# Secular variations in carbon-14 and their geophysical implications[§]

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**Cosmic ray production of the radioactive carbon isotope $^{14}$C, which is the basis for the radiocarbon dating method, has not remained constant over time. The result is that radiocarbon dates show significant deviations from the true age. The identification of the causes and magnitudes of these deviations has created a new tool that is contributing to the investigation of different geophysical phenomena. Variations in the activity of the Sun produce fluctuations of the $^{14}$C level in the atmosphere and biosphere, with resulting distortions in radiocarbon dates of up to 200 years. The detailed record of these fluctuations over the past 12 000 years provides a valuable data set for assessing the effect of changes in solar activity on global climate. The modulation of the cosmic ray flux by the magnetic dipole field of the Earth causes more significant longer-term changes in the production rate of $^{14}$C. Once the $^{14}$C levels in the environment back to 50 000 years ago have been established with sufficient precision, they will become an important indicator of changes in the geomagnetic moment and facilitate the identification of local non-dipole effects that occur at various places on Earth.**

## Introduction

The radioactive carbon isotope, $^{14}$C, on which the radiocarbon dating method is based, is continuously produced in the atmosphere by the action of the cosmic rays on nitrogen in the air. These carbon atoms are rapidly oxidized and, together with common carbon dioxide, are gradually assimilated into the biosphere and mixed into the oceans. With a half-life of 5730 years, a balance is established between radioactive decay and cosmic ray production. Initially it was assumed that the rate of production was a constant and that the level of $^{14}$C in the exchangeable carbon reservoir had not changed in the past, that is, that the $^{14}$C/$^{12}$C ratio in living organisms and in the oceans had always been as it is today. Thus, by comparing the $^{14}$C level of dead organic matter with the present value, one could deduce when the plant or animal had died. By analysing samples of known age, the discoverer of the technique, Willard F. Libby and co-workers found this to be approximately true,[1–3] but the suspicion soon arose that discrepancies did exist.

A minor factor influencing the calculated ages concerns the half-life of the isotope. Originally, Libby estimated this to be 5568 years, but subsequent more elaborate determinations of the decay constant produced a value of 5730 ± 30 years. To avoid confusion, the radiocarbon community in 1964 decided to continue using the old half-life rather than the 3% higher value and henceforth to report results as 'conventional radiocarbon ages before the present (BP)', where the present was defined as AD 1950. The reason for this is that there are also other factors which cause the age to differ from the historical date, as will be seen below, and these factors need to be taken into account to arrive at an actual true age.

## Fluctuations during the Holocene

Early $^{14}$C analyses of material from the Roman period tended to provide satisfactory dates, but Bronze Age samples appeared to be too young. A case in point was the results obtained by Hessel de Vries in Groningen[4] for early Egyptian sites, which had been dated more or less accurately by means of ancient historical documents. Some examples of such discrepancies are listed in Table 1.[5] They show that the radiocarbon ages are a few hundred years younger than the expected historical dates.

In 1957, Karl Otto Münnich in Heidelberg also noted that the early sixteenth-century annual rings of dendrochronologically dated oak trees appeared to be some 160 years too young when compared with samples from the mid nineteenth century.[6] This prompted de Vries to investigate the matter in more detail. Using the bole studied by Münnich, he showed that significant fluctuations in the $^{14}$C level had occurred over the last few centuries.[7]

Subsequently, Hans Suess, working at La Jolla in California, undertook the systematic analysis of wood from the ancient bristlecone pine trees that grow in the White Mountains of California, using dendrochronologically dated material from the Tree-ring Research Laboratory in Tuscon, Arizona. Suess confirmed the 'de Vries effect' and also established that the $^{14}$C level beyond 2000 years ago increasingly deviates from the expected value.[8] By 1970 he had extended the measurements back to 5500 BC.[9] The data tended to explain the differences between the radiocarbon results and the early Egyptian chronology mentioned above.

Since these early days, a vast amount of effort has been invested in accurately recording the variations in the radiocarbon time scale. It resulted in the publication in 1986 of a volume containing high-precision calibration curves by means of which $^{14}$C ages can be converted to historic dates.[10] Four laboratories, of which Pretoria was one, were mainly involved in this process, but the most comprehensive data set was produced by Minze Stuiver and co-workers in Seattle.[11] Much of their data was based on tree-ring material from the South German dendrochronological sequence derived from sub-fossil oak trunks recovered from river gravels.

In Pretoria we also used samples from the South German oak sequence, but specifically focused on the period covering the Early Bronze Age in the Near East and Egypt, because it represented the transition from pre-history to recorded history.[12] The results of our effort are reproduced in Fig. 1. This calibration curve shows that a $^{14}$C age determination of, for instance, 4300 BP (i.e. before AD 1950), corresponding to a 'conventional' $^{14}$C date of 2350 BC, actually dates to 2900 BC, or 550 years earlier. Similarly, the three results for the Saqqara tombs in Table 1 give a combined radiocarbon age of 4410 ± 33 years BP (2460 BC), which calibrates to 3010 BC. The beginning of the First Dynasty after the unification of Egypt would have been some 100 to 150 years earlier, i.e., at *c.* 3130 BC. Furthermore, the calibrated date for the

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§The article is a brief survey of the rather extensive subject matter. It presents the major findings from a historical perspective, with emphasis on the author's personal experience. Sufficient references are, however, given for further reading.

**Table 1.** Examples of early radiocarbon dates from Ancient Egypt.[5]

| Lab. no. | Sample | Historical date BC | Conv. $^{14}$C date BC |
|---|---|---|---|
| **Middle Kingdom** | | | |
| GrN-1178 | Dyn. XII. Dahshur, Funerary boat of Sesostris III | 1843 | 1635 ± 40 |
| GrN-1177 | Dyn. XI. Deir el Bahri, Pyramid of Mentuhotep II/III | 2000 | 1705 ± 40 |
| **Old Kingdom** | | | |
| GrN-5657 | Dyn. IV. Abu Roash, Pyramid of Radjedef, wood | 2570 | 2140 ± 40 |
| GrN-5658 | charcoal from same | 2570 | 2135 ± 90 |
| **Early Dynastic Period** | | | |
| GrN-902 | Dyn. I. Saqqara Tomb, reign of Ka | 3000 | 2435 ± 70 |
| GrN-689 | Dyn. I. Saqqara Tomb, reign of Den | 3040 | 2490 ± 100 |
| GrN-1100 | Dyn. I. Saqqara Tomb, reign of Zet | 3060 | 2465 ± 40 |
| GrN-4704 | Dyn. I. Arad, Israel | 3200–3000 | 2385 ± 65 |

Abu Roash pyramid of Dynasty IV (Table 1) is *c.* 2580 BC and, if one accepts the historic evidence that it was constructed 500 years after unification, this places the event at *c.* 3080 BC. The calibrated radiocarbon dates are thus in good agreement with the 'long' historical chronology, i.e. 3100 BC, adopted by many historians today.[13]

In 1986 our high-precision Pretoria data turned out to be systematically 20 years older than those of Stuiver. Subsequently, Stuiver revised his measurements and republished them in 1993.[14] This brought the two data sets into excellent agreement. Our 173 data points for the third millennium BC were now, on average, 2.9 ± 1.8 years younger than his, and those for the 19th century AD, 1.7 ± 3.6 years younger.[15] Recently, Stuiver again slightly adjusted his data[16] and a new combined calibration curve, INTCAL98, extending back to 11 857 years ago, was presented in a special volume.[17] Our data set now appears to be 6 years older when compared with the INTCAL98 data. These differences are, however, insignificant considering that the uncertainty of a normal radiocarbon date is ±50 years or more.

The problem with comparing results from different laboratories is that there is a limit to the accuracy with which the reference standards can be assessed. It requires regular measurements over the years to adjust for any slight changes in the operation of the detectors. Most laboratories can probably claim precision no better than ±20 years for their equipment.

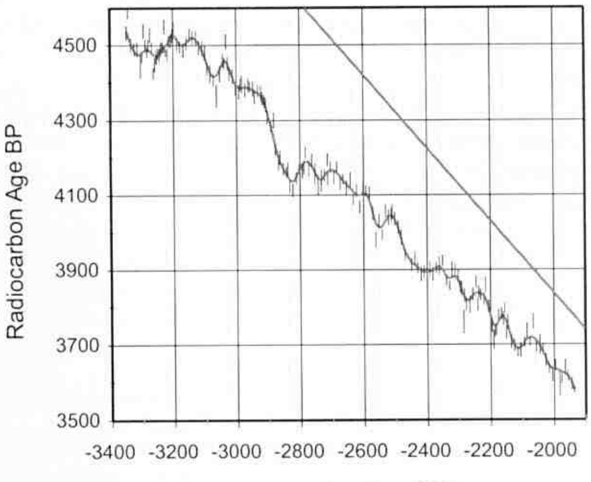


**Fig. 1.** Radiocarbon calibration curve for the Early Bronze Age in the eastern Mediterranean.[15] The straight diagonal line shows the expected correlation if the $^{14}$C level had always been constant at the present-day standardized value and taking into account that the conventional half-life of $^{14}$C is used for age calculation rather than the correct value. The vertical lines give the standard errors of the 173 samples analysed, and the continous line is a spline curve through the points. It is seen that, in the third millennium BC, the radiocarbon dates are several hundred years younger than the actual dates.

## Causes of variations in $^{14}$C production

The level of $^{14}$C in the environment is primarily determined by the rate of production by the cosmic rays and the regular and constant radioactive decay of the isotope. Current evidence derived from meteorites shows that the intensity of the galactic cosmic rays has not markedly varied over time,[18] but there are two factors that are variable and which modulate the flux of cosmic particles that impinge on the Earth's atmosphere. These are: i) the magnetic fields associated with the interplanetary plasma emitted by the Sun, which diverts especially low-energy particles from reaching the Earth's atmosphere and producing $^{14}$C; and ii) the geomagnetic field that forms a shield around the Earth and which has the same effect.

### Fluctuations in solar activity

There is a close correlation between the solar emission of plasma and the number of spots on the face of the Sun, so that sunspots can serve as proxy data for past solar activity. The well-known eleven-year sunspot cycle has only a very small effect on the $^{14}$C level[18,19] because the inertia of the exchangeable carbon system on Earth is too great.[18] The more gradual changes in the intensity of solar activity, on the other hand, do show a correlation with $^{14}$C production.[20–22] In Fig. 2 the sunspot data over the past millennium that were compiled by Schove from documented observations[23] are compared with the $^{14}$C levels in tree-rings, adjusted for radioactive decay. The figure clearly indicates that, during periods of low solar activity, the $^{14}$C level rises and *vice versa*.

Recognition of this inverse correlation suggests a useful geophysical application of the $^{14}$C tree-ring data: The nearly 12 000-year record of $^{14}$C fluctuations can potentially provide details of solar activity for periods far exceeding direct observations of the Sun. This is of special interest in the light of the increasing evidence that variations in solar activity have an influence on global climate.[24,25]

### Variations in the Earth's magnetic field

Solar modulation of the cosmic rays can account for an off-set of up to 200 years in radiocarbon ages. Larger deviations, such as those observed in the Egyptian samples in Table 1, call for a different explanation. It is to be found in the changing geomagnetic dipole moment.[26] In Fig. 3 the global dipole field strength is compared with the $^{14}$C data, expressed as deviations from the expected value.[27] A marked inverse correlation is evident. Quantitative calculations of this effect appear to satisfactorily explain this major component of the $^{14}$C variations during the Holocene.[18,28] Here again, $^{14}$C data of earlier periods, back to the limit of radiocarbon dating at *c.* 50 000 years, can possibly be used to identify major changes in the geomagnetic field intensity in this time range.

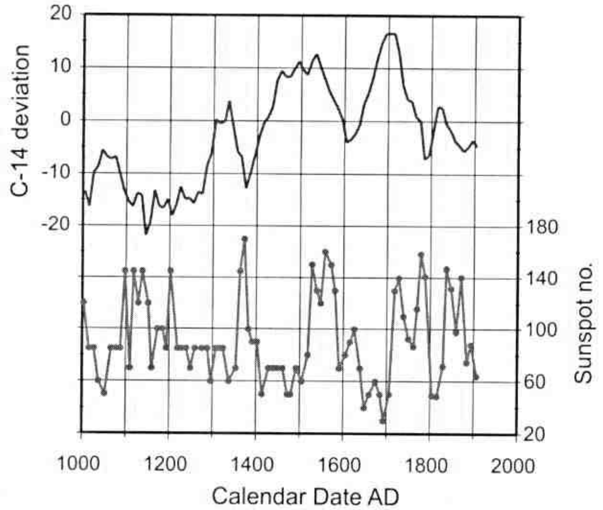


**Fig. 2.** Comparison of the atmospheric $^{14}C$ levels with the intensity of the sunspot cycles. In the upper part of the figure the deviation from the expected $^{14}C$ value in parts per thousand (‰) are shown,[17] while in the lower section the average sunspot numbers of the successive eleven-year cycles compiled from documentary records are presented.[23] It is seen that, when the sunspot values are high, the $^{14}C$ levels decrease and *vice versa*.

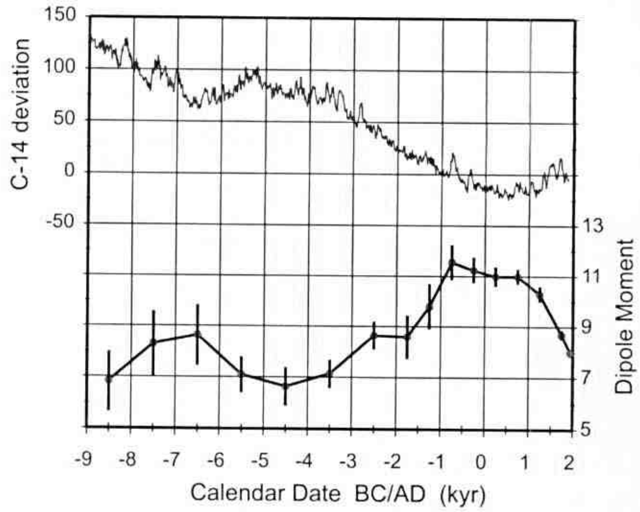


**Fig. 3.** Comparison of the relative $^{14}C$ levels over the past 11 000 years with the geomagnetic dipole moment, showing an inverse correlation. In the upper section of the figure is a spline curve through the INTCAL98 tree-ring data,[17] expressed as deviations from the expected $^{14}C$ value in parts per thousand (‰), while in the lower section, the averaged geomagnetic dipole moment is represented ($A.m^2 \times 10^{22}$).[26]

### Variations during the Upper Pleistocene

The prospect of obtaining precisely dated wood for radiocarbon dating during the Last Ice Age or Upper Pleistocene is limited. Currently, attempts are being made to extend the tree-ring sequence back into the Late Pleistocene, but the link-up with the Holocene poses a problem and the time-range that could possibly be covered will not be long. The other option is to compare radiocarbon dates with data obtained from other radiometric dating methods. At present the only technique for dating Upper Pleistocene material with sufficient precision is that of uranium-series disequilibrium dating. The two other methods that are being developed, namely, luminescence dating and electron spin resonance dating, involve too many assumptions to be useful at this stage.

The parallel use of radiocarbon and uranium-series dating does, in fact, lead to interesting results. Some of the earliest evidence for discrepancies between the two dating methods comes from the Lisan sediments in the Jordan valley, Israel. These aragonite lake deposits were U-series dated by A. Kaufman and radiocarbon dated by us.[29,30] Comparison of the results shows that the radiocarbon dates for the top and bottom of the Upper Lisan deposit are several thousand years younger than the U-series dates, while there was apparent concordance at about 30 000 years ago.[31] The data are summarized in Table 2.

#### Cango Caves stalagmite

More detailed evidence has been obtained from the analysis of a stalagmite from the Cango Caves in the southern Cape Province. This slender, 2.8-m-tall stalagmite was standing about 1 km from the mouth of the caves. With the initial assistance of Hilary Deacon, sections were gradually removed during several visits, starting in September 1978. The speleothem consists of large calcite crystals and is virtually impervious, thus making it ideal for both radiocarbon and U-series dating. A series of parallel $^{14}C$ and uranium-series analyses were performed on samples taken from the axis of the stalagmite. The results showed very regular growth, starting nearly 50 000 years ago, except for a major stratigraphic break 95 cm from the top, at which point no growth took place for about 10 000 years.

Before the results can be compared directly, it is necessary to adjust the radiocarbon ages in order to take account of the 'reservoir effect' or apparent age of the carbonate in the seepage water from which the stalagmite is formed. This adjustment can be made by considering the dates obtained for the upper 95 cm. The uranium series dates show linear growth from the present back to 6500 years ago. If 1450 years are subtracted from the radiocarbon ages and then corrected for $^{14}C$ variations using the tree-ring calibration curve, complete concordance is achieved.[32]

It is conceivable that the 'reservoir age' was different during the colder climate of the Last Ice Age. However, a similar age comparison on a stalagmite that covered the period of rapid climatic change between 15 500 and 11 000 years ago show an identical offset of 1450 years with no evidence of change over time.[33] It therefore seems reasonable to accept the same age correction for the older samples from the Cango Caves. Conservatively, a maximum uncertainty of ±500 years can be assumed

**Table 2.** Comparable radiocarbon and uranium-series dates for the Upper Lisan sediments in the Jordan Valley, Israel.[29,30]

| Position | Sample | $^{14}C$ age (yr)* | Sample | | U/Th age (yr) | Difference (yr) |
|---|---|---|---|---|---|---|
| Top | 35 D vc | 15 590 ± 110 | 35 D | | 20 000 ± 2 000 | 2 910 ± 1 420 |
| | | | 34 B | | 17 000 ± 2 000 | |
| | | | | Average | 18 500 ± 1 410 | |
| Middle | 35 B vc | 29 840 ± 390 | 35 B | | 30 500 ± 2 500 | 660 ± 2 520 |
| Base | L1 | 36 020 ± 930 | 24 B | | 37 000 ± 3 000 | 5 000 ± 1 870 |
| | | | 35 A | | 40 000 ± 2 000 | |
| | | | 33 A | | 46 000 ± 3 000 | |
| | | | | Average | 41 020 ± 1 620 | |

*$^{14}C$ dates expressed in terms of the 5730-yr half-life.

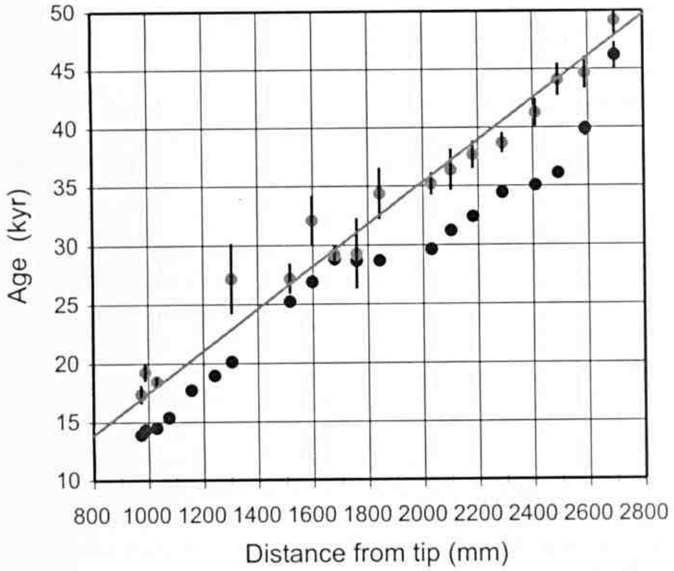


**Fig. 4.** Uranium series (●), and radiocarbon (●) dates for the lower section of the Cango Caves stalagmite V3.[34] The bars indicate the 1σ uncertainty of the measurements. The U-series ages show essentially linear growth, while the $^{14}C$ values deviate significantly from this straight line.

and this will not seriously affect the general patterns revealed in the following discussion.

After adjusting the data for an apparent initial age of 1450 years, the radiocarbon dates for the lower section can be compared with the uranium-series dates of the samples. The results are shown in Fig. 4.[32,34] In this figure it is seen that the uranium series dates show a remarkably constant growth rate of 5.6 mm/century. Second, it is obvious that the radiocarbon dates are mostly younger than the corresponding uranium-series ages, but to a varying degree. If it is accepted that these discrepancies are due to variations in the $^{14}C$ levels of the atmosphere over time, it means that these levels were considerably higher during most of the period between 49 000 and 18 000 years ago. The third remarkable feature of this figure is the very slow decrease in radiocarbon ages between 35 000 and 29 000 (U-series) years ago, and to a lesser extent, also between 41 000 and 39 000 years ago. This implies a marked decrease in the atmospheric $^{14}C$ production rate during these periods.

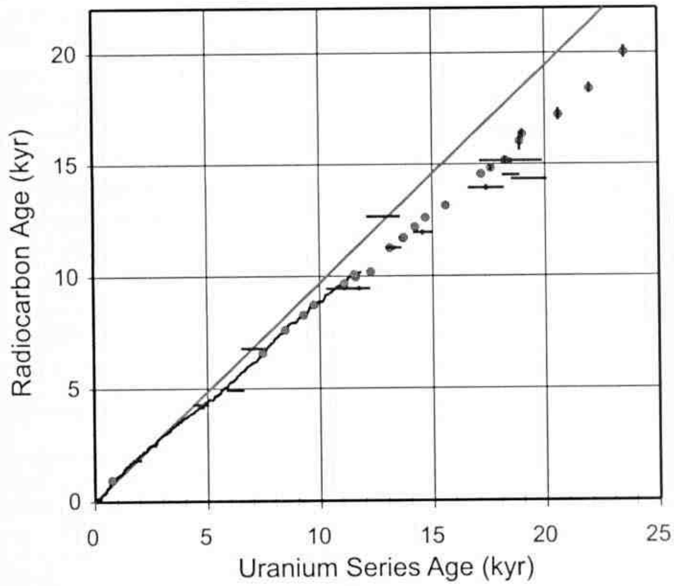


**Fig. 5.** Correlation of conventional $^{14}C$ ages with U-series ages. The straight diagonal line represents the expected values, taking the correction for the $^{14}C$ half-life into account. The line back to 11.8 kyr is a spline curve through the INTCAL98 tree-ring data.[17] The grey circles are the coral data,[38] and the bars are our stalagmite measurements whereby the length of the bars gives the 1σ uncertainty.[34] The value for the Lisan sediment at 18.5 kyr from Table 2 is also included. By 22 kyr the $^{14}C$ ages are some 3500 years too young, as shown by the vertical offset from the straight line.

### Lynd's Cave stalagmites

The stalagmite from the Cango Caves has provided a continuous record over the entire range to which radiocarbon can be applied, except for the period between 17 000 and 7000 years ago. Fortunately, we managed to obtain some good material from two stalagmites in this time range from a cave in Tasmania on which parallel dating could be undertaken.[35] Here again, a correction for the initial radiocarbon age of the cavestone must be made, and an amount of 1500 years is subtracted from each date. This is most probably correct to within ±500 years and the uncertainty does not change the general observation that the discrepancy between the radiocarbon and uranium series ages increases from *c.* 1600 years at the end of the tree-ring dated series to *c.* 2500 years at 14 kyr ago.[34,36]. Subsequently, Bard and co-workers produced a closely spaced set of age pairs that cover this time range on a core from the coral bank off Barbados.[37] By using a thermal ionization mass spectrometer they are able to achieve much more precise uranium-series dates than is the case with conventional radioactivity measurements. These authors have since added four new age pairs on a short coral sequence from Mururoa, so that their data set now covers the period back to 24 000 years ago.[38] The results, together with our data from Lynd's Cave and the younger ones from the Cango Caves, are shown in Fig. 5. The coral data confirm our findings based on the stalagmites and effectively provide a calibration curve for radiocarbon dates back into the Late Pleistocene with an accuracy of 100–200 years.

### Extension of the record

The results from the Cango Caves can be used to produce a tentative calibration curve for the period between 24 kyr and 50 kyr (Fig. 6).[34] Since age measurements with margins of error greater than ±2000 years are not useful in revealing trends in the sequence, they are not included in the figure. Some other U-series /$^{14}C$ age pairs available in the literature may be used to corroborate the validity of the major trends revealed in Fig. 6. If, as before, only such data with margins of error of less than ±2000 years are considered, these are notably the two data points on isolated coral samples reported by Bard *et al.* at 30.2 and 41.1 kyr, respectively,[38] two further results near 41 kyr obtained from sites in Europe,[39,40] and the new evaluation of Searles Lake sediment with U-series dates between 20 and 34 kyr.[41] These data, together with our relevant results, are listed in Table 3.

In the upper part of the table, the five $^{14}C$ ages are all substantially younger than the corresponding U-series dates at about 41.5 kyr. The weighted average of the difference is 5840 ± 600 yr or, if the correct half-life for $^{14}C$ is used instead of the conventional half-life to calculate the ages, the offset becomes 4800 years. The concordance of these five age-pairs provides strong evidence that the environmental $^{14}C$ level was indeed significantly higher at this time. The lower section of Table 3 refers to that period where the $^{14}C$ age in the Cango Caves stalagmite shows little increase between the absolute (U-series) ages of 29 and 35 kyr. The same near 'plateau' in $^{14}C$ is recorded in the Searles Lake data set. By contrast, the $^{14}C$ age of 25 870 years for

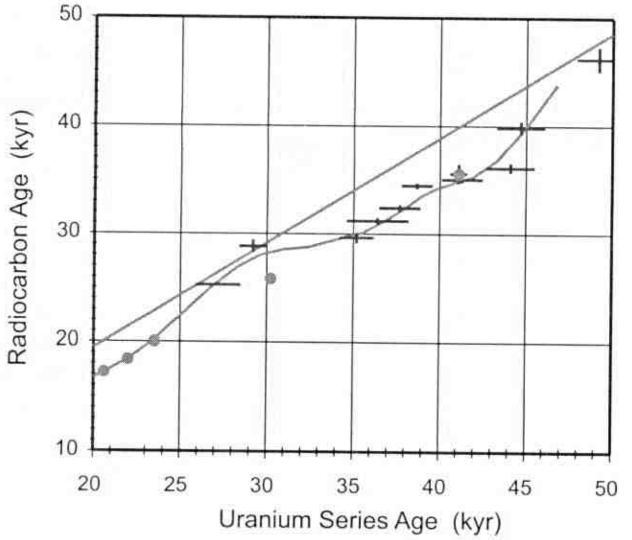


**Fig. 6.** Correlation of conventional $^{14}C$ ages with U-series ages beyond 20 kyr. The grey circles are the coral data,[38] while the crosses are the results for the Cango Caves stalagmite whereby the length of the bars gives the 1σ uncertainty.[34] The diagonal line represents the expected values as in Fig. 1, while the thin curve is a spline through the points (excluding the coral value at 30.23 kyr), representing a tentative calibration curve for radiocarbon dates.

the Barbados coral sample is distinctly younger than the other values. Future research will have to resolve this discrepancy.

Various studies covering this time range have recently been reported, whereby other methods of deriving the absolute age of radiocarbon dated samples is employed. In one such investigation, the counting of annual laminae in a sediment core from a lake in Japan is used for the purpose.[42] After linking the varve count to the accepted absolute ages between 9 and 22 kyr, the $^{14}C$ ages are all, with two exceptions, younger than the allocated absolute ages, but the offsets are generally smaller than those in Fig. 6. The authors do, however, warn that the varve count may underestimate the true age and that the error increases with age. In another extensive project, the radiocarbon ages of foraminifera from a deep-sea core off Iceland was measured and variations in their oxygen-18 content (which is ascribed to ice-rafting events) was correlated with the oxygen-18 record in a Greenland ice core to derive absolute ages.[43,44] The correlation was achieved with the aid of some reliable fixed points in the sequence, but interpolation between these points can be performed in more than one way and this gives rise to some uncertainty in the detail. Nevertheless, the data back to 43 kyr also show the negative offset of the $^{14}C$ ages. The resulting curve, however, matches neither Fig. 6 nor the curve derived from the Japanese varves. Other published data sets do not provide clarification concerning these discrepancies and more work will be needed before a definitive calibration curve can be constructed.

## Comparison with palaeomagnetic records

During the 1990s, a number of records were published of the relative geomagnetic field intensities in marine and lacustrine sediment cores reaching back to 50 kyr ago and beyond. For complete coverage of the pertinent literature up to 1998, see the extensive review by Jacobs.[45] Later reports are referred to below. The results vary considerably, but most show high values around 50 kyr ago comparable to those of the present, followed by a distinct minimum around 40 kyr. Thereafter the records, however, differ in detail. This can be ascribed to the effect of localized non-dipole fields and to variations in the magnetic properties of the minerals in the sediment, and it is difficult to derive a reliable record of the global dipole moment from the data. When comparing details, a further complication arises in that the time-scales used are derived in various manners and are not identical. Differences of several thousand years have been noted.[46]

Before comparing the $^{14}C$ data with the palaeomagnetic record, another matter needs to be mentioned and that is the influence of the dynamics of the carbon system on Earth. Most of the exchangeable carbon is dissolved in the deep oceans, which have a relatively slow turnover time. The result of this is that the $^{14}C$ levels in the atmosphere and terrestrial biosphere will lag behind any change in the production rate caused by an alteration in the geomagnetic dipole field intensity. A further complication is that there is evidence for a change in the ventilation rate of the oceans during the Ice Age. However, a detailed survey of the available data on benthic foraminifera in the glacial oceans led Broecker and co-workers to the conclusion that the higher $^{14}C$ levels reported for glacial times were primarily caused by a higher global $^{14}C$ inventory and were not due to changes in the mixing rate of the ocean.[47]

In order to arrive at a record of the global dipole intensities, it has been proposed to combine the natural remanent magnetization signals of all the available data sets.[48] This procedure is questionable since the differences between regions cannot be ascribed merely to statistical fluctuations, but must be due to local effects,. For comparison with the $^{14}C$ results presented above, I here use the stacked record of four Mediterranean cores.[49] The trends revealed in this compilation are well matched by measurements on lava flows,[49] and also very similar to results from the Equatorial Pacific[50] and the Somali Basin off northeast Africa.[51] Specifically, they all show an increase to relatively high field intensities after the minimum at *c.* 40 kyr before they again decline to lower levels at *c.* 22 kyr — a feature which is not

**Table 3.** Comparison of selected uranium-series and radiocarbon age-pairs including the relevant samples from the Cango Caves and one from Table 2.

| Location | Material | Sample | U-series age (yr) | Conv. $^{14}C$ age (yr BP) | Difference (yr) |
|---|---|---|---|---|---|
| Cango Caves, South Africa[34] | Stalagmite | V3/7c | 41300 ± 1200 | 35070 ± 300 | 6230 ± 1267 |
| Lisan Lake, Israel[29,30] | Aragonite | Table 2 | 41020 ± 1620 | 35000 ± 900 | 6020 ± 1853 |
| Rosegg, Austria[39] | Peat | — | 40670 ± 1080 | 36800 ± 600 | 5970 ± 1729 |
| New Guinea, East Indies[38] | Coral | KWA-I-1 | 41100 ± 500 | 35600 ± 920 | 5500 ± 1047 |
| Abri Romani, Spain[40] | Tufa/charcoal | AR2,5,4 | 42600 ± 1100 | 36800 ± 600 | 5800 ± 1253 |
| | | | | Weighted average: | 5840 ± 600 |
| Cango Caves, South Africa[34] | Stalagmite | V3/4a | 29200 ± 800 | 28850 ± 610 | 350 ± 1180 |
| | Stalagmite | V3/4b | 35200 ± 1000 | 28660 ± 500 | 6540 ± 1120 |
| Searles Lake, California[41] | Halite | S5 | 28000 ± 300 | 27600 ± 1100 | 400 ± 1170 |
| | Burkeite | S4 | 31800 ± 250 | 28100 ± 600 | 3700 ± 650 |
| | Trona | S2 | 34400 ± 300 | 29600 ± 500 | 4800 ± 580 |
| Barbados, West Indies[38] | Coral | RGF12-30-2 | 30230 ± 160 | 25870 ± 410 | 4360 ± 440 |

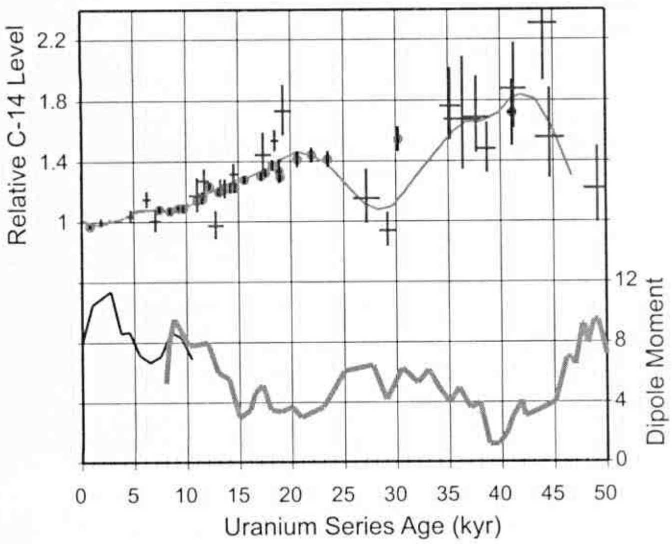


**Fig. 7.** The $^{14}$C levels in the atmosphere relative to the present standard value compared with the geomagnetic dipole moment (A.m$^2$ × $10^{-22}$) over the past 50 000 years, revealing a clear inverse relationship. In the upper section of the figure, the grey circles are the coral data of Bard and co-workers,[38] while the crosses are our values from stalagmites whereby the length of the bars gives the 1σ uncertainty.[34] The thin line is a spline curve fitted to the data (excluding the coral value at 30.23 kyr). In the lower half of the figure the solid line is taken from Fig. 3, while the thick gray line is a simplified version of the palaeomagnetic dipole data derived from Mediterranean sediment cores by Tric and co-workers.[49]

revealed, for instance, in the records from the Azores and Borneo.[52,53] Six cores from the north Atlantic also show the same trends as the Mediterranean cores, except that there is a distinct additional minimum of short duration at *c*. 34 kyr.[43,54,55] The more extensive minimum at *c*. 40 kyr coincides with the Laschamp geomagnetic excursion, when the axis of the dipole deviated significantly from its normal N–S orientation. The less well documented event at *c*. 34 kyr is considered coeval with the smaller Mono Lake excursion.[43,55]

In Fig. 7 the $^{14}$C levels relative to today's are shown together with a somewhat simplified record of the dipole moment derived from the Mediterranean cores.[49] An inverse correlation is evident. Quantitatively, the $^{14}$C variations also appear to be of the right order of magnitude. Using the relationship for the modulation of the $^{14}$C production rate calculated by Lal,[18] the production at the major turning points on the palaeomagnetic curve are expected to be: at 40 kyr, 1.85 times higher than at present, at 28 kyr 1.08 times higher, and at 22 kyr, 1.46. These figures correspond closely with the values recorded on the $^{14}$C curve. The time-lag and attenuation of the $^{14}$C response, however, need to be taken into account. Considering the magnetic data to be quasi periodic with a period of *c*. 20 000 years and using the model developed by Hautermans, one would expect a lag time of *c*. 3000 years.[56] At the turning points this shift would hardly be noticeable. Furthermore, the uncertainty in the time scale of the Mediterranean cores is probably of the same order.

Models developed to predict the response of the $^{14}$C levels to production rate changes thus far do not reflect the actual $^{14}$C data, whichever data set one chooses.[57,58] It is also not yet possible to decide which of the palaeomagnetic records best reflect the dipole moment changes during Glacial times.

Once the precision of the $^{14}$C calibration has been improved sufficiently, the record will no doubt become an important tool, both for establishing the actual intensities of the global dipole field over the period, and for testing models of the dynamic carbon cycle.

## Conclusion

The radiocarbon dating method which was introduced fifty years ago, has had a major impact on archaeology, Quaternary science and various other disciplines. It provided an independent absolute time scale for that part of the Earth's history that is most relevant to the present and thereby created a reliable means of correlating events on a worldwide basis. In archaeology it facilitated a more detailed understanding of social and technological developments in pre-historic times. It has also placed a wealth of geomorphological phenomena in their proper perspective and, in addition, has enabled the correlation of especially palaeoclimatic evidence on the different continents and thereby contributed to the construction of a detailed history of past climate.

Apart from radiocarbon being a mere dating facility, the review presented here shows that it has become an integral part of several branches of geophysical research. The demonstrated correlation with solar activity has produced proxy data of the variations in the activity of the Sun which extends far beyond the sunspot record. In view of the accumulating evidence that these changes affect global climate, this information is increasingly being used in palaeoclimatological investigations. The correlation of $^{14}$C with variations in the geomagnetic dipole field is contributing to the interpretation of palaeomagnetic data recorded around the world and at the same time it is providing information on the mixing and circulation of the oceans. In the coming years the use of radiocarbon in these aspects of geophysics is bound to increase as detail of the record improves.

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