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Radiocarbon dating

Nobel Lecture, December 12, 1960

Introduction

Radiocarbon dating had its origin in a study of the possible effects that cosmic rays might have on the earth and on the earth's atmosphere. We were interested in testing whether any of the various effects which might be predicted could actually be found and used. Initially the problem seemed rather difficult, for ignorance of billion-electron-volt nuclear physics (cosmic ray energies are in this range) was so abysmal at the time and incidentally fourteen years later still is so abysmal, that it is nearly impossible to predict with any certainty the effects of the collisions of the multibillion-volt primary cosmic radiation with air.

Formation of radiocarbon

However, in 1939, just before the war, Professor Serge Korff of New York University and others discovered that the cosmic rays produce secondary neutrons in their initial collisions with the top of the atmosphere. The neutrons were found by sending counters, designed to be sensitive to neutrons, up to high altitudes and they were found to have an intensity which corresponded to about two neutrons being generated for each square centimeter of the earth's surface per second. Whereas it was extremely difficult to predict the types of nuclei that might be produced by the billion-volt primary cosmic rays, the neutrons being secondaries were in the million-volt energy range and therefore subject to laboratory tests. So at this point the question was : "What will million-electron-volt neutrons do if liberated in the air?" The answer to this question was already available - in fact, Professor Korff noted in one of the papers announcing the discovery of the neutrons that the principal way in which the neutrons would disappear would be to form radiocarbon. The reaction involved is a simple one. Oxygen is essentially inert to neutrons but nitrogen is quite reactive. Nitrogen-14, the abundant

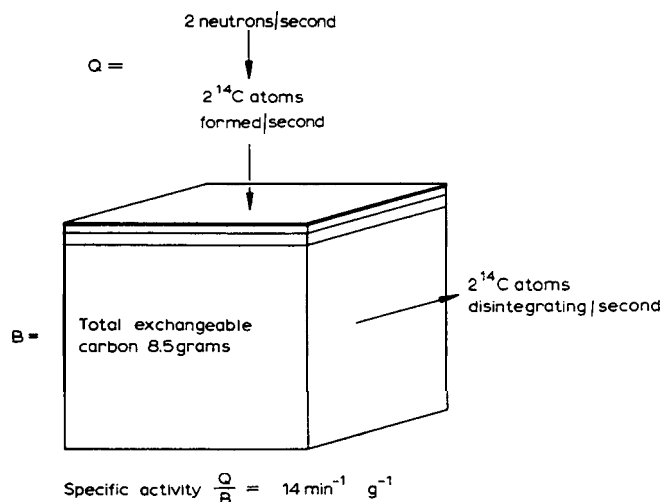


Fig. 1. Radiocarbon genesis and mixing.

nitrogen isotope, reacts essentially quantitatively to form carbon-14 with the elimination of a proton. It also reacts about one percent of the time to produce tritium, radioactive hydrogen, which is another story leading to a method of dating water and wine.

To return to radiocarbon dating - knowing that there are about 2 neutrons formed per square centimeter per second, each of which forms a carbon-14 atom, and assuming that the cosmic rays have been bombarding the atmosphere for a very long time in terms of the lifetime of carbon-14 (carbon-14 has a half-life of about 5,600 years) - we can see that a steady-state condition should have been established, in which the rate of formation of carbon-14 would be equal to the rate at which it disappears to reform nitrogen-14. This allows us to calculate quantitatively how much carbon-14 should exist on earth (see Fig. 1); and since the 2 atoms per second per cm^2 go into a mixing reservoir with about 8.5 grams of carbon per cm^2 , this gives an expected specific activity of living matter of $2.0/8.5$ disintegrations per second per gram of carbon.

The mixing reservoir consists not only of living matter which dilutes the radiocarbon, but of the dissolved carbonaceous material in the oceans which can exchange carbon with the atmospheric carbon dioxide and thus dilute it. In fact, the ocean is the larger part of the diluting carbon reservoir (see Table 1). For each square centimeter of the earth's surface, there are about 7.25 grams of carbon dissolved in the ocean in the form of carbonate, bicarbonate,

and carbonic acid, and the biosphere itself contains about 0.33 gram per square centimeter of surface. Adding all the elements of the reservoir, we get a total of 8.5 grams of diluting carbon per cm^2 , and the 2.0 carbon-14 atoms disintegrating every second should be contained in 8.5 grams of carbon. Thus, the specific activity of living carbon should be that number. We find this to be the actual value observed to within about 10 percent (see Table 2). Of course, the times for mixing of all parts of the reservoir must be short compared to the average lifetime of radiocarbon, 8,000 years. The time for mixing of the oceans is the longest, about 1,000 years on the average.

This is interesting, for it means the following : The present intensity of the cosmic radiation (unless there have been canceling errors in our calculations) corresponds to the average intensity over the last 8,000 years, the average life of carbon-14. It says also that the ocean is mixed nearly perfectly to its bottom depths in 8,000 years. This we know because we included all of the dissolved carbon in the sea. Also, direct measurement of the carbonate and bicarbonate in deep ocean water confirms this. These conclusions could be false if errors in the very different quantities - the intensity of the cosmic rays and the mixing rate and depths of the oceans - should happen just to cancel one another. Being so unrelated, we believe this to be very unlikely and conclude that the agreement between the predicted and observed assays is encouraging evidence that the cosmic rays have indeed remained constant in intensity over many thousands of years and that the mixing time, volume, and composition of the oceans have not changed either.

Table 1. Carbon reservoir make-up (g C/cm^2).

	<i>Anderson and Libby</i>	<i>W. W. Rubey</i>
Ocean, «carbonate»	7.25	6.95
Ocean, dissolved organic	0.59	0.78
Biosphere	0.33	
Humus	0.20	
Atmosphere	0.12	0.125
Total	8.5	7.9

We are in the radiocarbon-dating business as soon as this has been said, for it is clear from the set of assumptions that have been given that organic matter, while it is alive, is in equilibrium with the cosmic radiation; that is, all the radiocarbon atoms which disintegrate in our bodies are replaced by the

carbon-14 contained in the food we eat, so that while we are alive we are part of a great pool which contains the cosmic-ray produced radiocarbon. The specific activity is maintained at the level of about 14 disintegrations per minute per gram by the mixing action of the biosphere and hydrosphere. We assimilate cosmic-ray produced carbon-14 atoms at just the rate that the carbon-14 atoms in our bodies disappear to form nitrogen-14. At the time of death, however, the assimilation process stops abruptly. There is no longer any process by which the carbon-14 from the atmosphere can enter our bodies. Therefore, at the time of death the radioactive disintegration process takes over in an uncompensated manner and, according to the law of radioactive decay, after 5,600 years the carbon that is in our bodies while we are alive will show half the specific carbon-14 radioactivity that it shows now. Since we have evidence that this has been true for tens of thousands of years, we should expect to find that a body 5,600 years old would be one-half as radioactive as a present-day living organism. This appears to be true. Measurements of old artifacts of historically known age have shown this to be so within the experimental errors of measurement.

The research on radiocarbon dating consisted of several stages. In the first place, my collaborator, E. C. Anderson, and I had to determine whether the expected radioactivity of living material actually existed. At that time we had no measurement techniques sufficiently sensitive to detect the radioactivities involved directly because they are quite low levels of radioactivity. Later we developed methods for the measurement but at that time we did not have them, so we used the method of concentrating the heavy isotope of carbon. Such an apparatus had been built by and was being used by A. V. Grosse of Temple University, then of the Houdry Process Corporation at Marcus Hook, Pennsylvania. He was concentrating the carbon-13 isotope for medical tracer purposes and kindly agreed to try to concentrate some biological methane for the test so crucial to our research. We had to use biological as contrasted with petroleum methane, for we had at this point arrived at a distinction between living and dead organic chemicals. We had both dead methane and living methane in the sense that methane from oil wells in which the oil has been long buried would be expected to be entirely free from radiocarbon while the methane made from the disintegration of living organic matter should contain 14 dpm (disintegrations per minute) per gram of carbon. The task was to take this living methane and concentrate it in the isotope separation column to see whether the heavy enriched product was radioactive. Happily for our research, it was found to be so and in

about the expected amount. The material used was methane gas from the sewage disposal plant of the City of Baltimore.

The second stage of the research was the development of methods of measurement which were sufficiently sensitive so that we could avoid the use of a ten thousand dollar thermal diffusion isotope column and thousands of dollars of operating expense to measure the age of a single mummy. Obviously, radiocarbon dating would have been an impractical method of measuring archeological ages if this phase of the research had been unsuccessful.

The counting method developed involves measuring the radioactivity of the carbon directly. We convert the samples by chemical methods into a suitable form - carbon dioxide or acetylene gas or even solid carbon - which then is placed inside of a Geiger or proportional counter where it itself constitutes the gas or lies on the inner counter wall. This is possible because carbon as lampblack is an electrical conductor, and the gases CO_2 and C_2H_2 are satisfactory counter gases. In this way a maximum count rate is achieved.

The counter itself is shielded from the background radiations in order to accentuate the carbon-14 count. A typical shield is shown in Fig. 2 (p. 598). It consists of eight inches of iron to absorb the radiations from terrestrial radioactivity, such as uranium, thorium, and potassium. The cosmic rays, however, which consist at sea level largely of μ mesons, penetrate the thick iron shield readily; and whereas the unshielded count rate is about 500 counts per minute, it is decreased to about 100 counts per minute by the iron shield. The 100 remaining counts due in main part to μ mesons have to be removed. In order to do this, we surround the counter with the carbon-dating sample in it with a complete layer of Geiger counters in tangential contact with one another and wire them so that when any one of these counters counts, the central counter with the dating sample is turned off for about one thousandth of a second. In this way the μ mesons are eliminated from the record, so the background comes down to something between 1 and 6 counts per minute, depending on detailed counter and shield design. This is for a counter of about one liter volume capable of holding up to 5 grams of carbon with counting rates of 75 counts per minute for living carbon, 37.5 counts for 5,600-year-old carbon, 18.7 counts for 11,200 years, and 0.07 counts for 56,000 years.

After developing a technique which could measure natural carbon relatively inexpensively with the requisite accuracy, our next job was to determine whether the assumption - that the variation of radiocarbon production due to the variation of the cosmic rays with latitude, which is very strong

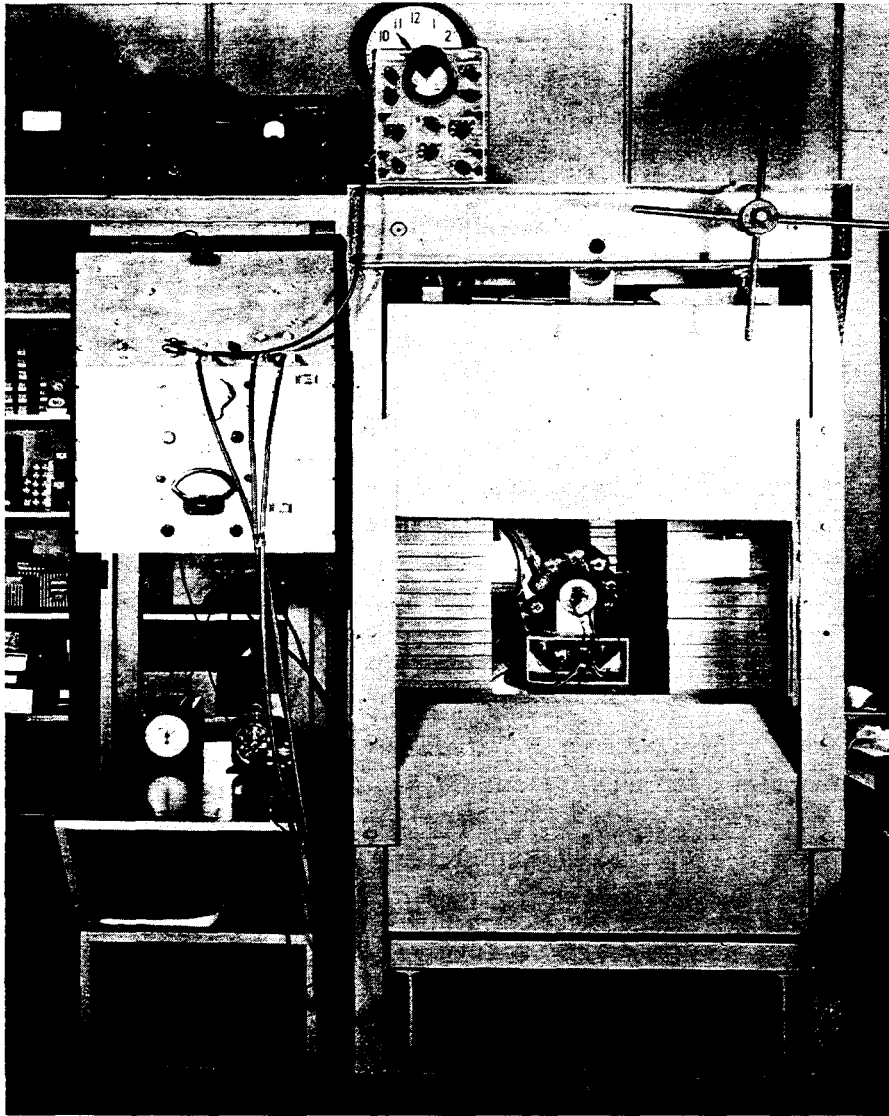


Fig. 2. Radiocarbon counting apparatus.

indeed, would be wiped out by the movement of the winds and the ocean currents in the 8,000-year lifetime of carbon-14 - was sound. The plan was to measure living materials from various places on earth and to see whether they had the same radiocarbon content per gram of carbon. These data on the natural abundance of radiocarbon in the earth were presented by E. C.

Anderson for his doctoral thesis at the University of Chicago. They show no appreciable differences even though they come from places varying in latitude from near the South Pole to near the North Pole (Table 2). At the present time, ten years later, no evidence for variation has been found except in areas of extensive carbonate deposits where the surface waters may carry a considerable amount of old carbon dissolved, and thus reduce the carbon-14 level below the world-wide average for the biosphere-atmosphere-ocean pool as a whole. Fortunately, such conditions are relatively rare and generally easily recognized.

Our whole research was supported generously by the Viking Fund of New York City (now the Axel Wenner-Gren Foundation), the United States Air Force, the Geological Society, the Guggenheim Foundation, and, of course, by the University of Chicago, where most of our research was done.

After the study of the natural occurrence of radiocarbon, the next stage was to see whether we had a method of dating artifacts of a known age. This led us to mummies. J. R. Arnold joined us at this stage. We had a decay

Table 2. Activity of terrestrial biosphere samples.

<i>Source</i>	<i>Geomagnetic latitude</i>	<i>Absolute specific activity (dpm/g)</i>
White spruce, Yukon	60° N	14.84 ± 0.30
Norwegian spruce, Sweden	55° N	15.37 ± 0.54
Elm wood, Chicago	53° N	14.72 ± 0.54
<i>Fraxinus excelsior</i> , Switzerland	49° N	15.16 ± 0.30
Honeysuckle leaves, Oak Ridge, Tenn.	47° N	14.60 ± 0.30
Pine twigs and needles (12,000 ft. alt.), Mount Wheeler, New Mexico	44° N	15.82 ± 0.47
North African briar	40° N	14.47 ± 0.44
Oak, Sherafut, Palestine	34° N	15.19 ± 0.40
Unidentified wood, Teheran, Iran	28° N	15.57 ± 0.31
<i>Fraxinus mandshurica</i> , Japan	26° N	14.84 ± 0.30
Unidentified wood, Panama	20° N	15.94 ± 0.51
<i>Chlorophora excelsa</i> , Liberia	11° N	15.08 ± 0.34
<i>Sterculia excelsa</i> , Copacabana, Bolivia (9,000 ft. alt.)	1° N	15.47 ± 0.50
Ironwood, Majoro, Marshall Islands	0°	14.53 ± 0.60
Unidentified wood, Ceylon	2° S	15.29 ± 0.67
Beech wood, Tierra del Fuego	45° S	15.37 ± 0.49
<i>Eucalyptus</i> , New South Wales, Australia	45° S	16.31 ± 0.43
Seal oil from seal meat from Antarctic	65° S	15.69 ± 0.30
Average		15.3 ± 0.1

curve drawn which predicted with no unknown factors, no adjustable constants, the specific activity of ancient organic matter. And so the question was to see whether it worked. The first thing we had to do, of course, was to get the materials for measurement. This was done by enlisting the cooperation of the American Anthropological Association and the American Geological Society. Geologists have been quite interested in the results of this dating technique from the beginning even though its reach in time is short for many of their problems. A committee of advisors consisting of Donald Collier, Richard Foster Flint, Frederick Johnson, and Froelich Rainey was appointed to select the samples for us and to help us collect them. These distinguished gentlemen worked hard for several years, assisting and collecting the samples and advising us. The research in the development of the dating technique consisted of two stages - the historical and the prehistorical epochs. The first shock Dr. Arnold and I had was when our advisors informed us that history extended back only to 5,000 years. We had thought initially that we would be able to get samples all along the curve back to 30,000 years, put the points in, and then our work would be finished. You read statements in books that such and such a society or archeological site is 20,000 years old. We learned rather abruptly that these numbers, these ancient ages, are not known accurately; in fact, it is at about the time of the First Dynasty in Egypt that the first historical date of any real certainty has been established. So we had, in the initial stages, the opportunity to check against knowns, principally Egyptian artifacts, and in the second stage we had to go into the great wilderness of prehistory to see whether there were elements of internal consistency which would lead one to believe that the method was sound or not.

For the prehistoric period our committee set up a network of problems which were designed to check, in as many ways as possible, points of internal consistency. They set out about a dozen major projects, and we collected samples from each of these projects and worked hard and measured them, and similar measurements are still going on now ten years later.

Fig. 3 shows the Curve of Knowns - the results obtained for samples of known age compared to the carbon-14 decay curve drawn from the present living matter value of 14 taken as unity, with a half-life of $5,568 \pm 30$ years. The half-life itself was measured in 1949 in collaboration with A. G. Engelkemeir, W. H. Hamill, and M. G. Inghram to be $5,580 \pm 45$ years, a value which when combined with independent values of $5,589 \pm 75$ by W. M. Jones, and $5,513 \pm 165$ by W.W. Miller, R. Ballentine, W. Bernstein, L.

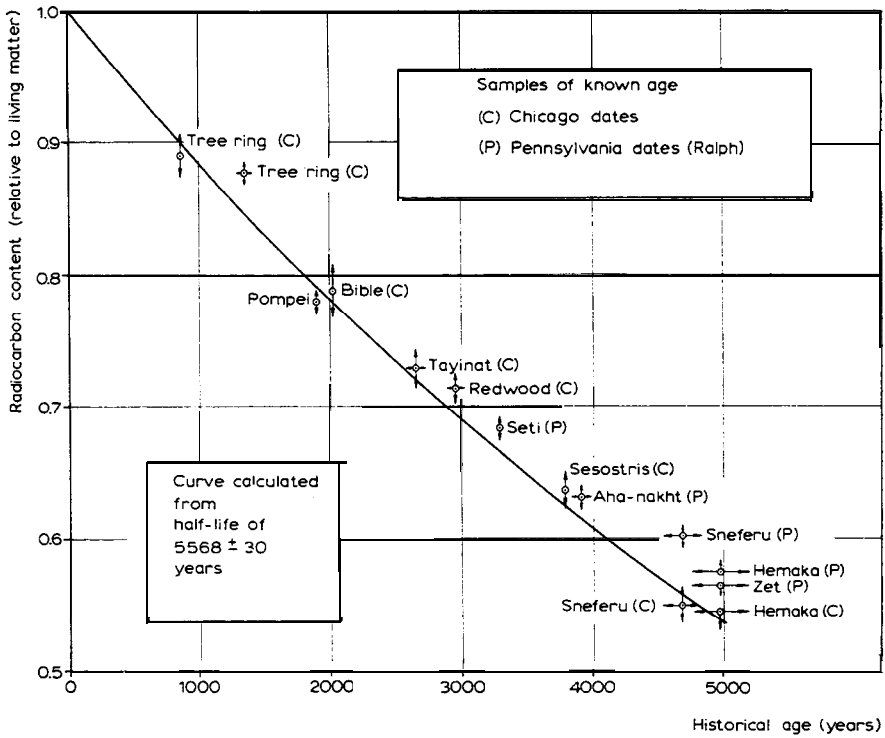


Fig. 3. Curve of Knowns.

Friedman, A. O. Nier, and R. D. Evans, gave $5,568 \pm 30$ by weighting according to the inverse square of the errors quoted. Re-measurements are in progress now by Mann at the National Bureau of Standards in Washington and by Olsson in Uppsala.

The knowns are in two main groups- those measured by us at the University of Chicago and those measured by Miss Ralph at the University of Pennsylvania labeled (C) and (P) respectively. One sample "Pompeii" was measured by E. A. Olson and W. S. Broecker of the Lamont Geological Observatory.

The oldest samples of known age measured were Hemaka and Zet from the First Dynasty in Egypt. Both were wood found in the subterranean brick structures of the First Dynasty tombs of the Vizier Hemaka and of King Zet, both at Saqqara. Hemaka was contemporaneous with King Udimu, and both tombs were generally agreed to be $4,900 \pm 200$ years before the present. The next oldest samples were cedar wood from the upper chamber of the Southern Pyramid of Sneferu at Dahshur. The next sample marked Sesostris is a very interesting one. It is a part of the deck of the funeral ship



Fig. 4. Hair of Egyptian woman, 5,000 years old.
Wood from glacial moraine, more than 20,000 years old.

which was placed in the tomb of Sesostris III of Egypt and is now in the Chicago Museum of Natural History. It is about 20 feet long, 6 feet wide, and is quite an imposing object, complete with paddles. Our sample came from the deck. The next sample is Aha-nakht. It consisted of wood, probably cedar from the outer sarcophagus of Aha-nakht, at El Bersheh. It was found in the tomb which was covered with earth. The coffin was presumably excavated by the natives at the same time as the El Bersheh coffin obtained for the British Museum by E. A. W. Budge after 1895.

Proceeding up the curve, the next sample is the heartwood of one of the largest redwood trees ever cut. The tree was known as the "Centennia Stump" felled in 1874 with 2,905 rings between the innermost (and 2,802 rings between the outermost) portion of the sample and the outside of the tree. Therefore, the known mean age, according to the tree-ring method of Douglas was $2,928 \pm 51$ years, as of the time it was cut. This is an interesting point, as it shows that in the heartwood of the *Sequoia gigantea* at least the sap is not in chemical equilibrium with the cellulose and other large molecules of the tree. In other words, the carbon in the central wood was deposited there about 3,000 years ago, although the tree itself was cut just a few years ago. The next sample, which is marked Tayinat, is from a house in Asia Minor which was burned in 675 B.C. It was wood from the floor of a central room in a large Hilani ("Palace" of the "Syro-Hittite" period in the city of Tayinat in Northwest Persia. Its known age is $2,625 \pm 50$ years.

The next is the linen wrapping of one of the Dead Sea Scrolls, the Book of Isaiah, which was found in Palestine a few years ago. The next sample, labeled "Pompeii", was carbonized bread from a house of ancient Pompeii still retaining the appearance of a baker's roll that seemingly was overdone, which was charred by the volcanic ashes that buried the city in 79 A.D., roughly 1880 years ago. The other samples are wood which were dated by the Douglas tree-ring counting technique. Taking these samples all together, the agreement with the predicted radiocarbon content seems to be satisfactory. The errors are given as the counting errors (standard deviations) only.

It is certainly possible that the decay curve, which is drawn according to the half-life of 5,568 years, could be drawn somewhat differently. However, it is well to know that all radiocarbon dates published today have been calculated on this half-life; and in order to avoid confusion, we should be careful in changing the basis of the calculation of radiocarbon ages until the evidence for a change in half-life is definite. The Curve of Knowns seems to indicate that a slightly longer half-life might be permissible. However, there are other possible explanations of a deviation of the Curve of Knowns from the theoretical curve. We will all await the results of the half-life researches of Dr. Mann and Miss Olsson with great interest.

It has been observed that fossil carbon dioxide from the combustion of coal and oil beginning at about 1870 began to dilute the biosphere and to reduce the radiocarbon content until 1954, when the explosion of atomic devices reversed the trend. The carbon-14 introduced by the neutrons produced in the explosions more than compensated for the reduction by the fossil carbon, which at that time had amounted to about 3 percent in the Northern Hemisphere as compared to the primeval level extending as far back as has been



Fig. 5. Peruvian rope, 2,600 years old.
Linen wrappings of Book of Isaiah of Dead Sea Scrolls, 2,000 years old.

possible to measure by tree rings. Hl. de Vries and Hans E. Suess have been particularly active in research on this point. Dr. Suess, in fact, discovered the fact that fossil carbon dioxide was reducing this specific activity in recent biospheric material as compared to the general level prior to 1870. Broecker and Olson have made careful studies of the carbon-14 content of ancient woods as well. And the general result is that prior to 1870 there appeared to be only very minor variations on the order of one percent or less in the radiocarbon content of living matter. The recent perturbations are of no great concern for present living archeologists and geologists. Of course, in the future it will be difficult to correct for the period when these perturbations were active; i.e., 5,000 years from now there may be some difficulty in understanding why for the period of a century or so, beginning in 1870, the radiocarbon level was so perturbed. However, the written records may well explain the anomaly. And, in fact, radiocarbon dating as such may not be needed to establish historical fact.

Following the test of the Curve of Knowns, the next step in the research was to test in the great periods of prehistory to see whether the dates obtained were reasonable. Perhaps the most interesting single general result in this prehistoric period is the time at which the last ice sheet moved down to cover the northern part of the United States and the European continent. The result $11,400 \text{ years} \pm 200 \text{ years}$ has now been well established by the radiocarbon technique; i.e. the radiocarbon dates for this cataclysmic development show first that it happened simultaneously in Europe and in North America and that the phenomenon was very widespread, and that it had a tremendous impact on the living habits of the people the world over; e.g., the oldest sign of man in Northern Europe and in England is younger than this, presumably because of the thoroughness with which the glacier removes all sorts of human artifacts. So the oldest of the Scandinavian and English occupation sites, all are about 10,400 years, corresponding presumably to the time when the ice sheet receded.

In Fig. 6, we have plotted for the Americas just the number of occupation sites versus age measured by radiocarbon. It is quite clear that there is an abrupt discontinuity at about the time of 10,400 years. In Europe, however, if instead of examining sites in northern regions we look at Mediterranean basin sites, there is no discontinuity, and evidences of human occupation extend back as far as the radiocarbon dating technique can reach - 50,000 years or so. There seems to be some contrast between this and the situation in the Americas, where, as shown in Fig. 6, one sees a decided difference in

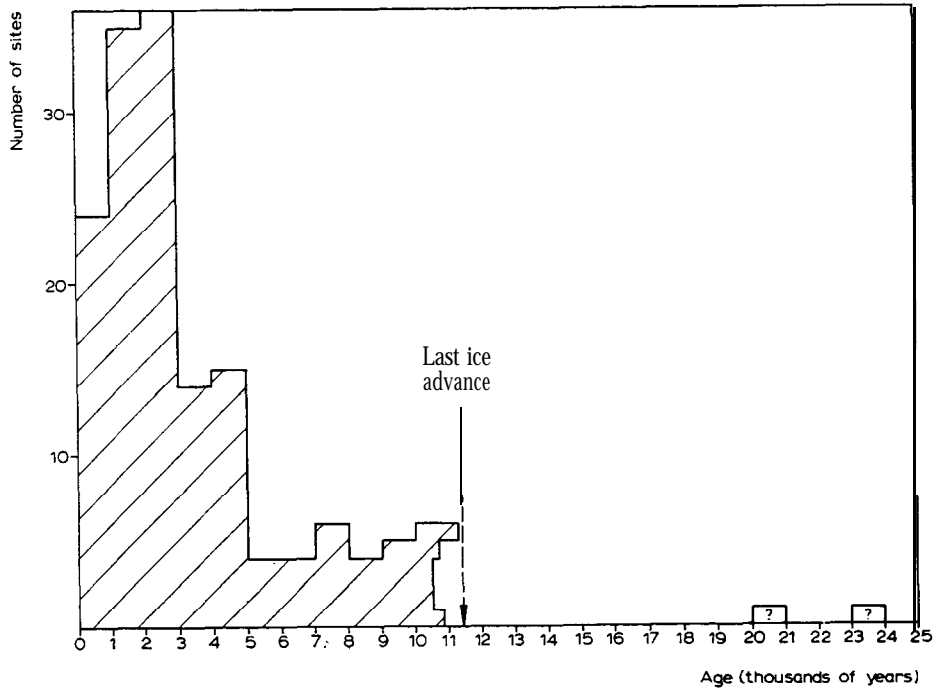


Fig. 6. Number of human sites in the Americas vs. age.

the total number of sites in preglacial times. In view of the fact that it is known that extensive areas of the Americas were not glaciated by the last ice sheet, this raises something of a question. There is, of course, the definite possibility that this is pure accident, and it even seems possible that we do now have human sites in the Americas which are definitely older than 10,400 years. However, just the weight of the evidence seems to indicate that something in the way of a discontinuity occurred at that time. Most of the sites that are older than 10,400 years are equivocal in one way or another, at least to the chemist or physicist who overhears the archeologists arguing about them. We have noticed that there is a considerable unanimity of opinion about American sites of 10,400 years or younger being human sites; whereas, there is considerable tendency for discussion and debate for the older sites. This is not true, however, in Southern Europe and Asia Minor. One of the most remarkable of the sites in Europe is the Lascaux Cave in Central France, which has the beautiful paintings on the walls, showing the ancient animals in such authentic style as to demonstrate the remarkable advancement of the culture of the people at that time. These paintings are presumably older than

15,000 years because the charcoal found in the soil of the cave had this value. Around Asia Minor and in the areas of the Middle East, there is no scarcity of materials which go back as far as radiocarbon can reach, with considerable evidence that the sites are human in nature.

In addition to the work on human history, radiocarbon has been used for geological purposes to a considerable extent. Of course, the time span of radiocarbon is so short compared to the history of the earth, that most geological problems are outside its reach. But recent history and recent events do fall within its grasp, and there have been a number of investigations, particularly the sorting out and measuring of the chronological events of the recent ice ages; i.e., the relative times of arrival of the various ice advances and the periods of time between them and the points of simultaneity, and the identification of particular moraines with particular advances. On these points, small as they are, and perhaps relatively unimportant, the geologists have found radiocarbon to be of some use.

In oceanography, the great question of the rate of mixing of the oceans has yielded to the radiocarbon technique to a considerable extent, particularly in the hands of Suess and Broecker and Olson; Suess particularly in the Pacific, and Olson and Broecker in the Atlantic. They have shown that the Pacific mixes relatively less rapidly, the turnover time being something between 1,500 and 2,000 years; whereas, the Atlantic mixes relatively more rapidly at a rate about twice this, or with a 750- to 1,000-year turnover time. It is clear from these researches that the fundamental assumption of radiocarbon dating, that the reservoir of the sea must be counted as a diluent for the cosmic ray carbon-14, is valid. Further, it has been shown by Suess that there will be opportunities of measuring the deep ocean currents. He finds evidence for velocities and directions of the deep ocean currents in the Pacific corresponding to some hundreds of years for the passage northward along the bottom.

In meteorology, radiocarbon dating has had some usefulness. It has been interesting to observe the changes of the radiocarbon content in living matter near large industrial centers where the rate of production of carbon dioxide from coal and oil was highest, and also to observe the dissemination of the radioactive carbon made by atomic explosions in the atmosphere. From these things we know that there is world-wide mixing which occurs. We observe the effects which generate very largely in the Northern Hemisphere quite clearly in the Southern Hemisphere, though they are reduced somewhat in intensity. This is the first time that there has been clear and incontrovertible

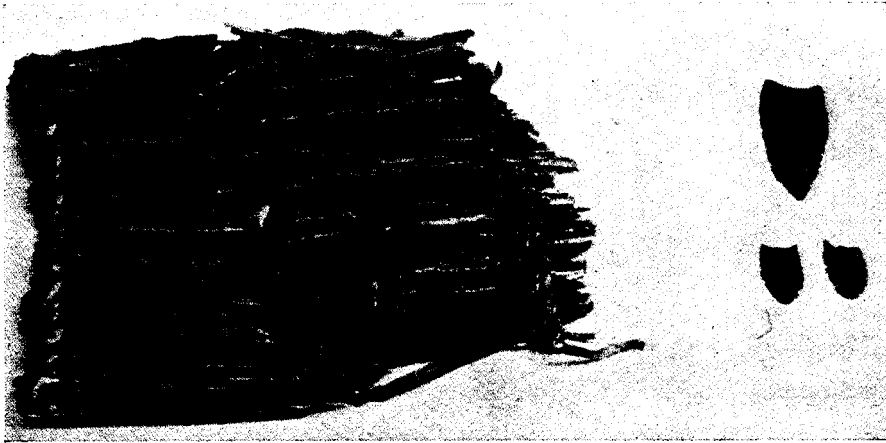


Fig. 7. Rush matting from Nevada cave, 3,000 years old.
North American arrowhead (replicas), 10,000 years old.

evidence for such a world-wide circulation and on a time scale of a matter of a very few years, particularly in the case of the bomb-test carbon-14.

Of course, the main point of radiocarbon dating is archeology and the investigation of the history of man through the use of chemistry, for most of the ancient men did not write and we have no written records except in Egypt, Asia Minor, and in limited areas of Central America. Yet it is perfectly clear that back 10,000 and more years ago, people lived so as to rival modern man in intelligence and capabilities. We have just to look at their handiwork to see this. The paintings in the Lascaux Cave, the handiwork of the ancient Indians in North America - particularly the basketry and the very skilfully made arrowheads - attest to their great capabilities. Where they came from perhaps we do not know, but we do know that they were very intelligent and very capable people.

Last spring, on an island off the coast of California, Santa Rosa Island, friends of mine found a 6-foot skeleton, 10,400 years old by the radiocarbon measurements of Dr. Broecker of Lamont Geological Observatory on some charcoal found next to the skeleton. This is the same 10,400 years date which we have observed so often and now marks the early sign of man in Santa Rosa Island; the Lindenmeier Site in Colorado; the Clovis Site; the Lamus Cave in eastern Nevada on the Utah-Nevada border, where continuous occupancy occurred from the time of the melting of the last glacier 10,400 years ago down to the time when modern man came into the area; the Fort



Fig. 8. Rope sandal found in Oregon Cave, 9,000 years old.
Dung of extinct ground sloth, 10,000 years old.

Rock Cave in Oregon, where the most beautiful basketry of ancient man was discovered - grass rope woven into sandals of beautiful shape and design - three hundred pairs of them neatly stacked just as though they were a community store of shoes 9,000 years old; and several other sites in the Americas. We see in this the evidence that man has been a long time learning to write history, but has been making history for many thousands and perhaps tens of thousands of years.

In Central Europe the element of simultaneity, which is revealed by the radiocarbon dates for the people who did not write or leave records, establishes conflicts and clashes between cultures which are interesting to examine and speculate upon. The Neanderthal man and Cro-Magnon man did not stay long together. The Neanderthal man disappeared and the Cro-Magnon man won - he may have been the man who painted the beautiful Lascaux Cave paintings, as I understand it from the archeologists.

We learn various details about the ancient peoples. For example, in the time of Hammurabi, the Babylonian King, there was an accurate calendar, but we were not certain about the correlation of this calendar with our own. It was a very good calendar the Babylonians had, but there is an uncertainty which, as I understand it, is due to the identification of a particular eclipse as we calculate it backwards in time in order to arrive at the correlation to our own calendar. Therefore, careful measurements were made on a portion of a house about 4,000 years old that was accurately dated on the Babylonian calendar. In this case, a serious attempt was made to test the limit of sensitivity of the radiocarbon dating method. The sample of wood came from a beam

from the roof of a house in Nippur which bore a clear and legible Hammurabian calendar date. The beam was divided into three equal portions which were carefully measured with a total measurement time of three months and the results on the three portions were then coordinated to arrive at a definite answer as to which of the most likely correlations of the Christian Calendar with the Babylonian Calendar was correct. We concluded that the younger of the possible calendars was strongly favored and that the odds against the other being correct were something like 9 to 1.

With the advancement of the radiocarbon dating technique and the consequent increase in accuracy, at least of the relative dates, it is possible to do more of these difficult jobs of pinpointing past events in time so as to drive back history into prehistoric periods and to more clearly delineate what really did happen in the development of man. The determination of the chronology of ancient civilizations may be said to be the main archeological problem and task of radiocarbon dating. As the technique is developed further and more fully and is more widely used, it should be possible to excavate and utilize sites which are now hardly more than dark spots in some remote area. Charcoal is one of the best materials for radiocarbon dating, providing adequate care is taken that intrusive rootlets and humic acids are removed before measurement.

We intend at UCLA to attempt to make a portable radiocarbon dater which will allow us to work in the field with the archeologists and geologists in obtaining dates which, though not as accurate as those which would be obtained in the laboratory, may be useful enough to serve as guides during the digging. The problem is to find a truck which will carry the rather heavy equipment over the rough country which is usually involved. If this effort is successful, it will be a development which will bring the carbon daters and the archeologists and geologists even closer together. Of all the rewards of research, none is greater than the meeting of people in different fields and the finding of interests in common. It will be most refreshing and rewarding for the radiocarbon daters to go out and partake, at least vicariously, in the great thrill of an archeological dig.

The large number of people who have contributed to the development of the radiocarbon dating technique, several of whom I have mentioned today, but many of whom I have been unable to mention, are largely responsible for whatever success it has had. We now have several thousand radiocarbon dates throughout the fields of archeology, geology, meteorology, oceanography, and other areas. From the examination of the results, it is possible to

form an opinion as to the general reliability and general weaknesses of the method. I am sure that Dr. Arnold would agree with me in saying that it has lived up to our fondest hopes. It was clear from the beginning that there would be difficulties about the samples. Anyone knows it is possible to get dirt into solid matter which is lying in the ground, even if it is there only for a brief period, let alone many thousands or tens of thousands of years. The saving aspect of the situation, however, is that it is very much more difficult to mix molecules in such a way that they cannot be separated chemically, particularly in the case of substances such as charcoal and wood and cloth, and even in certain cases for limestone and shale. One can separate and distinguish the contaminant from the original material and in this way disclose the real radiocarbon content. The researches of a number of people have validated the assumption that it is possible and that, indeed, it is not too difficult to obtain authentic samples in the field. In general, the samples may have to be inspected with some care under a relatively high-powered glass and then possibly treated with properly chosen chemicals. But all of these things can be done and with techniques that are no more difficult than those used by the average hospital technician, and a sample can be obtained which should give authentic radiocarbon dates. The dating technique itself is one which requires care, but which can be carried out by adequately trained personnel who are sufficiently serious-minded about it. It is something like the discipline of surgery - cleanliness, care, seriousness, and practice. With these things it is possible to obtain radiocarbon dates which are consistent and which may indeed help roll back the pages of history and reveal to mankind something more about his ancestors, and in this way perhaps about his future.

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

R. F. Flint and E. S. Deevey, Jr., (Eds.), *American Journal of Science, Radiocarbon Supplement*, Vol. I (1959), 218 pp.

R. F. Flint, E. S. Deevey, Jr., and Elizabeth G. Weinman, (Eds.), *American Journal of Science, Radiocarbon Supplement*, Vol. II (1960), 228 pp.