YU ISSN 0015-3206
FZKAAA 12 (S2) 37 (1980)

PROGRESS IN RADIOCARBON DATING, PROMISING TECHNIQUES AND TRENDS IN THE RESEARCH

By

Ingrid U. Olsson, Institute of Physics, University of Uppsala, Uppsala, Sweden

Abstract

The technical improvements for radiocarbon dating from the black-carbon method to accelerator measurements are presented in a general survey. The principle is explained and the problems inherent in the assumptions discussed. A survey of current research seeking to solve the problems is included.

FIZIKA 12(1980) S2, 37-68.

Introduction

Over three decades have elapsed since Professor W.F. Libby discovered the relevance of radiocarbon, the heavy isotope ^{14}C, to dating, and 30 years since he released the first dates. He described the technical problems in measuring radiocarbon and explained the principle involved of the method. I am convinced that his book still has value for we are still discussing problems which he raised 30 years ago. The radiocarbon method of age determination is used throughout the world to solve different problems and I will here explain its scope at the same time as I must discuss the modifications which allow us to study details Libby was unable to penetrate three decades ago.

The principle of radiocarbon dating is that cosmic rays produce a known amount of radiocarbon, or for most problems that the content of radiocarbon was constant throughout the relevant period. Since the carbon is oxidized to carbon dioxide, assimilated by plants, dissolved in water, and therefore ingested by animals, radiocarbon is present in the reservoirs as a fraction of the total carbon. This fraction remains constant as long as exchange occurs with the environment, i.e. as long as the plant or animal is alive, since the decay is recompensed by new radiocarbon which is continuously added. In a tree the exchange ceases for some components of a tree ring when its growth is completed. Thus a record of the activity is locked in the ring, which enables us to study the activity over thousands of years. When the plant or animal dies, the exchange ceases and the decay reduces the ratio $^{14}C/^{12}C$. The half-life being 5,730 years, it takes 5,730 years for the activity to decline to half the original value, and a further 5,730 years to decrease by another factor 2, i.e. to one quarter of the original value. After six to seven half-lives one per cent of the activity remains. Dating by the radiocarbon method can be summarized thus: we measure the present activity of a sample, assuming a known amount of activity when the sample was interacting with its environment, calculate how many half-lives have elapsed, using an appropriate value for the half-life, and then calculate the age in years.

Already three decades ago Libby said we could not be sure that the relative concentration of radiocarbon had been constant. Accordingly he collected samples of known age and contemporaneous samples to measure the activities. He could not prove that variations arose. Using a better technique, however, we have known for over 20 years, that variations did occur. Research is still in progress to determine these variations in detail, so this problem too must be considered.

The half-life was improperly determined when Libby started dating, but after new determinations c. 1950 he adopted the value 5,568±30 years. Later, in 1961 and 1962, three new determinations were released, yielding a mean value of 5,730±40 years, which are still used by physicists. Another determination yielding 5,660±30 years was published in 1968.

The measurement of the activity

The technique has been improved during these three decades of radiocarbon dating. Libby started with elementary carbon, also called black carbon, which he spread over the inside wall of a Geiger counter. Since the natural activity is only 13.56±0.07 disintegrations per minute and gram carbon, corresponding to $10^{-10}\%$ ^{14}C of the naturally occurrent carbon, it is difficult to measure the radioactivity precisely. Libby could attain an accuracy of a few percent of the activity, but nowadays it is feasible to achieve an accuracy of half a percent and a few laboratories, such as those in Seattle, Groningen, Heidelberg and Belfast, claim an accuracy of about 0.2% and within one or two years several accelerator laboratories will probably reach the same standard. This long process (Fig. 1) has been characterized by diverse major improvements, such as a reduction of the background and its variations with a consequent improvement of the stability.

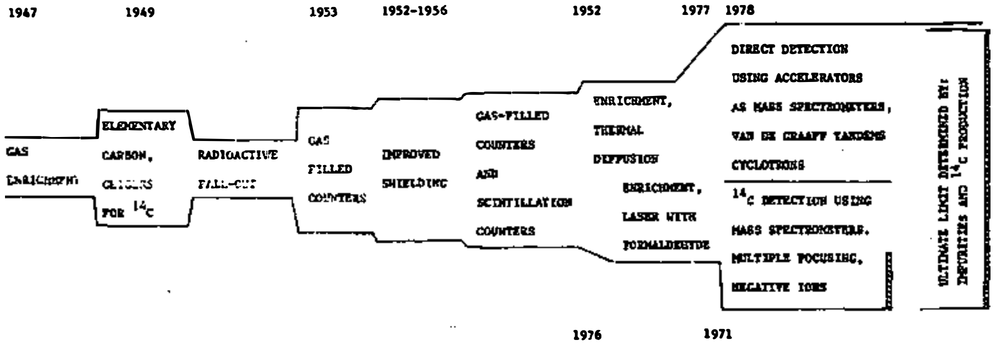

Fig. 1 A schematic picture of the development of the technique used for radiocarbon dating. Many improvements occurred in parallel. The years give an indication when the most important changes were introduced. The accelerators are, in 1979, not yet in routine use.

For years the radiocarbon activity was measured using the radioactive decay by emission of beta particles with low energy — a continuous spectrum with all energies up to 156 keV but half of the particles having energies below 50 keV. These particles have the ability to ionize different types of materia which ability was used for long time and still is used. Because of the long half-life, however, only 1 of 10^6 ^{14}C atoms is used even if the measurement time is as long as 3 days and nights.

The question frequently arose why mass spectrometers were not used, with their greater efficiency due to the employment of differences in the masses. Since there is a weight difference here of almost 10% for each step between ^{12}C, ^{13}C and ^{14}C such an instrument would have many advantages. The answer, for years, was that the sensitivity did not suffice. A ratio $^{14}C/^{12}C$ of about 10^{-8} was required rather than the natural ratio of 10^{-12}. The use of mass spectrometers with triple focusing of the beam or negative ions was suggested. Yet these alternatives were not very practical or successful. Another possibility was to enrich the radiocarbon and measure the enriched sample in a mass spectrometer. Enrichment has long been performed by thermal diffusion of gases. Unfortunately large sampels are required. About 1/3 of the sample is used, and for an increase of the sample by a factor of 2 the age limit will be extended by one half-life (almost 6,000 years). An enrichment by a factor of 12 thus extends the age-limit to c. 75 000 years but needs about 120 grams of carbon. The enrichment proceeds for about one month. It is also possible to enrich a sample with the help of a laser. This is because molecules with different masses, such as formaldehyde with natural ^{12}C, ^{13}C and ^{14}C, have different resonance frequencies. A laser may be tuned to one typical frequency to break down a molecule containing ^{14}C into carbon monoxide and hydrogen, whereupon the carbon monoxide is recovered. This process is often compared with the breakage of a glass when an opera singer takes a specific tone.

In the last two or three years experiments have been performed in different laboratories using accelerators as cyclotrons and tandem Van de Graaff accelerators as mass spectrometers. Naturally the over-all efficiency of an accelerator falls far short of 100%. As a comparison between the amounts of carbon necessary is of interest, we may say that the same number of ^{14}C atoms are detected in a conventional system during a 3-day period as in about 3 hours run in a tandem accelerator, while the amount of sample is 10^6:1. A Van de Graaff mass spectrometer may consist of an ion source, a velocity filter, a Van de Graaff generator with a stripping foil, a magnetic filter, an electrostatic filter and a detector (different designs may be used) and is thus a complicated device. A great effort must be made to design a suitable source. Graphite has been used but is inconvenient as the preparation takes a long time. Memory effects and stability problems have contributed to the real uncertainty still seen in the values. It is to be hoped that these problems will be eliminated within a year or two and an accuracy of 0.2% reached. At present we can say that the accelerators yield results comparable with those from a normal laboratory with conventional dating.

Isotopic fractionation

The isotopes of an element present the same chemical behaviour, but because of the different weights the vibration energies will vary and the isotopes behave slightly differently. The reaction speed and equilibrium constants will diverse. These phenomena are seen in nature in elements with masses up to 40, and are thus of importance for radiocarbon dating. The abundance of the two stable isotopes ^{12}C and ^{13}C is 98.9% and 1.1% of the total carbon. The fractionation can thus be studied using these two isotopes and a mass spectrometer. The fractionation of ^{14}C is expected to be almost exactly twice that of ^{13}C. The two prime cases of fractionation in nature are the enrichment of the heavier isotopes in the bicarbonate when carbon dioxide is dissolved in water, and the depletion of the heavy isotopes when assimilated by plants. Thus it is natural that we should always correct for this fractionation by normalizing to a common ^{13}C content. By tradition that of wood is chosen and usually has 25 $^{o}/oo$ less ^{13}C carbonate precipitated in shells from sea water. Using belemnite as the standard we then say that $\delta^{13}C$ for normal wood is -25 $^{o}/oo$. Examples of the normalization are given in Fig. 2. Different pathways for carbon at photosynthesis lead the $\delta^{13}C$ values to cluster around three values. A $\delta^{13}C$ value typical of maize kernels is -9.5 $^{o}/oo$. Such a fractionation can be used for tracing changes in food or agriculture.

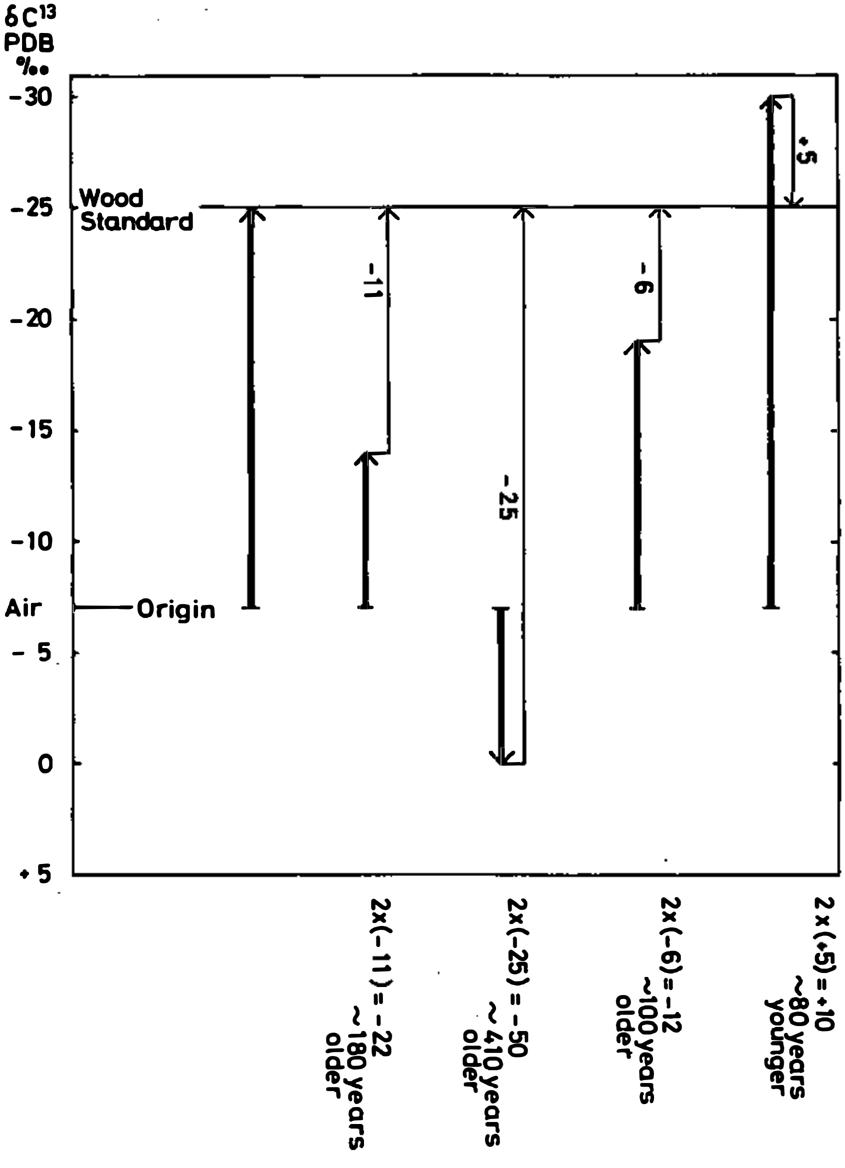

Fig. 2 Examples of the $\delta^{13}C$ normalization to -25 $^{0}/oo$ and the corresponding ^{14}C and age corrections.

Unfortunately many laboratories do not have access to a mass spectrometer in order to perform the measurements for the corrections. Tables are available however with suggestions for corrections (Table 1). As we saw the correction for a sea-water shell is about 400 years. Since it was not known when radiocarbon dating started that such corrections were necessary several dates are still published without corrections. This may cause confusion. More and more laboratories are endeavouring to include these corrections. It should be mentioned that the isotopic fractionation is temperature dependent so that we have a record of temperature variations in the tree rings. Work is in progress in various laboratories to develop methods of reading these records.

The reservoir effect

It is tacitly assumed that natural radiocarbon is absorbed by the atmosphere without any detectable delay. The artificial radiocarbon produced by all nuclear bomb tests has acted as an injection, allowing us to study the mixing procedure. We have learned that mixing above the equator is delayed but in one hemisphere the process is complete inside one year. The early-summer values are sligthly different, being higher at mid-latitudes and lower at higher and lower latitudes. There are no indications of a detectable latitudinal effect of natural radiocarbon in the northern hemisphere although the activity in the southern is probably a few per mille lower.

There is a delay in the dissolution of carbon in the water. In the simple box-model with the atmosphere as one box,

Table 1. Some $\delta^{13}C$ values of samples dated in Uppsala (round figures where appropriate)

Sample	Measured range $\delta^{13}C$ $^{o}/oo$ PDB	Range Number of samples Included	Excluded	Mean o/oo	Age correction Range, years	Mean age correction
Marine mollusc shells	+6 to -8.5	116	2	-0.8	515 to 270	400
or	+3.5 to -4.5	107	11		470 to 330	
Foraminifera	+4 to -8	79	3	-1.7	480 to 280	380
or	+4 to -6.5	77	5		480 to 300	
Fresh water shells	-8.5 to -12	2		-10	270 to 210	245
Fresh water concretions	-13.3 to -14.4	4		-13.9	190 to 170	180
Brackish water shells	-4.5 to -12	14		-9	330 to 210	260
Brackish water concretions	-1.5 to -3.1	6		-2.3	385 to 360	375
Whales (collagen)	-12.5 to -20	36		-16.5	200 to 80	140
Seals (collagen)	-12.5 to -18	4		-15.5	200 to 115	155
Terrestrial animals	-22 to -24.5	4		-23	50 to 10	30
Wood, not identified	-21 to -29	26		-25	65 to -65	0
Wood (*Picea, Pinus silvestris, Larix, Juniperus, Quercus, Betula*)	-22 to -27.5	14		-25	50 to -40	0
Leaves (*Betula, Salix*)	-27 to -29.5	7		-28	-30 to -70	-50
Leaves (*Solanum, Typha*)	-22 to -27.5	7		-25	50 to -40	0
Leaves (*Desmostachya bipinnata*)	-10.5 to -12	8		-11	235 to 210	95
Charcoal, not identified	-22.5 to -29.5	86	5	-25.5	40 to -70	-10
Charcoal (*Pinus, Sorbus*)	-22.5 to -25.5	10		-24.5	40 to -10	+10
Resin (archaeological finds)	-25 to -34	15		-28	0 to -145	-50
Peat	-19 to -34	69		-27	95 to -145	-30
Gyttja, mud and dy	-16 to -35	117		-26	145 to -160	-15

the mixed surface water of the ocean as another, and the mixed deep water as a third, we must take into account the resistance to mixing across the box boundaries, and also that the deep-water box is much larger than the other two. Thus some radiocarbon will decay in the deep-water box before mixture with the content of the surface water. In consequence the carbon in the deep water contains less radiocarbon than the surface water. This in turn will have a lower activity than the atmosphere. In other words it seems that the surface water is older than the atmosphere, and the deep water is older than the surface water, and this is also described as: these reservoirs have an apparent age known as the reservoir age. After the correction for isotopic fractionation the surface water will have a reservoir age of slightly less than 400 years for large areas of the oceans but the reservoir age may be appreciably greater for other areas. We still have too few values, and need shells and bones from seals and whales for better corrections for the reservoir age of the sea-water samples.

In fresh-water systems the situation may be still more complicated because of the groundwater which may contain less radiocarbon than the atmosphere. This may be due to dissolved carbonate, to isolation of the water from the atmosphere, or to the slowness of the exchange. When the submerged (and also floating) plants use the dissolved bicarbonate they will appear older than terrestrial plants – they present a reservoir age.

Local sources of inactive carbon may cause samples to be assigned too early a date. There is evidence of release of inactive carbon at volcanic eruptions and from fumaroles. Grass from the neighbourhood of artesian aquifers has been proven to present much lower activity than the normal atmosphere. I have undertaken an extensive investigation in Iceland to see whether such phenomena may explain my dating of the *landnam* earlier than it traditionally occurred.

Sample purity

A sample must naturally be free from contaminants if a reliable result is to be obtained, and there is no point in accurate measurement of a poor sample. In dating terminology one expression should be borne in mind: "closed system". For radiocarbon dating this means that no radiocarbon is added to the system, and no radiocarbon has disappeared otherwise than by radioactive decay. Since we measure the amount of radiocarbon in relation to the inactive carbon, no inactive carbon should have been added or removed since the sample was deposited.

Unfortunately the sample may have been contaminated already before deposition. For instance lake sediments composed of material co-precipitated with autochthonous organic material. If the co-precipitated material is partly organic or contains very old material, such as elemental carbon or graphite the material to be dated is contaminated, and will yield too early a result. Geologists using and studying pollen diagrams must take into account this source of error, and try to compare their results from lakes with corresponding investigations from peat bogs. Another source of error must there be considered, namely the possibility that roots penetrate deep into the peat. Thus the true radiocarbon age should fall between the ages yielded by a lake and a near-by bog, although I myself am convinced that the bogs yield more reliable results. One drawback with peat is that we sometimes have an uneven growth with hummocks. In such cases we must take great care. Often, however, we can choose a suitable site to take the core. Macrofossils such as cones and small pieces of wood are dated too by preference but the roots should be removed. We often use sieving. Even a lake with gyttja or limnic peat may contain roots which should be removed. Since lake deposits, especially clay, partly and sometimes mostly consist of allochthonous material it may be worth selecting embedded macrofossils such as leaves for dating with accelerators.

When working with real soils, not originally lake sediments, many problems may arise. Unfortunately my experience from such accumulations is very poor although I report some problems which appear in other contexts too. Wind-borne material may contain organic material of any age dependent on the source. I have bad experience of carbonate from Sahara deposited in the Mediterranean Sea and embedded together with foraminifera samples. Water-permeable layers may be penetrated by dissolved humic acid, which may be redeposited deeper in the soil accumulation, causing samples to appear younger than they are. I have repeatedly seen such contaminations in charcoal samples. Even if the system was thus not closed it is often possible to remove, mechanically or chemically, many of the contaminants to yield a sample which can be regarded as a closed system. We leave the treatment for the moment to discuss other cases of contamination.

Carbonate as shells may be contaminated in different ways. It is well known and easily understood that shells may be contaminated on the surface, at least if the groundwater level is high enough. I had an example from a shell assemblage where the deepest shells in the mound appeared youngest although there was every reason to believe that these shells should be the oldest or at least no younger than the others. On asking for further geological details I was told of the groundwater and the explanation was no longer difficult since the uppermost shells lay above the groundwater level. A normal procedure is to leach the shells with HCl to remove the outer layer so that each shell is partitioned in outer, intermediate and inner sections. Dating these separately provides indications of whether or not the shell is contaminated. I had suspected contamination at storage even under normal conditions in a museum since we could usually detect some activity in very old shells when stored for years, even if they were so old that no radiocarbon should be discernible. We then stored some samples in dry air to which we had added ^{14}C and these samples were seriously contaminated when the activity was measured a year later. We tried to remove the outer layers and date the inner ones but some hot carbon dioxide had penetrated the innermost parts of the samples.

You should therefore treat your shells with care and the smaller they are the greater the risk of contamination if they are washed with normal water or stored in a moist atmosphere. Try to use boiled distilled water or add some acid to the water to remove the carbon dioxide. A pH of about 3 is recommended. Try to store your shell samples in a dry atmosphere, preferably sealed from the air. These precautions are essential if you have very old samples.

You often find enormous amounts of bones at excavation and can date them although they are easily contaminated. Reliable dates can be obtained after good pretreatment to recover pure collagen. This means more work in the laboratory than normal samples require. The porous parts contain more foreign material than the solid as can be seen from chemical analyses but sometimes also by the naked eye. In this case I am thinking of roots and rootlets. X-rays may reveal foreign carbonate. Methods of extracting and dating the bone apatite do exist, but need to be further tested and improved. The isolation of amino acids is a promising method but the yield is usually so small that we must wait for the accelerators to be in smooth operation for radiocarbon samples.

Finally it is worth studying quantitatively how large the error may be when a sample is contaminated (Fig. 3). For instance 1% of infinitely old material yields a result which is 80 years too old. If the sample itself is infinitely old and contaminated by 1% of modern material the sample will have an apparent age of 37 000 years.

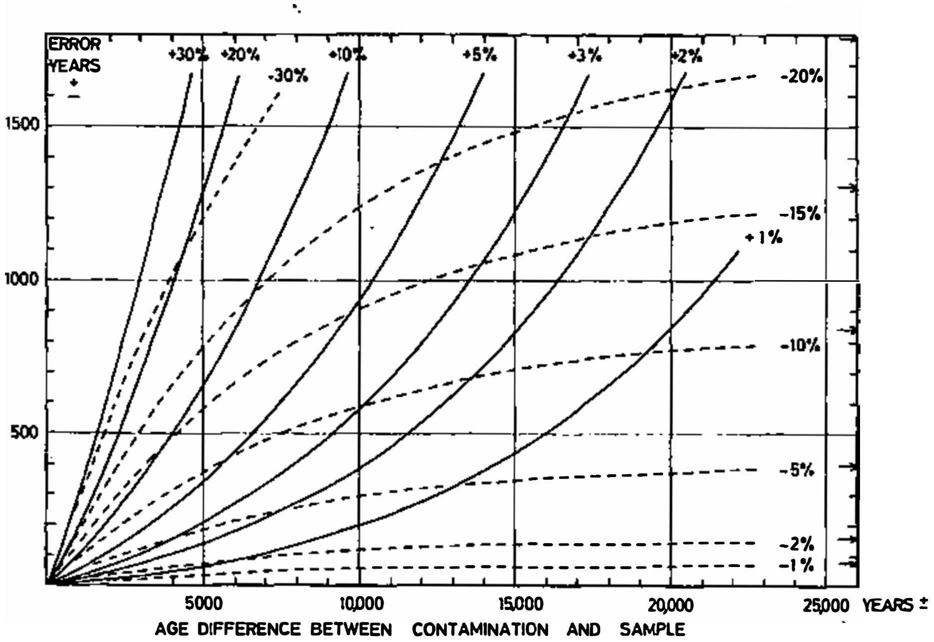

Fig. 3 The error (ordinate) obtained in a ^{14}C *dating if a certain fraction of a sample, indicated by each curve, consists of contaminants having a higher (continuous curves) or lower activity (dashed curves) than the original sample, expressed as an age difference (abscissa) between the sample and the contaminant.*

How to check radiocarbon dates

A chronology is always checked by comparison with other chronologies. The best absolute chronology is dendrochronology. Trees normally add one tree ring per year. When the conditions are very severe a ring may be missing. Sometimes it seems as if two tree rings grew in a single year, which may be caused by poor conditions, for instance by early drought, causing interruption of growth which may however resume during the same growing season. Thus it is understandable that trees growing under marginal conditions may lay down a very thin ring if the season is too dry or cool for normal growth. Similarly a broad ring may be created when the conditions are especially favourable. We then say we have a sensitive pattern. The construction of a dendrochronology thus involves careful analysis of whether or not a ring derives from a whole year or one ring is missing. When there are marginal conditions for the trees yielding sensitive records we can correlate rings from dead trees with those from living trees, and extend our record to a time before the living tree started to grow. With other, still older, logs we can go further back and, like climbing a stair-case, reach very ancient times. One condition is that the patterns overlap, guaranteeing the correlation. Preferably we should have about 100 overlapping tree rings. Othervise we get floating chronologies. Careful analyses have yielded a dendrochronology for American trees for the last 7,400 years. Similar chronologies are in preparation for European trees in Northern Ireland and in Germany, but there are gaps in both cases.

Independent checks can be made using historical samples. The uncertainty in the real age usually comprises decades. Moreover it is a delicate question to judge whether or not the provenience is sure.

The Swedish varve chronology can also be used independently, but its certainty does not yet suffice for conclusions. Similarly varves deposited in lakes can be used. In both cases there are certain risks of the addition of older material, contamination, and the use by the plants of old bicarbonate, the reservoir effect. The risk of contamination is so great for varved clay that it is never directly used for calibration purposes. Instead, a pollen-analytical level or a special event may be dated by varves and then by using peat in a nearby bog.

The radiocarbon time-scale

Since radiocarbon is produced by the interaction of cosmic rays with the atmosphere the question is whether or not the intensity of the cosmic rays was constant when entering the atmosphere. The cosmic rays are charged and such particles deviate in magnetic fields so that the cosmic-ray intensity is dependent on variations in the earth's magnetic field. The stronger the field – the smaller the ^{14}C production. Similarly solar activity will modulate the production of radiocarbon since charged particles are emitted, but radiocarbon is also produced so that two conflicting phenomena must be considered. The temperature changes cause changes in the amount of carbon dioxide dissolved in the oceans, the vegetation etc. I have only mentioned a few of the factors which affect the radiocarbon concentration of the atmosphere to demonstrate that one should expect the radiocarbon concentration to vary (Fig. 4).

It has been known since 1957 that the concentration varies. In 1958 de Vries tried to explain the variations, and the conference in Groningen the following year provided further evidence of such variations. Ten years later, in 1969, the

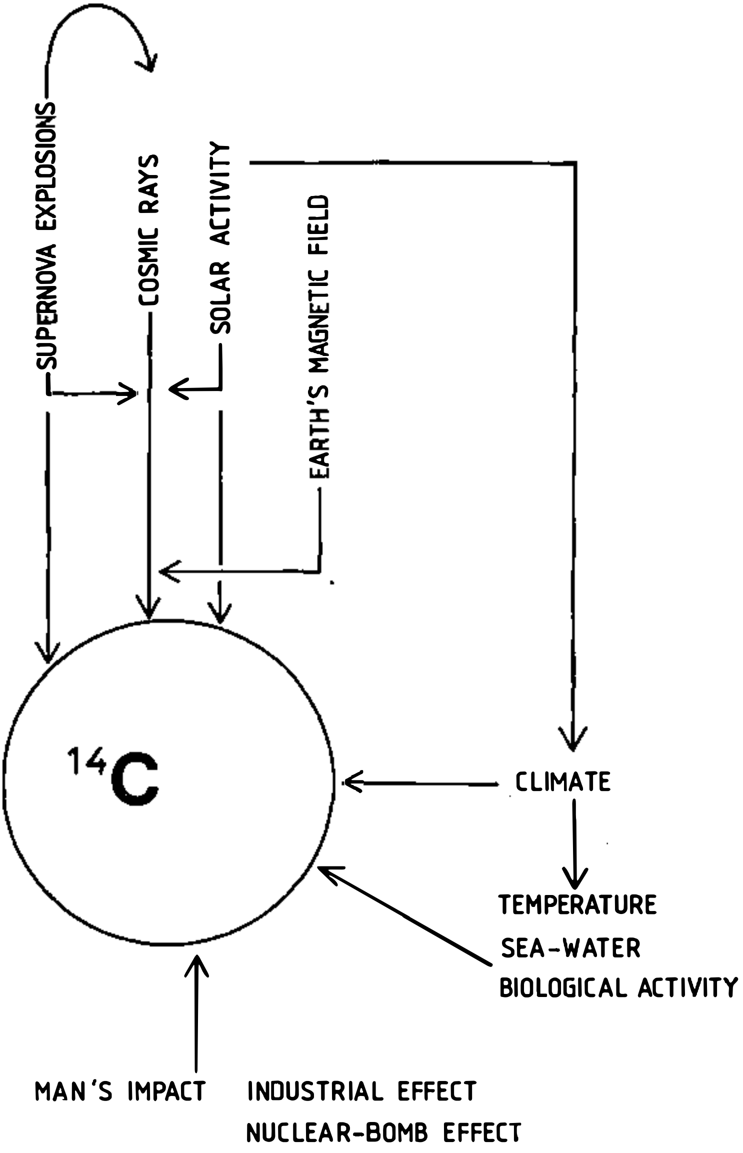

Fig. 4 A schematic diagram from 1969, illustrating possible sources of radiocarbon variations as discussed at the Twelfth Nobel Symposium.

variations and their causes were discussed at the Twelfth Nobel Symposium held in Uppsala. We were then convinced of the existence of long-term and short-term variations, but did not agree on the details although the accuracy of the measurements here improved enormously since 1959. At the 10th radiocarbon conference held in 1979 in Berne and Heidelberg many new results were available. It was stated that oscillations (called wiggles or wriggles), short-term variations, undoubtedly exist and appear to have a typical shape indicating a sudden change followed by a recovery over time. Much research is still needed but it seemed appropriate to try to coordinate the interpretations to yield a set of data for general use in the discussion of radiocarbon dates.

The radiocarbon variations can be depicted in different ways. We often plot the radiocarbon age, using the old half-life 5,568 years, as a function of the true age. Figure 5 illustrates important deviations during the last 400 years, but the radiocarbon ages are more or less correct for older samples back to about 2000 years ago. For still older samples the results are lower when expressed in radiocarbon years than in calendar years. The difference is about 800 years 6,000 to 7,000 years ago.

The last radiocarbon conference agreed to support a committee which will collect the data, search for possible errors, use statistical processing to combine the data into a curve over the secular variations, and advise the users how to interpret the dataset for different purposes, such as short-lived and long-lived samples. This will be a difficult and time-consuming task but the present confusion, with many different curves will be eliminated. The curve will naturally be revised when new data are released. New accurate determinations must be performed.

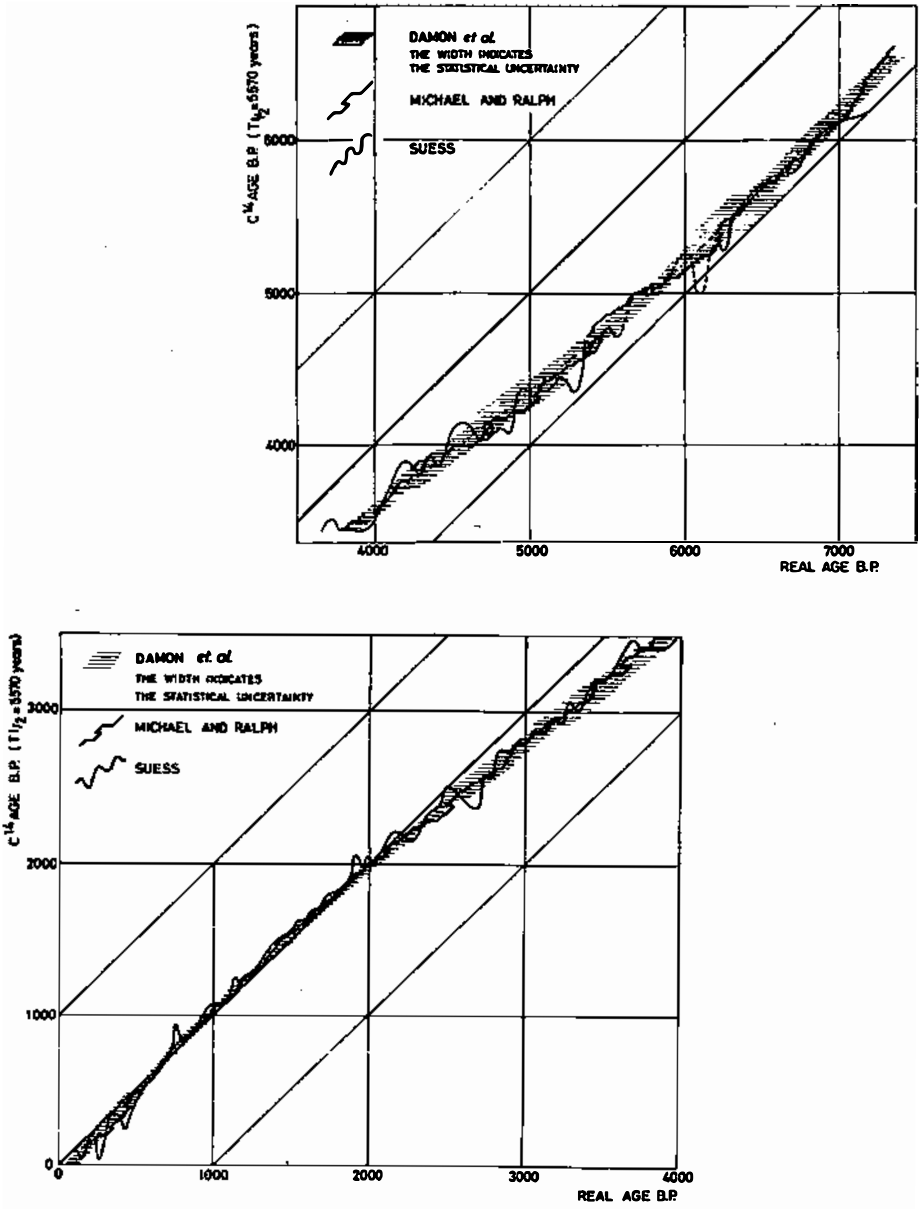

Fig. 5 Comparison between the calibration tables or curves published by Suess (1970) and by Damon et al. and by Michael and Ralph at the New Zealand conference.

Amount of sample

Most laboratories need 1 to 3g pure carbon for a normal dating. The amount is dependent on the construction of the equipment, which in turn is dependent on the requirements for the problems to be solved. Thus there are laboratories working with counters constructed for samples of about 0.1 gram or even samller. In Brookhaven small counters requiring 10 to 20 mg carbon have been constructed and an accuracy of 2% corresponding to an uncertainty of 160 years for a modern sample can be attained within 2-3 weeks. With measurements for 70 days the error thus can be reduced to about 80 years.

Most promising is, however, the small amount of sample which is needed for determination with an accelerator. A high accuracy can be achieved with 10 mg of carbon but samples as small as a fraction of a mg will probably be used in some cases. The preparation apparatus and technique must be improved.

Accelerators and radiocarbon in future

A normal question is whether or not accelerators will render the conventional dating counters obsolete. I believe we will appreciate having access to both techniques. Many samples are large enough to be treated in the conventional manner. We shall use the accelerators for small important samples and some of the research. Nobody is willing today to estimate the real costs of accelerator dating, and we will certainly see different figures in the immediate future, depending on the principles for the calculations and the accuracy desired. There is no indication that accelerator-produced dates will be cheaper than conventional dates.

I explained the contamination issue in considerable detail to demonstrate that the pretreatment problems cannot be avoided by the use of another method of measuring the activity. Other samples may, however, be selected and the work may then be different. Considering the higher accuracy expected and the longer time span to be covered the pretreatment will be of the greatest importance for the quality of the sample. This is obvious from the fact that a sample which is 70,000 years old retains only 0.03% of its original activity, and a sample 100,000 years old only 0.0005%. Thus I believe that more complicated pretreatment techniques must be developed to remove more of the contaminants.

I anticipate the isolation and dating of specific amino acids of bones instead of collagen. Research is in progress on the different compounds of wood. As far as we know holocellulose and lignin are suitable for dating and calibration work although the extractives are mobile at least in the sapwood and thus not representative of the activity of the atmosphere in the year corresponding to the relevant tree ring. Such studies are of interest for wood chemists too, who indeed prompted my own work on this problem. Since the clay in the varves used for the Swedish varve chronology is a typical material which should be avoided at radiocarbon dating I would appreciate the recovery of small macrofossils such as leaves and grains, whenever found, for dating with an accelerator. This would provide an excellent independent means of calibrating the radiocarbon time-scale, when the present revision of the Swedish varve chronology has proceeded so far as to reduce the uncertainty. Similar samples should be used for lake sediments, especially for checking the varves in lakes often found nowadays, since the coring technique has been improved. The selection of different samples from a sediment will allow us to study mixing phenomena such as bioturbation, and evaluate the uncertainty thereby caused. Pollution problems will be easier to study. Such studies are in progress using mini-counters. The use of small samples will enable us to date valuable samples from museums, which would be too seriously damaged by the present technique. Pieces of cloth represent one example. Single grains of cereals found at an excavation can be used to yield more accurate dates than charcoal since the cereals are short-lived and trees long-lived samples.

Geoscientists will certainly use accelerators in connection with diverse investigation. One will be groundwater dating. Sometimes large samples can and should be collected. This is the case when large amounts of water must be pumped to get representative samples. But sometimes there is a risk of disturbing the system, and then a small sample is representative. For conventional dating 30 to 50 l are usually collected. The amount depends on the amount of carbon dioxide dissolved. I must, however, insert a warning that the activity measurements are very difficult to interpret. Most of us prefer to avoid the word dating in connection with radiocarbon measurements of groundwater samples, and so do I. Such measurements are needed and of the greatest importance in connection with discussions of the disposal of nuclear waste.

Oceanographers will adduce radiocarbon for the discussion of mixing rates in the oceans. Much research will be devoted to the collection of data to enable scientists to arrive at better judgements of the ultimate fate of fossil carbon dioxide in the oceans. This is of importance to predict man's impact on the climate. One approach to the problem investigates the ^{14}C activity, total carbon and pH along profiles at different stations in the oceans. Since 200 l is the amount now usually collected for conventional dating it is easy to see how much work can be saved on board the research ships if samples less than 1 liter are sufficient, especially as the collection should be done also in deep water.

Glaciologists have been able to date very few ice samples and special (small) counters have therefore been built. They will have a fair chance to get their samples dated.

Acknowledgements

I wish to express my gratitude for the financial support for my work from the Swedish Natural Science Research Council.

REFERENCES

Books, proceedings

Libby, W.F., 1955: *Radiocarbon Dating*, 2nd ed. Univ of Chicago Press, 175 p.

Proceedings of the Sixth International Conference Radiocarbon and Tritium Dating, Washington State University Pullman, Washington, June 7-11, 1965. (Distributed by the Clearing house for Federal Scientific and Technical Information, 5285 Port Royal Road, Springfield, Va. 22151, USA).

Proceedings of the Eighth International Conference on Radiocarbon Dating, The Royal Society of New Zealand, Lower Hutt City, Wellington, New Zealand, October 18-25, 1972 (Distributed by Royal Society of New Zealand, 6 Halswell Street, P.O. Box 12249, Wellington, New Zealand.)

Proceedings of the Ninth International Conference Radiocarbon Dating, University of California, Los Angeles and San Diego, June 20-26, 1976. (In the press).

Proceedings of the Tenth International Radiocarbon Conference, Universität Bern, and Universität Heidelberg, Berne, Switzerland, and Heidelberg, Germany, August 19-26, 1979 (To be published in Radiocarbon).

Radiocarbon Variations and Absolute Chronology. Twelfth Nobel Symposium, Uppsala, Aug. 11-15, 1969, Almqvist & Wiksell, Stockholm, and John Wiley & Sons, New York.

For this survey the reference list has been kept short although relevant and easily accessible papers have been selected and included. I refer to the various lists found in the single papers and the conference proceedings.

Enrichment

Grootes, P.M., 1978: Carbon-14 time scale extended: Comparisons of Chronologies. *Science, 200,* 11-15.

Grootes, P.M., and Stuiver, M., 1979: The Quaternary isotope laboratory thermal diffusion enrichment system: Description and performance, *Radiocarbon, 21,* 139-164.

Hedges, R.E.M., and Moore, C.B., 1978: Enrichment of ^{14}C and radiocarbon dating. *Nature, 276,* 255-257.

Isotopic fractionation

Craig, H., 1954: Carbon 13 in plants and the relationships between carbon 13 and carbon 14 variations in nature. *J. Geol., 62,* 115-149.

Libby, L.M., and Pandolfi, L.1976: Isotopic tree thermometers: Correlation with radiocarbon. *J. Geophys. Res., 81,* 6377-6381.

Lyon, T.D.B., and Baxter, M.S., 1978: Stable carbon isotopes in human tissues. *Nature, 273,* 750-751.

van der Merwe, N.J., and Vogel, J.C., 1978: ^{13}C content of human collagen as a measure of prehistoric diet in woodland North America. *Nature, 276,* 815-816.

Olsson, I.U., and Osadebe, F.A.N., 1974: Carbon isotope variations and fractionation corrections in ^{14}C dating. *Boreas, 3,* 139-146.

Stuiver, M., and Polach, H.A., 1977: Reporting of ^{14}C data. *Radiocarbon, 19,* 355-363.

Stuiver, M, and Robinson, S.W., 1974: University of Washington Geosecs North Atlantic carbon-14 results. *Earth and Planetary Science Letters, 23,* 87-90.

Wigley, T.M.L., Gray, B.M., and Kelly, P.M., 1978: Climatic interpretation of δ^{18}O and δD tree rings, *Nature 271,* 92-94.

Wilson, A.T., and Grinsted, M.J., 1977: ^{12}C/^{13}C in cellulose and lignin as palaeothermometers. *Nature, 265,* 133-135.

Accelerator dating

Bennett, C.L., Beukens, R.P., Clover, M.R., Elmore, D., Gove, H.E., Kilius, L., Litherland, A.E., and Purser, K.H., 1978: Radiocarbon dating with electrostatic accelerators: Dating of milligram samples. *Science, 201*, 345-347.

Bennett, C.L., Beukens, R.P., Clover, M.R., Gove, H.E., Liebert, R.B., Litherland, A.E., Purser, K.H., and Sondheim, W.E., 1977: Radiocarbon dating using electrostatic accelerators: Negative ions provide the key. *Science, 198*, 508-510.

Doucas, G., Garman, E.F., McK. Hyder, H.R., Sinclair, D., Hedges, R.E.M., and White, N.R., 1978: Detection of ^{14}C using a small van de Graaff accelerator. *Nature, 276*, 253-255.

Hedges, R., 1978: New directions in carbon-14 dating. *New Scientist*, 2 March, 599-601.

Muller, R.A., 1977: Radioisotope dating with a cyclotron. *Science, 196*, 489-494.

Muller, R.A., Stephenson, E.J., and Mast, T.S., 1978: Radioisotope dating with an accelerator: A blind measurement. *Science, 201*, 347-348.

Nelson, D.E., Korteling, R.G., and Stott, W.R., 1977: Carbon 14: Direct detection at natural concentrations. *Science, 198*, 507-508.

Stuiver, M., 1978: Carbon-14 dating: A comparison of beta and ion counting. *Science, 202*, 881-883.

The reservoir effect and contamination problems

Broecker, W.S., Gerard, R., Ewing, M., and Heezen, B.C., 1960: Natural radiocarbon in the Atlantic Ocean. *J. Geophys. Res., 65,* 2903-2931.

Deevey, E.S., Gross, M.S., Hutchinson, G.E., and Kraybill, H.L., 1954: The natural ^{14}C content of materials from hardwater lakes. *Proc. Natl. Acad. Sci. U.S., 40,* 285-288.

Donner, J.J., Jungner, H., and Vasari, Y., 1971: The hard-water effect on radiocarbon measurements of samples from Säynäjälampi, north-east Finland. *Commentationes Physico-Mathematice, 41,* 307-310.

Geyh, M.A., Merkt, J., and Müller, H., 1970: ^{14}C-Datierung limnischer Sedimente und die Eichung der ^{14}C-Zeitskala. *Naturwissenschaften, 57,* 564-567.

Hjort, C., 1973: A sea correction for East Greenland. *Geol. Fören. Stockh. Förh., 95,* 132-134.

Mangerud, J., and Gulliksen, S., 1975: Apparent radiocarbon ages of recent marine shells from Norway, Spitsbergen, and Arctic Canada. *Quaternary Research, 5,* 263-273.

Olsson, I.U., 1979: A warning against radiocarbon dating of samples containing little carbon. *Boreas, 8,* 203-207.

Peng, T-H., Broecker, W.S., Kipphut, G., and Shackleton, N., 1976: Benthic mixing in deep sea cores as determined by ^{14}C dating and its implications regarding climate stratigraphy and the fate of fossil fuel CO_2. *In:* Andersen, N.R. & Malahoff, A. (eds.), *The fate of fossil fuel CO_2 in the ocenas.* Marine Sciences 6, Plenum Press, New York and London, 355-373.

Robbins, J.A., Krezoski, J. R., and Mozley, S.C., 1977: Radioactivity in sediments of the Great Lakes: Post-depositional redistribution by deposit-feeding organisms. *Earth and Planetary Science Letters, 36,* 325-333.

Shell dating

Chapell, J., and Polach, H.A., 1972: Some effects of partial recrystallisation on ^{14}C dating of Late Pleistocene corals and molluscs. *Quaternary Res.*, *2*, 244-252.

Donner, J., Eronen, M., and Jungner, H., 1977: The dating of the Holocene relative sea-level changes in Finnmark, North Norway. *Nor. Geogr. Tidsskr.*, *31*, 103-128.

Donner, J.J., and Jungner, H., 1975: Radiocarbon dating of shells from marine Holocene deposits in the Disco Bugt area, West Greenland. *Boreas*, *4*, 25-45.

Olsson, I.U., and Eriksson, K.G., 1965: Remarks on C^{14} dating of shell material in sea sediments. *In* Sears, M. (ed.) *Progr. Oceanogr.*, Pergamon, Norwich, *3*, 253-266.

Olsson, I.U., Göksu, Y., and Stenberg, A., 1968: Further investigations of storing and treatment of Foraminifera and molluscs for C^{14} dating. *Geol. Fören. Stockh. Förh.*, *90*, 417-426.

Bone dating

Bada, J.L., Hoopes, E., Darling, D., Dungworth, G., Kessels, H.J., Kvenvolden, K.A., and Blunt, D.J., 1979: Amino acid racemization dating of fossil bones. I. Interlaboratory comparison of racemization measurements. *Earth and Planetary Science Letters*, *43*, 265-268.

El-Daoushy,M.F.A F., Olsson, I.U., and Oro F.H., 1978: The EDTA and HCl methods of pre-treating bones. *Geol. Fören. Stockh. Förh.*, *100*, 213-219.

Hassan, A.A., Termine, J.D., and Haynes, C.V., 1977: Mineralogical studies on bone apatite and their implications for radiocarbon dating. *Radiocarbon*, *19*, 364-374.

Ho, T.Y., Marcus, L.F., and Berger, R., 1969: Radiocarbon dating of petroleum-impregnated bone from tar pits at Rancho La Brea, California. *Science*, *164*, 1051-1052.

Longin, R., 1971: New method of collagen extraction for radiocarbon dating. *Nature*, *230*, 241-242.

Olsson, I.U., El-Daoushy, M.F.A.F., Abd El-Mageed, A.I., and Klasson, M., 1974: A comparison of different methods for pretreatment of bones. I. *Geol. Fören. Stockh. Förh.*, 96, 171-181.

Absolute chronology (dendrochronology and varve chronology)

Ferguson, C.W., 1968: Bristlecone pine: Science and Esthetics. *Science*, *159*, 839-846.

Becker, B., 1979: Die postglaziale Eichenjahr ringchronologie Süddeutschlands und ihre Bedeutung für die Datierung neolithischer Chronologien aus der Schweiz. *Zeitschrift f. Schweizerische Archäologie und Kunstgeschichte 36*, 91-92.

La Marche, V.C., Jr., and Harlan, T.P., 1973: Accuracy of tree ring dating of bristlecone pine for calibration of the radiocarbon time scale. *J. Geophys. Res.*, *78*, 8849-8858.

Lundqvist, J., 1975: Ice recession in central Sweden, and the Swedish Time Scale. *Boreas*, *4*, 47-54.

Pilcher, J.R., Hillam, J., Baillie, M.G.L., and Pearson, G.W., 1977: A long sub-fossil oak tree-ring chronology from the north of Ireland. *New Phytol.*, *79*, 713-729.

The radiocarbon fluctuations

Clark, R.M., 1975: A calibration curve for radiocarbon dates, *Antiquity*, *49*, 251-266.

Damon, P.E., Ferguson, C.W., Long, A. & Wallick, E.I., 1974: Dendrochronologic calibration of the radiocarbon time scale. *Am. Antiquity*, *39*, No. 2, 350-366.

Damon, P.E., Lerman, J.C., and Long, A., 1978: Temporal fluctuations of atmospheric ^{14}C: Causal factors and implications. *Ann. Rev. Earth Planet. Sci.*, *6*, 457-494.

de Jong, A.F.M., Mook, W.G., and Becker, B., 1979: Confirmation of the Suess wiggles: 3200-3700 B.C., *Nature*, *280*, 48-49.

Münnich, K.O., 1957: Heidelberg natural radiocarbon measurements. *Science, 126,* 194-199.

Pearson, G.W., Pilcher, J.R., Baillie, M.G.L., and Hillam, J., 1977: Absolute radiocarbon dating using a low altitude European tree-ring calibration. *Nature, 270,* 25-28.

Ralph, E.K., Michael, H.N., and Han, M.C., 1973: Radiocarbon dates and reality. *Masca Newsletter, 9,* no. 1, 1-20.

Stuiver, M., 1978: Radiocarbon timescale tested against magnetic and other dating methods. *Nature, 274,* 271-273.

Suess, H.E., 1978: La Jolla measurements of radiocarbon in tree-ring dated wood. *Radiocarbon, 20,* 1-18.

Tans, P.P., de Jong, A.F.M., and Mook, W.G., 1978: Chemical pretreatment and radial flow of ^{14}C in tree rings. *Nature, 271,* 234-235.

de Vries, Hl., 1958: Variations in concentration of radiocarbon with time and location on earth. *Koninkl. Ned. Akad. Wetenschap., Proc. Ser. B., 61,* 94-102.