Radiocarbon timescale tested against magnetic and other dating methods

Minze Stuiver

Departments of Geological Sciences and Zoology, University of Washington, Seattle, Washington 98195

A detailed comparison of conventional radiocarbon years with calendar years covering the past four centuries is given. Relatively large atmospheric ^{14}C changes are encountered over this time, and even very precise ^{14}C dating cannot entirely solve the problems of age calibration. By matching radiocarbon ages with ages derived from ^{230}Th/^{234}U, thermoluminescence and magnetic dating, the ^{14}C 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 ^{14}C activity with an atmospheric ^{14}C 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 ^{14}C levels are determined by measuring the present-day ^{14}C activity of tree rings of known age. Palaeo-^{14}C levels are then calculated by applying a correction for the ^{14}C 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 ^{14}C levels back to ~7,500 yr BP (where BP is before AD 1950).

The tree-ring studies demonstrate convincingly the appreciable changes in past ^{14}C levels[1–3]. A long-term change in ^{14}C levels causes radiocarbon ages to be 800 yr too young by 7,000 yr BP. This long-term increase in ^{14}C 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 ^{14}C variations during the past 450 yr; and (2) the possible long-term timescale changes beyond the time span covered by tree-ring research.

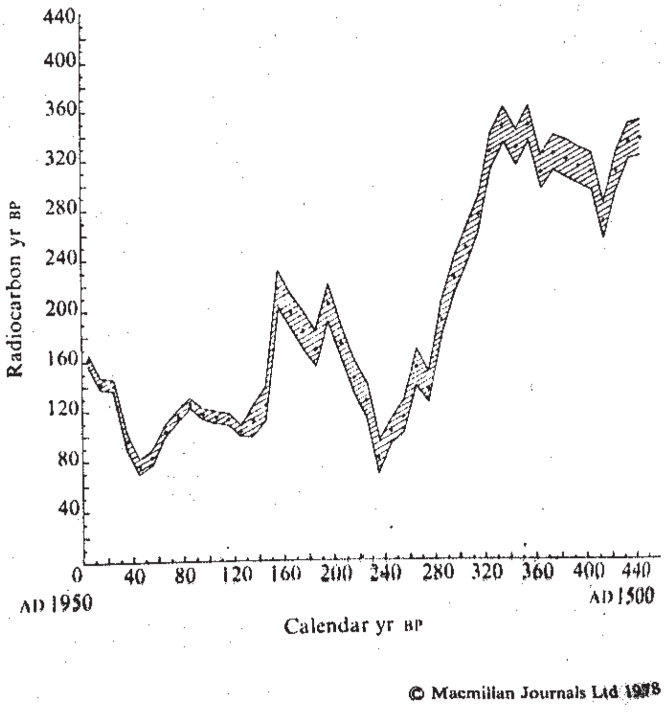
Calibration of the post-AD 1500 radiocarbon timescale

Wood from Douglas fir from Washington was used for the ^{14}C 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 ^{14}C 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 ^{14}C 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 formation[4,5]. 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 ^{14}C, or 2.4 radiocarbon yr. For twentieth-century wood the influence of nuclear bomb ^{14}C is much more pronounced, and pure α cellulose fractions were used for the post-AD 1910 data points in Fig. 1.

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

Fig. 1 The relationship between conventional radiocarbon ages[22] (5,568 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‰s larger than the counting error. 0 yr BP is AD 1950.



0028-0836/78/0273—0271$01.00

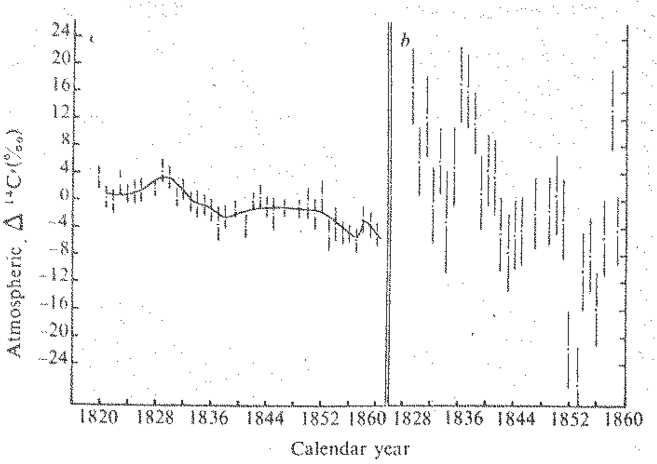


Fig. 2 A comparison of the atmospheric ^{14}C variability obtained from two series of measurements, one for Douglas fir from Washington (*a*) 48° N and one for oak[7] from the Forest of Dean (*b*) 52°N.

reservoir modelling of the ^{14}C variations. The reduction in twentieth century atmospheric ^{14}C levels by industrial CO_2 release will also be discussed elsewhere. This anthropogenic lowering of ^{14}C level (Suess effect) results in an increase in radiocarbon ages for the twentieth century (Fig. 1).

The width of the calibration curve in Fig. 1 is twice the standard deviation in the ^{14}C activity measured for single decade samples. The curve shows that a lifetime in radiocarbon years would have many surprises: the years can be stretched or compressed, or even change sign. Instead of ageing by 100 calendar years in the eighteenth century, one would be 130 radiocarbon years younger near the end of the century. In the seventeenth century, however, the ageing process accelerates to about 260 radiocarbon yr. Clearly, the short-term calibration problems are of major concern in chronological studies where age separation of about a century is needed.

Even when a radiocarbon age is determined with a precision of ±16 yr, or better, there is only one interval of a few decades near AD 1650 that potentially yields only one calendar date for one radiocarbon age. In all other instances either multiple calendar dates, or a much broader continuous spectrum of calendar ages, are derived from a single radiocarbon date.

Not all time intervals have the fairly large ^{14}C variability found for the past four centuries. Pearson *et al.*[5] have shown ^{14}C variability around the main trend to be only ±6‰ (±50 yr) in a European oak series between 3,600 and 4,600 radiocarbon yr BP. Here the variabilty of ±50 yr over ~1,000 yr interval is much less than the variability of ~±120 yr encountered in the Douglas fir study over the past 450 yr. The oak study demonstrates the existence of time intervals where detailed age calibration will yield more positive results than given here for the past 450 yr.

Previous reports by Suess on bristlecone pine wood[3] show a somewhat larger ^{14}C variability than found in the European oak[6]. Similarly, although our study shows in itself large changes on a century scale, the work on single-year tree rings shows much less variability in annual ^{14}C changes than reported by Baxter and Farmer for an English oak from the forest of Dean[7]. The results obtained for the forest of Dean oak were thought to prove the existence of an 11-yr-solar cycle with a ^{14}C amplitude of several per cent change in ^{14}C. These data conflict with a twentieth-century tree ring series measured at the University of Arizona[8], and also are contradicted by the small year to year changes in the Pacific Northwest Douglas fir (Fig. 2). In fact, a more extensive series of single-year Douglas fir measurements each with 2‰ precision, do not show statistically significan 11-yr periodicity between AD 1820 and 1950 (M.S., in preparation).

The standard experience with analytical work is that 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 ^{14}C variability on a century scale can be attributed to experimental problems. For instance, in the Douglas fir study the difference in atmospheric ^{14}C level between the beginning and end of the eighteenth century is equal to 12 times the standard deviation of single measurements.

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

Because the 2,000–7,000 yr long-term change in atmospheric ^{14}C 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 2,000 yr over a 32,000-yr-interval.

Some evidence comes from the ^{230}Th/^{234}U 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 ^{14}C dates give the absolute chronology of the sediments[9–10]. Additional ^{14}C analysis of organic materials of the so-called Lower Salt stratum gave a very precise ^{14}C record[11]. This was used by Peng *et al.*[12] for a comparison with their ^{230}Th chronology of Lower Salt deposits.

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

A comparison of the ^{14}C and ^{230}Th 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 ^{14}C ages in Fig. 3 are obtained by taking the mid point of the ^{14}C age of the top of the organic layer below the salt layer; and the ^{14}C age of the bottom portion of the organic layer above the salt. The standard errors in the ^{14}C 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 (○) 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. ^{14}C age anomalies exceeding 2,000 yr seem unlikely over the 22,000–32,000 yr BP interval.

Further evidence on the reliability of ^{14}C dating can be derived from Berry's thermoluminescence studies of Hawaiian basalts[13]. Four tholeiitic basalt flows from Mauna Loa and Kilauea are part of these studies. The ^{14}C ages were derived from organic materials associated with these flows. The specific thermoluminescence correlates linearly with the ^{14}C ages ranging from ~3,000 yr to 17,000 yr. The crossed data points in Fig. 3 near 10,100 and 17,400 radiocarbon yr were derived from this study.

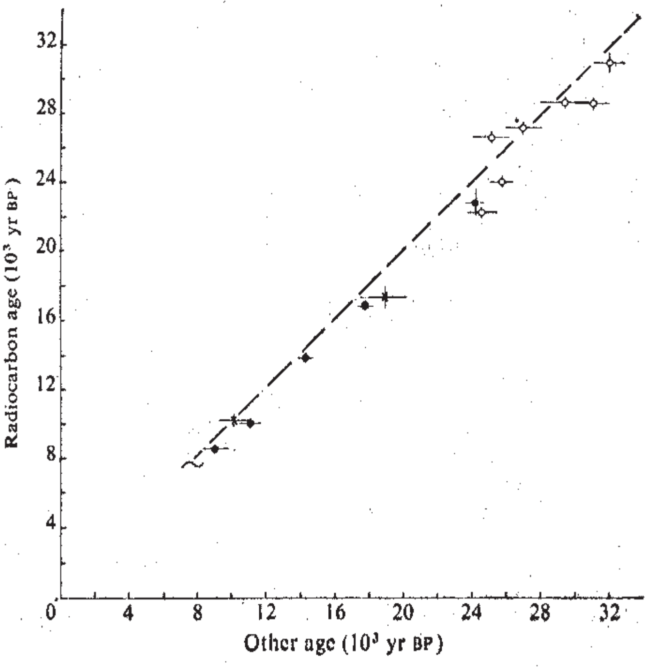
The cyclicity in the pattern of secular variation of the geomagnetic field provides additional information on long-term changes in atmospheric ^{14}C content. A classic example of these variations is found in sediment of Lake Windermere[14]. There are clear patterns of east to west cyclic shifts in declination, 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 date beyond tree-ring calibration (maximum 8) also falls 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[15].

The main geomagnetic dipole does not seem to be the source of the secular oscillations[16]. 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 sediment[17]. Here Creer 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 ^{230}Th 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 3,090 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.

Fig. 3 A comparison of ^{14}C ages with ages determined through other geochronological methods. These include ^{230}Th/^{234}U dates on lake sediments (○), thermoluminescence dates of basalt (×) and magnetic dates (●). Vertical and horizontal bars denote one standard deviation. The dashed line indicates the ideal one-to-one relationship.



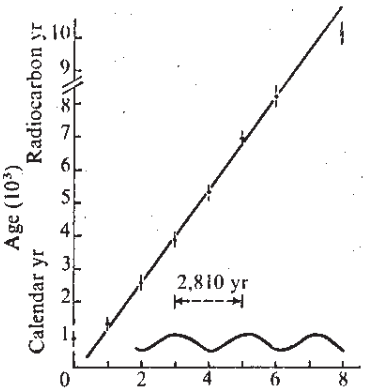


Fig. 4 Geomagnetic declination oscillation index number of Lake Windermere sediment plotted against tree-ring corrected ^{14}C dates. The index number was obtained by consecutive numbering of the geomagnetic extrema in declination. Tree-ring age calibration of the ^{14}C date near 10,000 yr (×) is not possible. The sinusoidal curve is a visual aid only.

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 $M = 6{,}600 + 2{,}810S$, 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, 0.82, 2.7, 4.0, and 6.2 at these depths[17]. Thus magnetic ages of, respectively, 8,900, 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 $\pm 0.2\ S$ 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 fairly 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[15]. 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 ^{14}C atmosphere–ocean exchange rate may be caused by lower sealevel and increased ice cover. Downward advection of ^{14}C into the deep ocean may be less because of a reduced rate of bottom water formation in the Atlantic[19,20]. A reduced rate of bottom water formation also reduces world-wide rate of oceanic upwelling, and brings less ^{14}C deficient water to the surface. All the above processes would point to a higher atmospheric ^{14}C level. However, oceanic thermal gradients are less during glacials, and downward eddy diffusive transport of ^{14}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 ^{14}C level.

Distortions in ^{14}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[21], and are not entirely excluded by the data presented here. It should also be noted that thermoluminescence and ^{14}C dates of the Lake Mungo geomagnetic polarity excursion near 30,000 radiocarbon yr BP agree with each other within the 4,300 yr thermoluminescence age error[23].

It has been standard practice in geochronology to compare other dating methods with ^{14}C dating mainly to prove the reliability of these other methods. Here, the best examples of these other methods (^{230}Th, thermoluminescence and magnetic dating) are used to check on the reliability of ^{14}C dating. The information thus obtained supports th concept of a reliable ^{14}C timescale back to 32,000 yr BP, within a maximum error of about 2,000 yr.

This work was supported by NSF grant EAR 768159 Geochemistry Program and ATM 75-22650, Climat Dynamics Program.

Received 23 January; accepted 22 March 1978.

1. Damon, P. E. *Radiocarbon Variations and Absolute Chronology* (ed. Olsson, I. U.) 571–594 (Interscience, New York, 1970).
2. Stuiver, M. *Science* **149**, 533–535 (1965).
3. Suess, H. E. *Radiocarbon Variations and Absolute Chronology* (ed. Olsson, I. U.) 303–312 (Interscience, New York, 1970).
4. Cain, W. F. & Suess, H. E. *J. geophys. Res.* **81**, 3688–3694 (1976).
5. Tans, P. P., De Jong, A. F. M. & Mook, W. G. *Nature* **271**, 234–23 (1978).
6. Pearson, G. W., Pilcher, J. R., Baillie, M. G. L. & Hillam, J. *Nature* **270**, 25–28 (1977).
7. Baxter, M. S. & Farmer, J. G. *Earth Planet. Sci. Lett.* **20**, 295–299 (1973).
8. Damon, P. E., Long, A. & Wallick, E. I. *Earth planet. Sci. Lett.* **20**, 300–306 (1973).
9. Smith, G. I. in *Proc. VII Congr. Int. Ass. Quat. Res.* (eds Morrison, R. B. & Wright, H. E., Jr) **8**, 293 (University of Utah Press, 1968).
10. Stuiver, M. *Am. J. Sci.* **262**, 377–392 (1964).
11. Stuiver, M. *Radiocarbon* (in the press).
12. Peng, T. H., Goddard, J. & Broecker, W. S. *Quat. Res.* (in the press).
13. Berry, A. L. *J. geophys. Res.* **78**, 6863–6867 (1973).
14. Mackereth, F. H. J. *Earth planet. Sci. Lett.* **12**, 332–338 (1971).
15. Stuiver, M. *Nature* **228**, 454–455 (1970).
16. Creer, K. M., Gross, D. L. & Linebeck, J. A. *Geol. Soc. Am. Bull.* **87**, 531–540 (1976).
17. Creer, K. M. *Earth planet. Sci. Lett.* **23**, 34–42 (1974).
18. Ross, D. A. & Degens, E. T. *AAPG Mem.* **20**, 183–199 (1974).
19. Streeter, S. S. *Geol. Soc. Am.* 1192 (1977).
20. Schnitker, D. *Nature* **248**, 385–387 (1974).
21. Stuiver, M. in *Late Cenozoic Glacial Ages* (ed. Turekian, K. K.) 57–70 (Yale University Press, New Haven, 1970).
22. Stuiver, M. & Polach, H. A. *Radiocarbon* **19**, 355–363 (1977).
23 Huxtable, J. & Aitken, M. J. *Nature* **265**, 40–41 (1977).