Radiocarbon timescale tested against magnetic and other dating methods

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A detailed comparison of conventional radiocarbon years with calendar years covering the past four centuries is given. Relatively large atmospheric 14C changes are encountered over this time, and even very precise 14C dating cannot entirely solve the problems of age calibration. By matching radiocarbon ages with ages derived from 234Th/230U, thermal luminescence and magnetic dating, the 14C timescale is shown to deviate by a maximum of 2,000 yr over the 9,000-32,000 yr BP interval.

A radiocarbon age is calculated by comparing the present-day measured 14C activity with an atmospheric 14C level which is assumed to have been constant in the past. This assumption, however, is only a first order approximation of reality, and radiocarbon ages often, therefore, deviate from calendar (solar) chronologies. Past atmospheric 14C levels are determined by measuring the present-day 14C activity of tree rings of known age. Palaeo-14C levels are then calculated by applying a correction for the 14C decay since the time of formation of the wood. Several sequences of dendrochronologically dated trees exist, of which the longest continuous one is for bristlecone pine trees of the White Mountains. The bristlecone pine series has yielded palaeo-atmospheric 14C levels back to ~7,500 yr BP (where BP is before AD 1950).

The tree-ring studies demonstrate convincingly the appreciable changes in past 14C levels. A long-term change in 14C levels causes radiocarbon ages to be 800 yr too young by 7,000 yr BP. This long-term increase in 14C level between about 2,500 and 7,000 yr BP is well known, but the shorter term variations lasting a few centuries or less are more difficult to assess. Here two different aspects of the calibration problem are discussed: (1) the 'short-term' atmospheric 14C variations during the past 450 yr; and (2) the possible long-term timescale changes beyond the time span covered by tree-ring research.

Calibration of the post-AD 1500 radiocarbon timescale

Wood from Douglas fir from Washington was used for the 14C variations study. Although single year measurements are now being made to complete the record, the calibration curve reported here is mainly based on the measured 14C activity of 10-yr (decadal) wood sections. For post-AD 1820 wood, single year measurements were averaged to give decadal means, resulting in smaller standard deviations for this time interval (Fig. 1). The precision of each 14C measurement was 2% or better, which is equivalent to an age error of 16 yr or less. The specific details of the experimental technique will be reported elsewhere (in preparation).

For most of the samples reported here the de Vries type of sample treatment was used. This treatment does not, however, remove all components added to the wood after the year of formation11. Extensive experiments with Douglas fir wood show that the feedback of the natural variations, with the de Vries treatment, results in maximum errors of 0.3%, in 14C, or 2.4 radiocarbon yr. For twentieth-century wood the influence of nuclear bomb 14C is much more pronounced, and pure a cellulose fractions were used for the post-AD 1910 data points in Fig. 1.

An important aspect of 14C studies are the climatic implications. A detailed comparison between 14C and climatic record will be made elsewhere, together with carbon

Fig. 1 The relationship between conventional radiocarbon ages (3,568 yr half life) and tree-ring calibrated calendar years. (Different calendar years often have the same radiocarbon age). The width of the curve is twice the counting error in the measurements. The total error in the measurement process is only a few 0.1% larger than the counting error. 0 yr BP is AD 1950.
extensive series of single-year Douglas fir measurements each with 2% precision, do not show statistically significant 11-yr periodicity between AD 1820 and 1950 (M.S., in prep).

The standard experience with analytical work is the experimental problems introduce larger variability. More interlaboratory calibration checks of high precision are needed to solve some of the problems mentioned. One should remember, however, that not all 14C variability on a century scale can be attributed to experimental problems. For instance, in the Douglas fir study the difference in atmospheric 14C levels between the beginning and end of the eighteenth century is equal to 12 times the standard deviation of single measurements.

Radioisotopic timescale changes between 9,000 and 32,000 yr BP

Because the 2,000-7,000 yr long-term change in atmospheric 14C level results in a radiocarbon age anomaly of 800 yr for 7,000-yr-old samples, the possibility of a much larger age discrepancy further back in time exists. It is shown here that such age anomalies are most likely restricted to less than 7,000 yr over a 32,000-yr interval.

Some evidence comes from the 230Th/210Pb ages of Searles Lake sediment. This Californian lake has been desiccated in modern times, but it has experienced several pluvial intervals in the past. A large number of published 14C dates give the absolute chronology of the sediments." Additional analysis of organic materials of the so-called Lower Salt stratum gave a very precise 14C record." This was used by Peng et al." for a comparison with their 230Th chronology of Lower Salt deposits.

The 230Th ages are based on absolute decay rates, and are fully independent of atmospheric 14C changes. Agreement between both dating methods would therefore indicate the lack of appreciable anomalies in 14C dates due to atmospheric 14C changes.

A comparison of the 14C and 230Th ages is given in Fig. 3 for the Lower Salt sediments (the 22,000-32,000-yr series). The thorium ages are for salt layers bedded between organic muds. The 14C ages in Fig. 3 are obtained by taking the mid point of the 14C age of the top of the organic layer below the salt layer; and the 14C age of the bottom portion of the organic layer above the salt. The standard errors in the 14C determinations are ~400 yr. The standard errors in the Th measurements depend on the number of samples analysed per salt layer and range from 800 to 1,500 yr. All data points (C) in Fig. 3 are within 2 standard deviations from the ideal one-to-one relationship. We conclude that this type of agreement can only be obtained if both methods give ages close to the actual age of deposition. 14C age anomalies exceeding 2,000 yr seem unlikely over the 22,000-32,000-yr interval.

Further evidence on the reliability of 14C dating can be derived from Berry's thermoluminescence studies of Hawaiian basaltic flows from Mauna Loa and Kilauea are part of these studies. The 14C age were derived from organic materials associated with these flows. The specific thermoluminescence correlates linearly with the 14C ages ranging from ~3,000 yr to 17,000 yr. The crossed data points in Fig. 3 near 10,100 and 17,000 radiocarbon yr were derived from this study.

The cyclicity in the pattern of secular variation of the geomagnetic field provides additional information on long-term changes in atmospheric 14C content. A classic example of these variations is found in sediment of Lake Windermere. There are clear patterns of east to west cyclical shifts in declination, caused by changes in the non-dipole component of the Earth geomagnetic field. Although the
position of the east–west maxima cannot always be precisely determined, the magnetic declination pattern shows an amazingly stable periodicity over the past 8,000 tree-ring calibrated years (Fig. 4). The older $^{14}C$ dates beyond tree-ring calibration (maximum 8) also fall on the line if an age correction of 800 yr is applied at about 11,000 yr BP. This implies a 10% higher atmospheric $^{14}C$ level near 11,000 calendar yr BP. However, the last maximum is not precisely determined magnetically, and more evidence is needed to support the above conclusion. Varve studies of Lake of the Clouds, however, do support the concept of a similar higher $^{14}C$ level for early Holocene time.

The main geomagnetic dipole does not seem to be the source of the secular oscillations. The oscillations are caused by the non-dipole Earth magnetic field, of which the intensity is only a fraction of the main dipole intensity. Thus, the oscillations of the non-dipole component itself cannot materially change atmospheric $^{14}C$ production. The $^{14}C$ dates therefore are independent of the registered non-dipole geomagnetic oscillations. The contours of the non-dipole field form several closed loops around centres of maximum strength, and can be explained by a number of radially placed dipoles in the Earth’s outer core. The magnetic oscillations of these radial dipoles need not have identical periodicities. Detailed $^{14}C$ control is often lacking in geomagnetic profile studies, and a similar stable periodicity as found for Lake Windermere has been found only in Black Sea sediments. Here Cresson used $^{14}C$ dating to demonstrate a constant periodicity of magnetic inclination similar to that of Lake Windermere. Our assumption of constant periodicity is a weak point in the $^{14}C$ against magnetic age calibration, but it seems to be a very reasonable and straightforward concept. The excellent agreement between the magnetic and $^{207}Th/^{230}U$ date near 24,000 yr BP (Fig. 3) supports the soundness of the assumption of constant periodicity of magnetic variations.

At a depth of 55 cm in the Black Sea core the first detectable minimum in geomagnetic inclination is encountered. The approximate $^{14}C$ age at this depth is 6,040 yr (based on interpolation between two dates of 7,000 and 3,900 yr BP (ref. 18)). The actual magnetic periodicity in the Black Sea region is not known because measurements covering the past 6,000 yr are lacking. Hence the assumption of equal periodicity as encountered at Lake Windermere.

The tree-ring calibrated age for a radiocarbon age of 6,040 yr BP is about 6,600 calendar yr. Magnetic ages (M) down the core are here calculated according to $M = 6,600 - 680 + 2,810$, where $S$ equals the number of magnetic cycles below the first inclination minimum at 55 cm depth in the core. There are four $^{14}C$ ages available for this core beyond the tree-ring chronology: 8,600 ± 150 yr BP at a depth of 120 cm; 13,850 ± 210 yr BP at a depth of 330 cm; 16,900 ± 270 yr BP at a depth of 580 cm; and 22,830 ± 800 yr BP at a depth of 1,120 cm (ref. 18). The number of magnetic cycles, $S$, below the first inclination minimum in the core are, respectively, 0, 1, 2, 3, 4, and 6. Thus magnetic ages are, respectively, 8, 9, 10, 14, 200, 17,800, and 24,100 yr are obtained.

The data points (●) in Fig. 3 are based on the above comparison of $^{14}C$ and magnetic ages. The error bar in the magnetic age is calculated by estimating the error in the determination of the position of the magnetic inclination to be ±0.2 $S$ units.

The $^{14}C$ ages, as plotted in Fig. 3, deviate at a maximum 2,000 yr from the ideal one-to-one relationship. Due to the relatively wide spacing of the data points, it is possible to draw a curve with some oscillations at selected ages. However, proof for such oscillations is lacking. The data given here should conservatively be interpreted as evidence for limited $^{14}C$ timescale variability between 9,000 and 32,000 yr BP.

Nearly all Fig. 3 points have $^{14}C$ ages slightly too young; these were calculated with the conventional 5,568 yr half-life. Using the more precise 5,730 yr value for the half-life increases the $^{14}C$ ages by 3%. Such a correction improves the agreement between $^{14}C$ ages and ages derived from the other methods, and systematically younger $^{14}C$ ages are no longer a problem. The half-life correction reduces the average radiocarbon age dispersion (Fig. 3) to only 700 yr.

Varve studies of Lake of the Clouds sediment have shown that somewhat higher atmospheric $^{14}C$ levels were encountered in the early Holocene. An increase in this anomaly further back in time seems unlikely in view of the good age agreement cited above. Evidently, the changes in $^{14}C$ distribution between atmosphere and oceans are relatively small for glacial–interglacial climatic changes.

Different processes, working in the opposite direction, seem to influence atmospheric $^{14}C$ level during glacial
episodes. A reduction in $^{13}$C atmosphere-ocean exchange rate may be caused by lower sea level and increased ice cover. Downward advection of $^{13}$C into the deep ocean may be less because of a reduced rate of bottom water formation in the Atlantic. A reduced rate of bottom water formation also reduces world-wide rate of oceanic upwelling, and brings less $^{13}$C deficient water to the surface. All the above processes would point to a higher atmospheric $^{13}$C level. However, oceanic thermal gradients are less during glacial, and downward eddy diffusive transport of $^{13}$C over the oceanic thermocline increases. Such transport also increases when vertical upward advection velocities are reduced. Whatever processes are occurring, their variability during glacial and interglacial times evidently has not resulted in a large change in atmospheric $^{13}$C level.

Distortions in $^{13}$C timescale can also be introduced by the Earth's geomagnetic field reversals. Age anomalies up to a few thousand years can be expected for 'events' lasting a few thousand years", and are not entirely excluded by the data presented here. It should also be noted that thermoluminescence and $^{13}$C dates of the Lake Mungo geomagnetic polarity excursion near 30,000 radiocarbon yr $^+$ agree with each other within the 4,300 yr thermoluminescence age error.

It has been standard practice in geochronology to compare other dating methods with $^{13}$C dating mainly to prove the reliability of these other methods. Here, the best examples of these other methods ($^{235}$Th, thermoluminescence and magnetic dating) are used to check on the reliability of $^{13}$C dating. The information thus obtained supports the concept of a reliable $^{13}$C timescale back to 32,000 yr $^+$, within a maximum error of about 2,000 yr.

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