Accuracy of Radiocarbon Dates

Apparent discrepancies are examined for geophysical significance and for a general principle of correction.

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The first test of the accuracy of dates obtained by the radiocarbon technique was made by determining whether dates so obtained agreed with the historical dates for materials of known age (*1*). The validity of the radiocarbon method continues to be an important question, especially in the light of the numerous results that have been accumulated and the greater precision of the technique during the past few years (*2*).

The radiocarbon content of the biosphere depends on three supposedly independent geophysical quantities: (i) the average cosmic ray intensity over a period of 8000 years (the average life of radiocarbon) as measured in our solar system but outside the earth's magnetic field (*1*); (ii) the magnitude (but not the orientation, because of the relatively rapid mixing over the earth's surface) of the magnetic field in the vicinity of the earth, averaged over the same period (*1, 3*); and (iii) the degree of mixing of the oceans during the same period (*1*). The question of the accuracy of radiocarbon dates therefore is of interest to geophysicists in general as well as to the archeologists, geologists, and historians who use the dates.

Previous workers in this area (*1, 2*) have reported some discrepancies, and it is the purpose here to consider the matter further.

The Historical Data

Figure 1 and Table 1 show the dates obtained from organic materials (mainly wood and charcoal) found in the sites for which we have the most reliable historical dates. [For each sample, the laboratory that made the measurement and the sample number assigned is given in the code followed in the *Radiocarbon Supplement* of the *American Journal of Science*.] All the dates given, with two exceptions—dates for the Buhen charcoal samples from Wadi Halfa, from the British Museum [described in July 1962 by I. E. S. Edwards, Keeper of the Department of Egyptian Antiquities (*5*), as being from the Second Intermediate Period and the IVth to Vth dynasties, respectively]—are given in the 1959, 1960, 1961, or 1962 editions of the *Radiocarbon Supplement* or in *Radiocarbon Dating* (*1*). Originally, in the "Curve of Knowns" (*1*, p. 10), the absolute radiocarbon content of organic matter of various historical ages was compared with the content calculated on the basis of the accepted value of 5568 years for the half-life of carbon-14 (*1*). In Fig. 1 the data are presented somewhat differently; the calculated specific radiocarbon content for biosphere carbon is taken for the historical age, and, on the basis of the value of 5568 years for the half-life, the observed percentage deviation in the radiocarbon content of the sample is given. [The value used for the modern assay is 95 percent of the observed radiocarbon content of the sample of oxalic acid prepared by the National Bureau of Standards. This 95-percent value is the determined value for the modern biosphere corrected for dilution with inactive fossil carbon dioxide (the Suess effect) and for enhancement by atomic and hydrogen bomb explosions in the atmosphere (the atomic bomb effect).] Figure 1 contains all the individual determinations available in the literature, together with the standard counting errors given in each instance. The agreement among different laboratories on determinations for a given site is, in general, good, although there are instances of apparent disagreement; Hemaka is one of these.

In Figs. 2, 3, and 4, the horizontal line that passes through the origin represents a half-life for carbon-14 of 5568 years. The dotted line, labeled 5730 [the half-life adopted by the 5th Radiocarbon Dating Conference at Cambridge University in July 1962 on the basis of three recent remeasurements (*6*)], shows the deviation when the half-life is taken to be 5730 instead of 5568 years, and when both the rate of radiocarbon production and the inventory are assumed to have remained strictly constant for the last 20,000 years or so.

The data in Table 1 are separated into two groups—Egyptian and non-Egyptian. This separation was made because the whole historical Egyptian chronology is interlocking and subject to possible systematic errors, whereas other historical dates are presumably more independent of each other and therefore relatively free of such errors. If a sample or site has been measured by more than one laboratory, the arithmetical average has been taken and the error has been recomputed through division by the square root of the number of laboratories. Finally, any estimated uncertainty in the historical age has been combined with the average counting error (by taking the square root of the sum of the squares); the resultant percentage error is given in parentheses in Table 1, column 3. These data are plotted separately for the two groups, in Figs. 2 and 3.

Figure 2 is a plot of radiocarbon and historical dates for Babylonia, Rome, Syria, Cyprus, and Norway; it indicates that the radiocarbon dates agree, within the error of measurement, with the historical dates back to 5000 years ago, although the uncertainty in the historical ages of the individual samples and the scatter beyond 4000 years ago are large. Figure 3 is a plot of radiocarbon and historical dates for Egypt; it indicates that the radiocarbon dates for Egypt for the period 4000 to 5000 years ago may be consistently too recent relative to the historical dates but that the two sets of dates agree back to 4000 years ago.

These plots of the data suggest that the Egyptian historical dates beyond 4000 years ago may be somewhat too old, perhaps 5 centuries too old at 5000 years ago, with decrease in the error to 0 at 4000 years ago. In this connection it is noteworthy that the earliest astronomical fix is at 4000 years ago, that all older dates have errors, and that these errors are more or less cumulative with time before 4000 years ago (*5*).

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The Tree-Ring Data

A good deal of work has been done on the radiocarbon content of the tree rings in *Sequoia gigantea, Sequoia sempervirens*, Douglas fir, and *Pinus aristata* (Bristlecone pine), particularly in the Radiocarbon Dating Laboratories of the Scripps Institution of Oceanography, La Jolla, California, and at Groningen, Columbia, the University of Pennsylvania, Cambridge, Copenhagen, the University of Washington, Heidelberg, and the University of Arizona.

Most of the results for *Sequoia gigantea* (*7*) are presented in Fig. 4; the basis is the same as for Figs. 1–3. It is clear that the carbon-14 dates are in good agreement with the tree-ring chronology curves for the period 800 to 2400 years ago. Between 3000 and 4000 years ago, however, the ages as determined from the number of tree rings are higher than the ages shown by radiocarbon dating. This discrepancy is analogous to that between the historical data and the radiocarbon data for Egypt for the period before 4000 years ago.

Since there appears to be good agreement (when the new value for the half-life of C^{14} is used) between the historical dates and the radiocarbon dates for Egyptian samples back to about 4000 years ago, whereas there appears to be a discrepancy of some 3 percent between the historical dates and the tree-ring dates for the 600-year period between 3000 and 3600 years ago (there are no tree-ring dates earlier than 3600 years ago), there appears to be a discrepancy between the two sets of data.

Recently, it has been reported that some trees add more than one ring per year, and thus a question has been raised about the accuracy of tree-ring dates. This finding indicates that rings sometimes have been incorrectly correlated with years (*8*), too great an age having been assigned from tree rings (see Fig. 4). Glock and Agerter (*8*) show that by careful correlation it is possible to obtain accurate tree-ring dates but that under many natural conditions it may be extremely difficult to do so, the difficulty apparently increasing with the age of the tree. Only through further measurement can this matter be clarified, but it seems that the data of Fig. 4 do not prove that radiocarbon dates for the period 2400 to 3600 years ago need special correction. The six radiocarbon dates of Fig. 1 that fall between 3000 and 4000 years ago show an average deviation from the historical dates of 0.65 percent (when the new value for the half-life of C^{14} is used), as compared with the 3-percent deviation of the tree-ring dates for the period 3000 to 3600 years ago.

It can be shown that a given change, lasting only a few centuries, in the percentage of radiocarbon in the biosphere requires a change about 10 times as great in the rate of production of radiocarbon, or in the rate of mixing in the oceans, or in both. This is because the buffering action of the ocean is so great. Thus, the deviations from the content of the modern biosphere that I have discussed indicate, if they are real, rather large changes in the cosmic ray flux at the top of the earth's atmosphere, in the strength of the magnetic field in the vicinity of the earth, or in the rate of mixing in the oceans—changes maintained throughout the centuries for which deviations are found. On the other hand, if we find that the historical data support the radiocarbon dates to within about 1 or 2 percent of the expected radiocarbon content (80 or 160 years), we conclude that the cosmic ray flux, the magnetic field in the vicinity of the earth, and the rate of

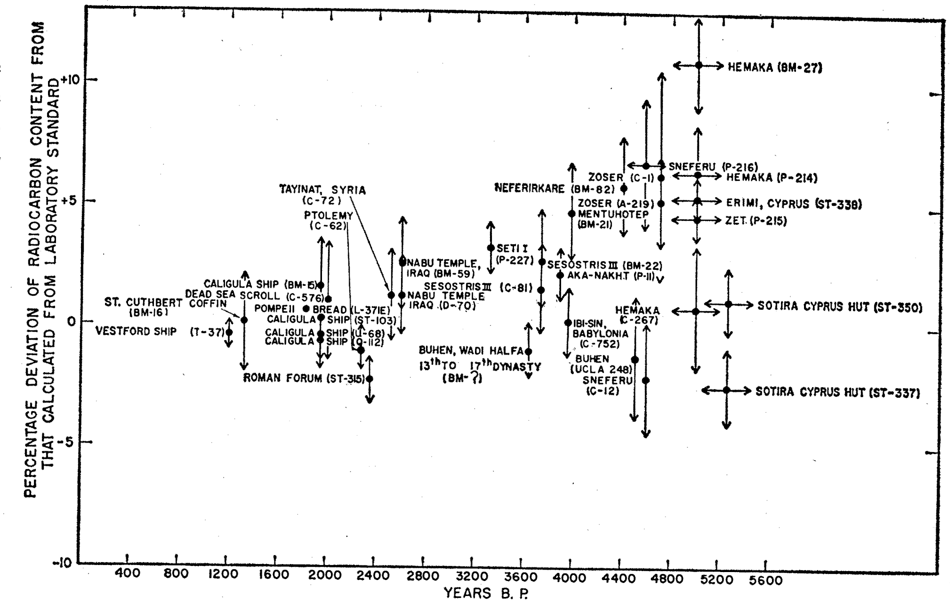
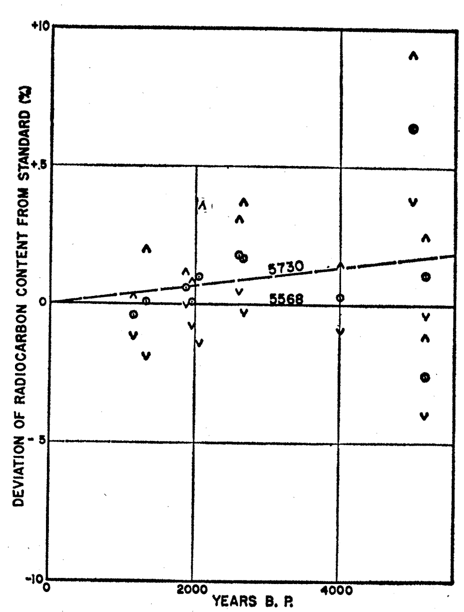


Fig. 1. Plot of historical dates.



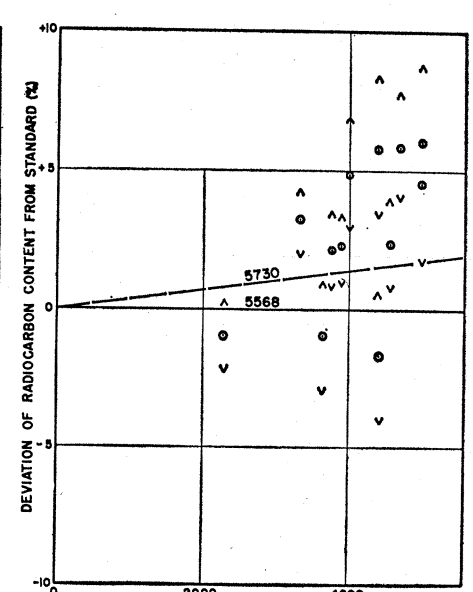


Fig. 2 (left). Plot of non-Egyptian known dates. Fig. 3 (right). Plot of Egyption known dates.

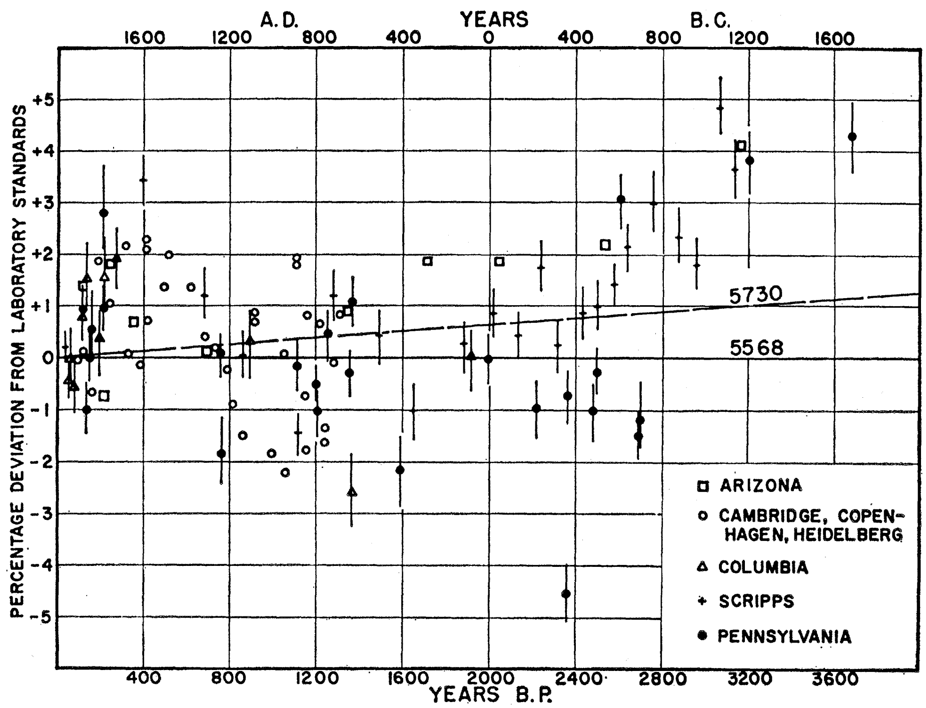


Fig. 4. Some tree-ring-dated samples (*13*).

mixing in the oceans have not varied from the average during the last 4000 or 5000 years by more than the equivalent of a 10- or 20-percent change in the rate at which radiocarbon has been fed into the biosphere over periods of 50 years or more. Evidence of the constancy of the cosmic rays outside the earth's and the sun's shielding magnetic fields is in keeping with the results (*9*) on cosmic-ray-induced radioactivities found in meteorites. Because of the variety in the lifetimes of these radioisotopes in meteorites, we can study the past intensities of cosmic rays, as averaged over different intervals, back to at least several hundred million years ago.

The question of the constancy of the magnetic field near the earth and its effect on the rate of production of carbon-14 is almost completely open. The available magnetic data on the field at the earth's surface show only changes in direction in past times—except for the last century, during which the magnetic moment decreased by 1 or 2 percent and then leveled off (*10*). However, as G. J. F. MacDonald (*11*) has pointed out, the magnetic shield for the earth is derived in large part from the sun's magnetism and not solely from the earth's. Therefore, our conclusion that the shield factor has probably remained constant to within the indicated limits of 10 to 20 percent over the past 4000 or 5000 years is of general geophysical interest, indicating rather rigid restraints on both the solar and the terrestrial magnetic dipoles.

As for the rate of mixing of the oceans, it is hoped that study of the carbon-14 content of deep sea water will bring further enlightenment (*12*). It is clear from the results presented here (*13*) that rather strict bounds to the possible changes can now be set.

Table 1. Deviations from historical dates of dates derived by the radiocarbon method.

Item	Historical age (yr)	Deviation in C^{14} content relative to modern standard* (%)
	Non-Egyptian	
Sotira Cyprus Hut (St-350)	5270±200	1.1±1.5(±2.9)
Sotira Cyprus Hut (St-337)	5270±200	−2.5±1.5(±2.9)
Erimi Cyprus (St-338)	5000±200	5.3±1.0(±2.7)
"Ibi-Sin of Babylonia" (C-752)	3930±20†	0.3±1.3(±1.3)
Nabu Temple, Iraq (D-70; BM-59)	2600±30	1.8±1.4(±1.5)
Tayinat, Syria (C-72)	2652±50	1.7±2.0(±2.1)
Caligula Ship (BM-15; St-103; U-68; Q-112	1950±30	0.2±0.7(±0.8)
Dead Sea Scroll (Isaiah) (C576)	2050±100	1.0±2.5(±2.8)
Pompeii Bread (L-371E)	1880±1	0.6±0.7(±0.7)
St. Cuthbert Coffin (BM-16)	1320±25	0.1±2.0(±2.0)
Vestford Ship (T-37)	1160±30	−0.4±0.7(±0.8)
	Egyptian	
Hemaka (BM-27; P-214; C-267)	5000±200	6.0±1.2(±2.8)
Zet (P-215)	5000±200	4.5±1.0(±2.7)
Zoser (A219; C-1)	4700±75	5.8±1.9(±2.1)
Sneferu (P-216; C-12)	4574±75	2.3±1.3(±1.6)
Buhen Wadi Halfa (IVth to Vth Dynasty Charcoal UCLA 248)	4430±135	−1.6±1.0(±2.4)
Neferirkare (BM-82)	4400±?	5.8±2.0(±?)
Mentuhotep (BM-21)	3980±20	4.8±2.0(±2.1)
Aka-nakht (P-11)	3900±75	2.2±1.0(±1.4)
Sesostris III (BM-22; C-81)	3828±19	2.1±1.4(±1.5)
Buhen, Wadi Halfa (BM-?) (XIIIth to XVIIth dynasties)	3640±100	−1.0±1.2(±1.6)
Seti I (P-227)	3320±30	3.2±1.2(±1.3)
Ptolemy (C-62; UCLA109)	2280±30	−1.0±1.0(±1.1)

* Corrected for decay during historical age on the basis of a half-life for C^{14} of 5568 years. Error includes error in historical age. † Authority for this date is the date of 1728–1686 B.C. for Hammurabi. Ibi-Sin lived 250 years earlier [W. C. Hayes, M. B. Rowton, F. H. Stubbings, *Cambridge Ancient History* (Cambridge Univ. Press, New York, rev. ed., 1962), vol. 1, chap. 6].

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7. Most of the data in Fig. 4 were presented by Elizabeth Ralph at the 5th Radiocarbon Dating Conference. The Arizona data were presented at the same conference by Paul E. Damon. I wish to thank both authors for permission to use these data.
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