at the next Radiocarbon conference.

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Note added in proof

In this paper, the calibration of the ^{14}C timescale for the complete dating range of ca. 50,000 years is discussed. Reference is made to a new dataset based on speleothems from the Bahamas, which was presented at the 17th International Radiocarbon Conference in Jerusalem (Beck et al., 2000). These data have now been published (Beck et al., 2001).

This means there are at present two independent high resolution records containing information for calibrating the glacial part of the ^{14}C timescale: the varved sediment from Japan (Kitagawa and Van der Plicht, 1998; 2000) and the Bahamian speleothem (Beck et al., 2001). A few additional words are needed for further clarification. The assumptions and pitfalls for 'calibration' are discussed above and can be summarized as follows. For the varved sediment, the weakness is the possibility of miscounting varves or a hiatus in the sediment; the strength is that the ^{14}C data are terrestrial. For the speleothem, the weakness is that also here there can be a hiatus (or periods of not constant growth) and possible errors in measuring the U-isotopes; in addition, the ^{14}C data are not terrestrial.

Since both records are not consistent with each other there is a problem with calibration of the ^{14}C timescale. Both records show excursions (increased ^{14}C levels) with profound consequences for the ^{14}C calibration curve; however, the excursions are observed at different times and have very different amplitudes. Calibration curves based on both these records therefore differ many millennia. This observation is in itself a *contradictio in terminis:* calibration should in principle be based on truly absolute dates, so that calibration curves can not be different. For this reason, the term 'comparison curve' has been introduced (Van der Plicht, 2000).

Bard (2001), in an accompanying commentary to the recent speleothem publication, seems to favor the new speleothem data above the varve record. This is mainly based on his 2 datapoints (at ca. 30 and 40 ka calBP) obtained for corals dated by both ^{14}C and U/Th (these 2 datapoints are plotted in fig. 2). These 2 datapoints are clearly closer to the speleothem data than to the varve data.

But, in an additional comment on the speleothem record, Richards and Beck (2001) state that their provisional data should not be used as a calibration tool. They follow here also the term 'comparison curve', and even now show a plot where the calendar axis is not given in 'calendar age' (calBP) as was done in Beck et al. (2001); they use now '^{230}Th age' instead.

Conclusion

For times ca. 30-50,000 years ago, large excursions in cosmogenic isotope concentrations are observed in a variety of records – ^{10}Be and ^{36}Cl in icecores, ^{10}Be in marine sediments, and ^{14}C in both the varved sediment from Japan and the speleothem from the Bahamas. The excursions are observed at different times and have very different amplitudes.

For ^{14}C calibration beyond 25,000 years ago, we should describe the status as 'work in progress'. Independent confirmation of one or the other dataset is needed.

The true nature of the dramatic excursions in the speleothem, as large as 'glacial nuclear bombs' needs to be explored. Thus, calibrating e.g. archaeological samples and making conclusions on Neandertal problems, Palaeolithic cave paintings, etc. is still premature. Nevertheless, the data from both the Japanese varves and the Bahamian speleothem constitute beautiful records, promising themes for exciting research in the time to come; and – last but not least – they illustrate the power of Accelerator Mass Spectrometry (AMS) for ^{14}C dating.

Definitions

Perhaps superfluous but for clarity reasons we give the following 'dictionary' definitions:

calibrate – to fix, check or correct the graduations of a measuring instrument.

compare – to examine, in order to observe or discover similarities or differences.

Additional references

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