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Ancient Egyptian radiocarbon chronology

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Radiocarbon dates have been measured which were obtained from historically well-dated Egyptian samples belonging to the time period from the I to XXX dynasties. The radiocarbon and historical chronologies go hand in hand for the entire period in which historical time placement can be independently verified by astronomical calculations, that is up to the time of Sesostris III of the XII dynasty. From this point on a calibration based on an empirical relationship between conventional radiocarbon dates and dendrochronologically determined wood ages derived from bristlecone pine approximates the presently recognized historical chronology of what amounts to mostly the time of the Old Kingdom in the 3rd millennium B.C. A number of reasons seeking to explain the differences between historical and radiocarbon chronologies in that millennium are offered. So far, conventional radiocarbon measurements of ancient Egyptian samples can be converted to dates coming close to fitting the presently accepted historical chronology by calibration against the bristlecone pine correlation. However, some ancient Egyptian dates appear to correlate better to the historical chronology if only the 5730-year half-life is used.

Introduction

For the first time the discovery of radiocarbon dating by Libby (1955) made it possible to date with good accuracy many archaeologic and geologic specimens of unknown age which had accumulated over the years in collections and museums everywhere. In retrospect it is easy to appreciate the fact that most of the early dating work was directed toward prehistoric samples. Libby had shown convincingly the veracity of the new method by correlating predicted against observed radioactivities in samples of known age. Indeed, most samples of known historical age gave the expected radiocarbon dates within experimental error, except for a few.

Over the years improvements were made in the accuracy with which radiocarbon could be determined in the laboratory. This led to the realization that there existed in fact discrepancies between certain samples of more or less well-known age and their radiocarbon content. These differences were thought to be due to secular variations in the level of radiocarbon activity in the atmosphere, and were first pointed out by de Vries, Barendsen & Waterbolk (1958). Subsequently a number of different investigators reported on this phenomenon such as Damon, Long & Gray (1966); de Vries (1958); de Vries & Waterbolk (1958); Kigoshi & Hasegawa (1965); Libby (1963); Lingenfelter (1963); Münnich, Östlund & de Vries (1958); Stuiver (1961, 1965); Stuiver & Suess (1966); Suess (1965); Willis, Tauber & Münnich (1960) and Wood & Libby (1964). More recently, these investigations were broadened by the work of Berger (1970); Berger & Libby (1967, 1970); Bucha (1969); Bucha, Taylor, Berger & Haury (1970); Lal & Venkatavaradan (1969); Labeyrie, Delibrias & Duplessy (1969); Lingenfelter & Ramaty (1969); Neustupny (1969); Ralph & Michael (1969); Säve-Söderbergh & Olsson (1969); Stuiver (1969); Suess (1969); Vogel (1969) and Vogel, Casparie & Munaut (1969).

Much of the earlier research into the possibility of secular variations of the ^{14}C content of the atmosphere was of a qualitative nature showing the occurrence of discrepancies rather than their exact quantitative character. The most intensive quantitative study carried so far is that by Suess (1969) who used dendrochronologically dated wood, mainly bristlecone pine

(*Pinus aristata*), to check the radiocarbon content of the atmosphere of the past. This work was carried out presupposing isotopic equality in the carbon isotopes of the atmosphere and wood contained in a tree-ring of the same year. Since the oldest bristlecone pine logs are only found in the White Mountains of California (Ferguson 1969) the question arose if it would not be possible to check the nature of the ^{14}C deviations by some other means. Unfortunately, up till now no trees of equally great age have been found anywhere in the world which can supply a continuous dendrochronological sequence from today far into the past, more than 7000 years.

Radiocarbon dates from ancient Egypt

The oldest and best understood historical sequence is the chronology of Egypt (Hayes 1964). Therefore it was decided to measure the radiocarbon content of historically well-dated and geochemically well-suited samples. In order to minimize errors due to inadequate sample selection or collection, a plan was developed by I. E. S. Edwards of the British Museum, London, in conjunction with W. F. Libby of the University of California, Los Angeles, to obtain the best material directly from Egypt. With archaeological cooperation of W. B. Emery, University College, London, G. T. Martin of Corpus Christi College, Cambridge, secured most of the samples dated below after consultation as to the best datable material with the author.

The sample materials held most suitable were those derived from plants growing within a single year such as reed or flax. All specimens dated at the University of California, Los Angeles (UCLA), were first treated in dilute hydrochloric acid to remove inorganic carbon, washed in water, treated repeatedly in dilute sodium hydroxide for removal of any humic acids, washed in acidic water to counter atmospheric CO_2 absorption during alkali immersions, washed in distilled water, and dried.

Then the decontaminated specimens were burnt in a stream of oxygen to carbon dioxide. This gas was purified extensively to reduce electro-negative impurities to parts per million level or less. For this purpose the gas was passed through hot copper oxide, wash towers containing 0.1 mol of silver nitrate and others filled with chromic acid. Finally, the pre-purified gas was circulated repeatedly through hot elementary copper turnings. After complete radon decay the carbon dioxide to be assayed was transferred into a 7.5 l proportional counter equipped with three energy channels. The all-solid-state unit is supplied with high voltage from a remarkably stable and interference-free battery source. All samples were counted repeatedly to a statistical counting error of at least 1 σ.

In the calculation of the radiocarbon age both the 5568-year half life recommended by the Sixth International ^{14}C and ^{3}H Dating Conference, June 1965, in Pullman, Washington, U.S.A., was used, as well as the newer and physically more correct value of 5730 ± 40 years. However, all dates are clearly identified as to which half life was applied in the equation below (by convention: mean life = half life divided by 0.693):

$$\text{Radiocarbon age} = \text{mean life of } ^{14}\text{C} \times \ln \frac{\text{intensity of contemporary biosphere standard}}{\text{intensity of sample}}.$$

The standard for the contemporary biosphere is 95% of the count rate of oxalic acid for radiocarbon laboratories supplied by the U.S. National Bureau of Standards, Washington, D.C. Background determinations were based on CO_2 obtained from marble. In addition, a wood sample of known age was used as a third check to ensure precise functioning of the dating equipment. Finally, $^{13}C/^{12}C$ isotope ratio measurements were made to correct the dates in the accepted manner.

Listed below are the samples measured beginning with the earliest dynasties. The first line in each entry below identified the specimen by laboratory number, dynastic origin and the radiocarbon age in years B.C. based on the new half life of 5730 years. This half life is 3 % greater than the conventional half life of 5568 years. Hence, several measurements calculated with the 5568-year half life have been averaged and multiplied by 1.03 to give the best possible time estimate.

UCLA-1200 Dynasty I 2685 ± 60 B.C.

Remains of reed matting used as bonding between mud-brick courses of west side of superstructure of Tomb 3357 (Hor-Aha) at the Archaic Cemetery, Sakkara (Emery 1939). Average age of three measurments using the conventionally agreed upon radiocarbon half life of 5568 years: 4490, 4460 and 4430 years. $\delta^{13}C$ = 22.65‰ with respect to the PDB standard of Craig (1953). Martin is certain that the sample has remained archaeologically sealed from the beginning of the I dynasty.

UCLA-1201 Dynasty I 2470 ± 60 B.C.

Reed matting remains used as brick course bonding on north side of superstructure of Tomb 3503 (Mer-Neit), Archaic Cemetery, Sakkara (Emery 1954). Two conventional radiocarbon age determinations gave 4230 and 4270 years. $\delta^{13}C$ = 22.36 ‰. Sample was found by Martin to be archaeologically sealed from about the beginning of the I dynasty.

UCLA-1202 Dynasty I 2410 ± 60 B.C.

Reed matting as used in the previous specimens from the south side of the superstructure of Tomb 3035 belonging to Hemaka at Sakkara's Archaic Cemetery (Emery 1938). Conventional radiocarbon ages were measured to be 4160 and 4215 years. $\delta^{13}C$ = −21.95‰. Martin secured the sample from an archaeologically sealed context, specifically the time of Udimu of the mid-first dynasty.

UCLA-1203 Dynasty I 2315 ± 60 B.C.

Similar material as found above from the inner enclosure wall of the west side of Tomb 3505 (Ka'a) in the Archaic Cemetery, Sakkara (Emery 1958). Conventional radiocarbon age was 4130, 4070 and 4120 years. $\delta^{13}C$ = −22.71‰. Historically this tomb is placed at the end of the I dynasty.

UCLA-739 Dynasty I 2440 ± 80 B.C.

Linen found in mastaba 2050 at Tarkhan (Petrie 1914) and considered to be I dynasty. Sample obtained through courtesy of I. E. S. Edwards.

UCLA-1204 Dynasty II 2365 ± 60 B.C.

Reed matting remains used as bonding between mud-brick courses from west side of superstructure, Tomb 3046, Archaic Cemetery at Sakkara (Emery 1961). Conventional radiocarbon age was 4200 and 4120 years. $\delta^{13}C$ = −23.05‰. According to Martin this tomb is securely dated to belonging to the II dynasty.

UCLA-1205 Dynasty III 2225 ± 60 B.C.

Similar material as above from west side of entrance stairway of Tomb 3030, also at Sakkara's Archaic Cemetery. Radiocarbon ages by conventional standards are both 4030 years. $\delta^{13}C$ = −23.36‰. Martin's analysis of architectural style places tombs firmly into the early III dynasty.

UCLA-1206 Dynasty III 2135 ± 60 B.C.

Wood from plank (238 cm × 38 cm × 55 cm) built into the superstructure of Tomb 3510 and subsequently sealed on all sides by brickwork of tomb. $\delta^{13}C = -25.36‰$. Conventional radiocarbon ages were determined to be 3940 and 4000 years. Martin is certain that this tomb excavated in 1964 by W. B. Emery in the Archaic Cemetery at Sakkara belongs into the III dynasty.

UCLA-1207 Dynasty III 2220 ± 60 B.C.

Reed matting used as bonding between mud-brick courses from south side of the superstructure of Tomb 3075–5 belonging to Kha-ban-Sokar, an official of the III dynasty. Conventional radiocarbon ages were 4040 and 4000 years. $\delta^{13}C = -23.12‰$. Martin reports that the sample he removed had remained archaeologically sealed since the days of the III dynasty at Sakkara.

UCLA-1208 Dynasty IV 2180 ± 60 B.C.

Flax cloth from a small and undisturbed mastaba at Sakkara between Tombs 3508 and 3510 which belong for architectural reasons to dynasty III. The mastaba between was excavated by Emery in 1964 and Martin dates it tentatively to the IV dynasty. Two conventional radiocarbon dates yield 3980 and 4050 years, and $\delta^{13}C = -25.62‰$.

UCLA-1389 Dynasty IV 2385 ± 60 B.C.

Rope manufactured from halfa-grass from the funerary boat of Cheops found at the south side of the Great Pyramid at Gizah (Nour *et al.* 1960). The sample was obtained from Z. Iskander and given to Martin for transmittal. Average conventional radiocarbon age is 4210 ± 60 years. $\delta^{13}C = -11.78‰$. Martin emphasizes that this sample has remained archaeologically sealed since the reign of Cheops, second king of the IV dynasty.

UCLA-928 Dynasty V 2300 ± 60 B.C.

Linen cloth from Pit B of excavation in western cemetery, G2220, at Gizah, carried out in 1932. This linen is part of padding of a well-preserved woman's body wrapped to simulate her dress and form and found in an unopened wooden coffin (Reisner 1942). Sample was obtained through the courtesy of W. S. Smith, Museum of Fine Arts at Boston. Average radiocarbon age by conventional standards is 4120 years.

UCLA-1403 Dynasty V to Late I Intermed Period 2105 ± 60 B.C.

Reed matting remains from bonding between mud-brick courses of east side of mastaba of Haishetef near the southern boundary wall of the Zoser enclosure. Average conventional radiocarbon age is 3935 years. $\delta^{13}C = -22.79‰$. According to Martin the tomb has not been published with the exception of a few scenes. It dates most probably to Unas, the last king of the V dynasty, yet, it may be as late as the First Intermediate Period.

UCLA-1387 Dynasty VI 2030 ± 60 B.C.

Similar material as above from casing in western wall of superstructure of tomb of Mereruka, high official of Teti, first king of the VI dynasty, located at Sakkara in Teti Pyramid Cemetery (Duell 1938). Conventional ^{14}C dating gives average age of 3860 ± 60 years. $\delta^{13}C = -22.47‰$. Martin is certain of authenticity of specimen.

UCLA-1388 Dynasty VI 2120 ± 60 B.C.

Wood from end of a beam (145 cm × 19 cm × 19 cm) upon which rests the royal sarcophagus of Teti, from his Pyramid at Sakkara (Leclant). Average ^{14}C ages give 3950 years. $\delta^{13}C$ = −22.13‰. Martin emphasizes that the royal sarcophagus cannot have been moved since emplacement.

UCLA-1413 Dynasy XI 1935 ± 60 B.C.

Wood fragment from a bow collected by T. Settgast at Gebelein and thought to be of the XI dynasty origin. Conventional radiocarbon age is averaged to 3770 ± 60 years. $\delta^{13}C$ = −25.59‰.

UCLA-1211 Dynasties XI to XII 1655 ± 60 B.C.

Two dowels from fragment of wood bearing part of coffin text found among debris outside of Tomb 386, on southern side. This tomb was owned by general Intef, a contemporary of Neb-hepet-re Mentuhotep II of the XI dynasty and was excavated in March 1966 by the Deutsches Archäologisches Institut at Thebes, Asasif. Radiocarbon dating by conventional standards gave ages of 3480 and 3515 years. $\delta^{13}C$ = −25.36‰. Since the specimen was found outside the tomb proper, Martin is cautious that it may not belong to the XI dynasty with certainty. However, there is a probability that it does, which the radiocarbon date supports.

UCLA-1398 End dynasty XI to end dynasty XII 1380 ± 60 B.C.

Flax cloth found in the entrance of Tomb T located on the northern side of the courtyard of Tomb 386 of general Intef, and immediately behind Tomb 411 at Thebes, Asasif. Sample was collected by T. Settgast of the Deutsches Archäologisches Institut during 1966–7 and given to G. T. Martin. Excavator dates tomb to late XI until late XII dynasties. Average conventional radiocarbon age is 3330 ± 60 years. $\delta^{13}C$ = −25.49‰.

UCLA-1399 End dynasty XI to end dynasty XII 1775 ± 60 B.C.

Charcoal found in entrance of Tomb I located on northern side of courtyard of Tomb 386 in same general area as preceding sample. This and the specimen below were collected also by Settgast and submitted by Martin. Conventional radiocarbon date averages to 3615 years. $\delta^{13}C$ = −26.52‰.

UCLA-1400 End dynasty XI to end dynasty XII 1860 ± 60 B.C.

Wood from coffin fragment found in the inner part of Tomb T described under UCLA-1398. Settgast thinks this sample also dates from late XI to late XII dynasties similar to the preceding two samples. Average conventional radiocarbon date is 3700 years. $\delta^{13}C$ = −25.25‰.

UCLA-1212 Dynasty XII 1800 ± 60 B.C.

Reed matting remains used as bonding between mud-brick courses from northern boundary wall of Sesostris II's Pyramid at El-Lahun. Conventional radiocarbon dating gives 3230 and 3290 years. $\delta^{13}C$ = −10.00‰. Martin reports the sample as having been archaeologically sealed to the reign of Sesostris II.

UCLA-900 Dynasty XII 1800 ± 60 B.C.

Deckboard from funerary ship of Sesostris III of the XII dynasty obtained by W. F. Libby for first radiocarbon measurements from Chicago Museum of Natural History. Average

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conventional radiocarbon age is 3640 years which compares well with Libby's original average date of 3621 ± 180 years (Libby 1955). This specimen is of crucial importance in Egyptian chronology as there is recorded a helical rising of Sirius during the seventh year of the reign of Sesostris III. The event can be astronomically and therefore independently calculated to lie between 1876 and 1864 B.C. with good probability in 1872 B.C. (Hayes 1962).

According to Manetho, Sesostris III reigned for 48 years (Gardiner 1961) which places his death at 1831 B.C. However, in the Turin Canon (column 5, lines 23 and 25), Sesostris reign is given as 13, or 19 or 30 years respectively. The papyrus is torn and partially missing so that these numbers may be larger (Gardiner 1959). Date was reported in 1965 by Berger, Fergusson & Libby.

UCLA-1390 Dynasty XIX 1220 ± 60 B.C.

Remains of reed matting used as bonding between mud-brick courses of storage magazine in northwestern corner of Ramesseum enclosures at Thebes, the funerary temple of Ramesses II of the XIX dynasty (Quibell 1898). Martin emphasizes that the sample originated from within the Ramesseum enclosure and was archaeologically well sealed. Average conventional radiocarbon age is 3075 years. $\delta^{13}C = -11.42$‰.

UCLA-1393 Dynasties XIX and XX 1110 ± 60 B.C.

Reed matting used to bond bricks from south side of pyramidal chapel of Tomb 158 of Tjanefer, Third Prophet of Amun who flourished from the reign of Seti II of the XIX dynasty to that of Ramesses III of the XX dynasty (Seele 1959). Average of conventional radiocarbon dates is 3060 years. $\delta^{13}C = -11.27$‰. Sample was obtained by Martin in 1967 at Thebes, Dra Abu el-Naga.

UCLA-1394 Dynasties XIX and XX 1170 ± 60 B.C.

Branch of a tree embedded in mud-brick superstructure of Tomb 158 in structure described under UCLA-1393 (Seele 1959). Average of conventional radiocarbon dates is 3030 years. $\delta^{13}C = -24.04$‰. Value of $\delta^{13}C$ correction is shown in comparison of UCLA-1393 and 1394 since isotopic composition is markedly different when plants were alive. A difference of 1‰ in ^{13}C is equivalent to an increment of 16 years of time. Hence 12.77‰ units correspond to about 200 years.

UCLA-1395 Dynasties XIX and XX 1015 ± 60 B.C.

Branch of tree enclosed in mud-brick superstructure of Tomb 283 belonging to Roma, High Priest of Amun, at Thebes, Dra Abu el-Naga. Sample is historically placed similar to both preceding specimens (Fisher 1924). More specifically, Martin remarks that Roma is thought to have flourished between 1214 and 1151 B.C. and may have been the father of the owner of the adjoining tomb (Tomb 35) from which sample below was dated. Average of conventional radiocarbon dates is 2880 years. $\delta^{13}C = -25.19$‰.

UCLA-1401 Dynasty XXVI 720 ± 60 B.C.

Wood fragment found in the burial chamber of Tomb 386 of general Intef (see UCLA-1211) at Thebes, Asasif (Arnold & Settgast 1965). Martin comments that the owner was a contemporary of Neb-hepet-re Mentuhotep I of the XI dynasty. However, the burial chamber was used again during the Saite period, XXVI dynasty, dating from *ca.* 600 B.C. The average of conventional radiocarbon dates is 640 years. The sample itself was collected in 1963–4 by Settgast and made available to Martin in 1967.

UCLA-1391 Dynasties XXV and XXVI 655 ± 60 B.C.

Reed remains used as brick bonding from east side of pylon of Tomb 34 of Mentuemhat, Fourth Prophet of Amun at Thebes, Asasif (Leclant 1961). Martin places Mentuemhat, a high official in Thebes, from the reign of Taharka (XXV dynasty) to that of Psammetichus I (XXVI dynasty). Conventional radiocarbon dating yields an average age of 2530 years. $\delta^{13}C = -11.15‰$.

UCLA-1397 Dynasty XXX 455 ± 60 B.C.

Reed matting used as brick bonding in enclosure wall of the Great Temple of Amun, Thebes-Karnak, immediately east of tenth pylon (Nims 1965). Martin dates enclosure wall by brick stamps to Nectanebo I of the XXX dynasty. Conventional radiocarbon ages average about 2335 years and $\delta^{13}C = -11.75‰$.

TABLE 1. COMPARISON OF HISTORICAL AND RADIOCARBON DATES IN YEARS B.C.

British† Museum	UCLA	dynasty	origin	material	historic age	age‡
10/66	1200	begin-I	Sakkara 3357	reed	*ca.* 3100?	2685
1/66	1201	early-I	Sakkara 3503	reed	*ca.* 3000?	2470
11/66	1202	mid-I	Sakkara 3035	reed	*ca.* 2950?	2410
2/66	1203	end-I	Sakkara 3505	reed	*ca.* 2900?	2315
—	739	I	Tarkhan 2050	linen	3100–2900?	2440
12/66	1204	II	Sakkara 3046	reed	*ca.* 2900–2700	2365
13/66	1205	early-III	Sakkara 3030	reed	*ca.* 2700	2225
4/66	1206	III	Sakkara 3510	wood	2690–2617	2135
3/66	1207	III	Sakkara 3075–5	reed	2690–2617	2220
6/66	1208	IV	Sakkara 3508–3510	linen	2617–2500	2180
3/67	1389	IV	Cheops funerary boat	grass	*ca.* 2600	2385
—	928	V	Giza 2220	linen	2500–2350	2300
17/67	1403	V-ed.IP	Unas pyramid cemetery	reed	2350–2200	2105
1/67	1387	VI	Sakkara, Mereruka	reed	*ca.* 2350	2030
2/67	1388	VI	Sakkara Teti pyramid	wood	*ca.* 2350	2120
18/67	1413	XI	Gebelein bow	wood	*ca.* 2100	1935
15/66	1211	XI–XII	Thebes 386	wood	*ca.* 2100	1655
12/67	1398	edXI–edXII	nr. Thebes 386–411, T	linen	*ca.* 2020–1820	1480
13/67	1399	XI–XII	nr. Thebes 386, I	charcoal	*ca.* 2020–1820	1775
14/67	1400	XI–XII	Thebes 386, T	wood	*ca.* 2020–1820	1860
15/66	1212	XII	Sesostris II pyramid	reed	1897–1877	1655
—	900	XII	Sesostris III funerary boat	wood	1831	1800
4/67	1390	XIX	Thebes, Ramesseum	reed	1290–1224	1220
7/67	1393	XIX–XX	Thebes 158, Tjanefer	reed	1214–1208	1200
8/67	1394	XIX–XX	Thebes 158, Tjanefer	wood	1214–1208	1170
9/67	1395	XIX–XX	Thebes 282, Roma	wood	1214–1151	1015
15/67	1401	XXVI	Thebes 386	wood	*ca.* 600	720
5/67	1391	XXV–XXVI	Thebes 34, Mentuemhat	reed	650	655
11/67	1397	XXX	Thebes, Gt. Amun temple	reed	380–363	455

† First part is sample number; second part year of collection.
‡ Radiocarbon age corrected for isotopic fractionation by considering $\delta^{13}C$ measurements. Half life of 5730 ± 30 years is used.

For more convenient comparison the core of the chronological data has been assembled in table 1. In addition, historic ages and sample numbers assigned by the British Museum have been added. However, the best comparison between the historically and isotopically derived chronologies can be made in figure 1. It is interesting to note that radiocarbon dates match well with the historical chronology up to the time of Sesostris III or *ca.* 1800 B.C. In other words, the radiocarbon and historical chronologies go hand in hand for the entire period in which the historical time placement can be independently verified by astronomical calculations.

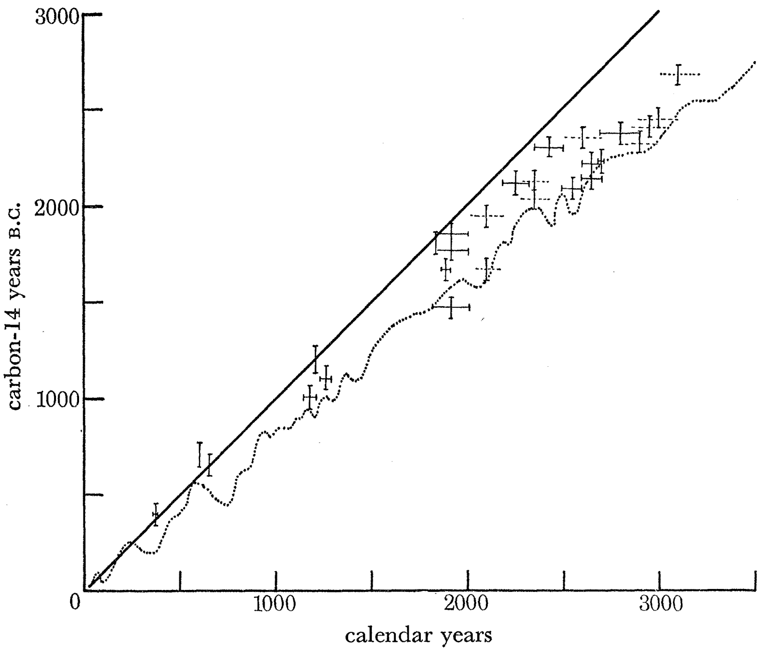

FIGURE 1. Empirical correlation between radiocarbon ages based on 5730-year half life and calendar years. Dotted line is bristlecone pine calibration curve of Suess.

THE QUESTION OF DISCREPANCIES

But when one examines the time periods before Sesostris III there appear to exist very obvious discrepancies. From the point of view of most modern Egyptologists the sequencing of events during the Old Kingdom is quite certain as presented in the work of Hayes (1964) with the understanding that not all chronologists agree entirely, such as Helck (1956). Yet the lack of unanimity among the knowledgeable with respect to the duration of individual regnancies or other reasons cannot account in their aggregate for the size of the discrepancies.

A considerable number of radiochronologists have given much thought to this problem, especially H. E. Suess of La Jolla, whose nearly complete bristlecone pine calibration of the radiocarbon time scale from 5300 B.C. to the present is illustrated in figure 2 with the permission of its author. Over the years the two radiocarbon laboratories of the University of California have been in constant touch with each other while working independently on these chronological problems. At the same time we endeavoured to cross-check appropriate samples since different chemical preparatory methods are used resulting in acetylene at the La Jolla laboratory and carbon dioxide at Los Angeles. On the whole we are satisfied that our individually different techniques produce virtually the same answers.

The correlation assembled in figure 2 possesses essentially two qualities. First, there are noticeable small-scale variations lasting on the order of a few centuries at most. Secondly, a very marked departure from the ideal relationship is evident which increases continually with greater age. Several years ago, at the outset of our investigations, which ultimately resulted in the bristlecone pine calibration curve of Suess, this laboratory was working on the dating of medieval timber structures in conjunction with Horn (1970) of the University of California at

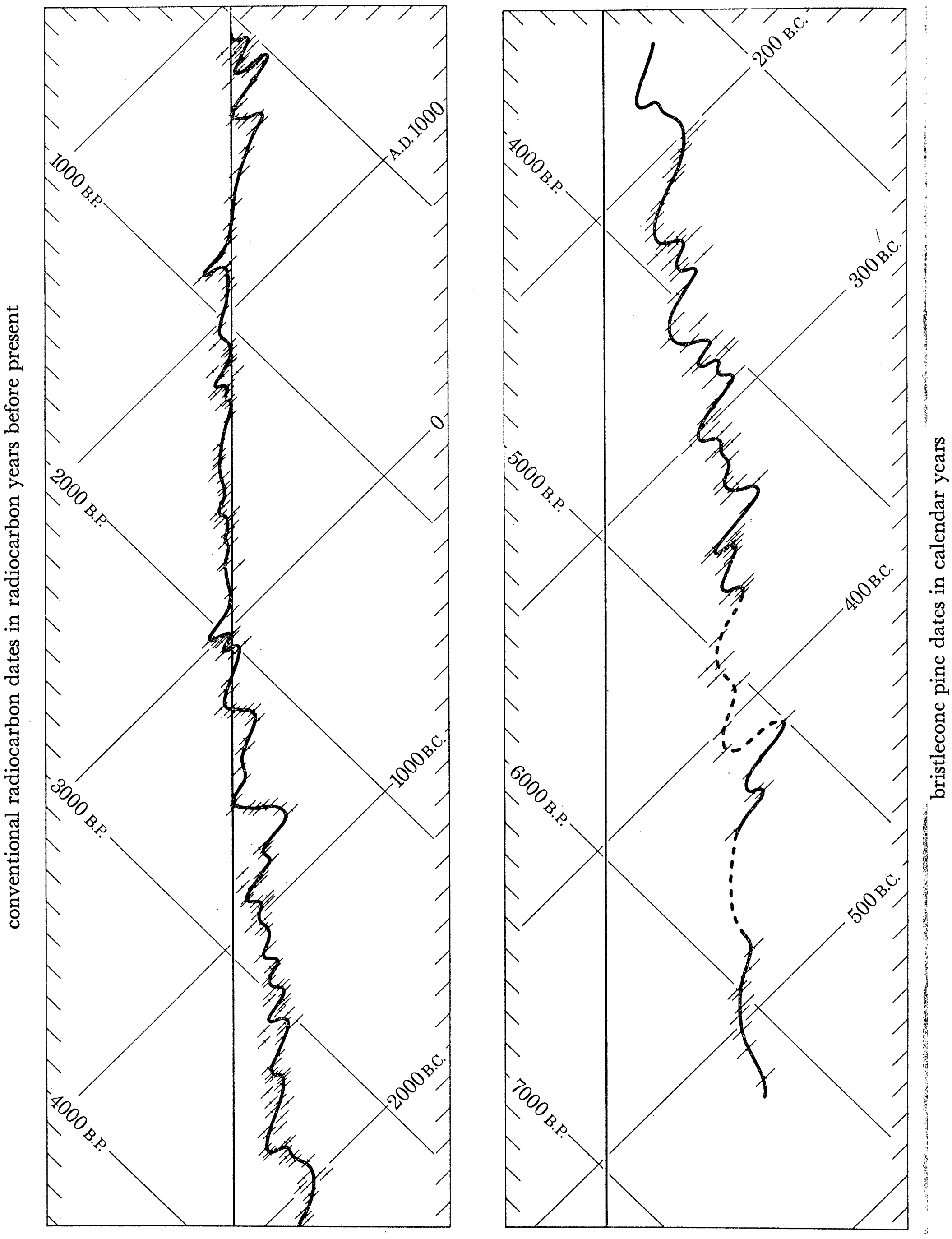

FIGURE 2. Empirical correlation between conventional radiocarbon ages based on 5568-year half life and bristlecone pine tree-ring ages after Suess.

Berkeley. The purpose of this investigation was twofold: on the one hand it was to provide Horn and his colleagues in architectural history with much needed temporal information not obtainable otherwise, and on the other hand, allow the radiochronologist to assess the degree of secular variations in the radiocarbon content of the biosphere in a quantitative manner. The evaluation in the latter case was based on radiocarbon dates of historically well-dated timber structures which served as a base of confidence for the isotopic dating of buildings of unknown age. That is to say, their age was uncertain within a period of several hundred years as far as the unknowns are concerned. The results of this study are listed in table 2. On balance the deviations of the radiocarbon content during the Middle Ages are of the same magnitude in both European oak wood used in timber construction and California bristlecone pines. Thus conventional radiocarbon dates from the medieval period can be calibrated (Berger 1970). In this manner the existence of the short-term variations has been verified by comparing the radiocarbon content of historically dated wood with its specific activity in carbon-14.

Table 2. Age measurements of medieval buildings of known age

UCLA	site	historic age (A.D.)	experimental age (A.D.)
1307	Arpajon	1450–70	1450
1316	Enstone	1382	14th century (1390)
1048	Gt. Coxwell	1250 ± 20	1250
1049	Gt. Coxwell	1250 ± 20	1245
1309	Maubuisson	1236	1050–1220
572	Méréville	1456–72	1470
1304	Méréville	1456–72	1460 or 1600
1311	Milly	1479	1290
1312	Milly	1479	1450
1313B	Parçay-Meslay	1211–27	1250
570	Parçay-Meslay	1211–27	1225–50
1310	Questembert	1675	1500, 1625–70
1303	Richelieu	1631–40	1480 or 1630
1306	Sully	1363	*ca.* 1300
1308	Troussures	1609	1450 or 1600
1214	Buddha statue	early 13th century	early 13th century

(Berger 1970; Horn 1970.)

The long-term variation in the radiocarbon content of the biosphere is much more difficult to prove. If one compares the historical samples, dated in this study by radioactivity, there are found considerable parallels between their deviation from the ideal correspondence and the bristlecone pine calibration (figure 1). As a matter of fact, the bristlecone pine correlation appears to exaggerate the magnitude of the deviations slightly, although not greater than, very roughly speaking, the maximum historical uncertainty.

At present there is available but one quantitative, long-range calibration curve based essentially on one species of wood from more or less the same geographical location. Ideally it would be desirable to check Suess's data by measurements carried out with a different species. However, up till now a search for a similar long-lived tree coupled with an environment providing excellent preservation conditions for fallen logs has failed to be successful. Despite these difficulties attempts are being made to locate suitable trees.

Concerning the isotopic integrity of tree-ring carbon

Among the effects which have been thought of as being capable of producing an erroneously high radiocarbon content in old tree-rings, and consequently too recent a radiocarbon date, is the possibility of recent tree sap invading older tree-rings. But if such an effect were to exist, it still would not explain discrepancies encountered in historically dated reed samples as used in many cases in this study. Nevertheless, the question of sap contamination was experimentally tested in an ancillary investigation.

To this end two different tree species were analysed, bristlecone pine and European oak. The main reason for this selection was that oak possesses rays which can serve as conduits from the outer rings of a tree deep into the region of the oldest rings. Conversely, bristlecone pine belonging to the conifers does inherently not feature such extensive rays. There existed somewhat of an enigma, since both European oak and bristlecone pine used in Suess (1965) first calibration study showed the same secular variations in radiocarbon despite the pronounced morphological differences.

TABLE 3. RADIOCARBON CONTENT OF RECENT BRISTLECONE PINE, OAK AND DOUGLAS FIR

U.C.L.A.	tree-ring age	^{14}C content (% excess)
Bristlecone pine		
1450A	1931–6	+0.7
1450B	1936–41	−0.2
1450C	1941–6	−0.9
1450D	1946–51	−0.7
1450E	1951–6	+1.8
1450F	1956–61	+18.3
1450G	1961–6	+64.1
Oak		
1539	1939	−3.2
1538	1941	−3.0
1537	1949	−3.0
1536	1951	−1.8
1535	1953	+0.5
1534	1955	+8.7
1533	1957	+14.5
1532	1959	+30.0
1531	1931	+25.1
1530	1930	+83.4
Douglas fir		
770	1923	−0.6
771	1928	−2.4
772	1933	−1.5

The bristlecone pine used was tree no. TRL–67–52 supplied by C. W. Ferguson, University of Arizona, Tucson. Since bristlecone pine has very narrow rings 5-year-wood increments were used.

The oak was a specimen grown in Reinbeck, near Hamburg, supplied by W. Liese, University of Hamburg, The Douglas fir, called the 'Hitchcock tree', was felled in 1951 in the Santa Catalina Mountains near Tucson. Arizona, and was also provided by the University of Arizona tree-ring laboratory.

The radiocarbon content is expressed in percentage excess over the normal biospheric reference level of 1890 equivalent to 0.95 the count rate of N.B.S. oxalic acid.

The trees selected contained in each case very recent rings whose radiocarbon content is greatly increased by the incorporation of the isotope produced in atmospheric nuclear weapons tests. By 1963 the atmosphere of the northern hemisphere contained almost twice as much radiocarbon as is normally produced by cosmic radiation. Consequently this enrichment, especially in the 1963 tree-ring, can be used as a tracer in following any suspected diffusion process. So long as the radiocarbon content of any individual tree-ring or group of rings matches the concentration in the atmosphere of the same year no sap movement across

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tree-rings can be postulated. The results are listed in table 3, and a comparison of atmospheric and tree-ring data is made in figure 3. In final analysis, the transmission of radiocarbon in bristlecone pines and oak from recent tree-trings to older rings is at best a minor effect which cannot amount to more than 1 or 2 % of the modern level of carbon-14. For oaks it means that its rays may transport moisture across tree-ring interfaces but not organic compounds. Since the bristlecone pine wood analysed was purposely not extracted for removal of resin, such material must also remain essentially confined within tree-rings and not move about. There is, however, the exception of sapwood where sap may be transported across tree-rings. In mature oaks of say 100 years of age the sapwood layer never appears to exceed about 25 tree-rings, in bristlecone pines the corresponding sapwood thickness in substantial trees amounts to some 100 rings. Thus contamination between the youngest and oldest rings in the sapwood is limited to the equivalent of maximally 25 years in oak and a century or so in bristlecone pine. In actual fact the effective contamination is much less since the innermost sapwood only carries a fraction of nutrients transported in the physiologically most active portions of the outer tree trunk.

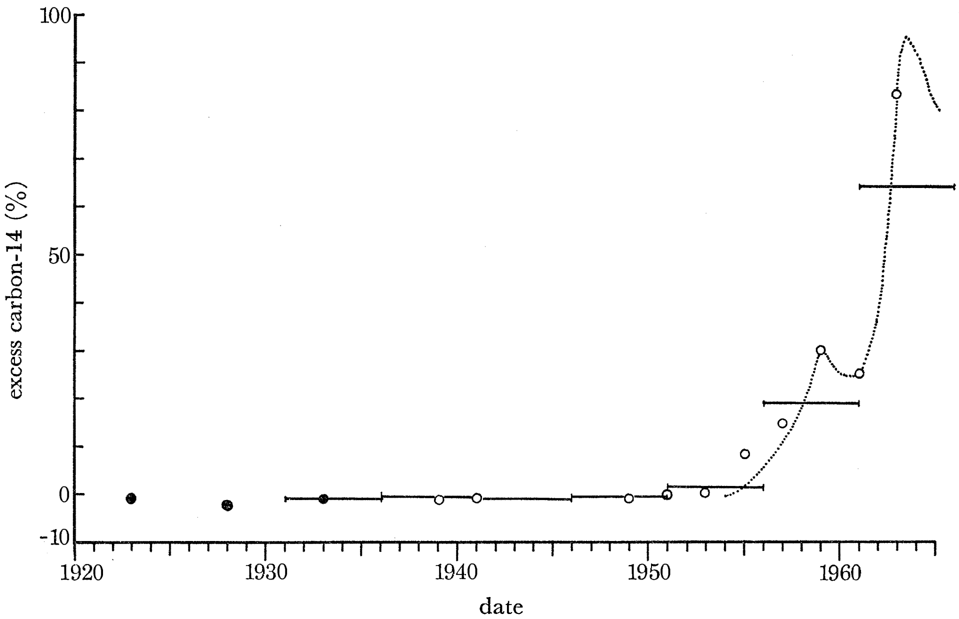

FIGURE 3. Comparison of radiocarbon content of recent tree-rings with that of atmosphere to show diffusion of bomb-^{14}C in wood. —, bristlecone pine, California; o, Hamburg oak, Germany; •, Douglas fir, Arizona; ......, atmospheric data.

The experiments conducted so far do not detect any very slow exchange of carbon compounds among widely separated tree-rings. To answer this question a study is now underway using high artificial levels of radiocarbon in living bristlecone pines.

DISCUSSION

As pointed out earlier no major differences exist between a radiocarbon-based chronology using the 5730-year half life and the historically accepted dates within the degree of archaeological resolution of this study up to the time of Sesostris III. From this point on the bristlecone pine calibration curve of Suess approximates the presently recognized historical chronology of what amounts to mostly the time of the Old Kingdom. Perhaps the reason that the bristlecone pine calibration curve does not exactly follow the historical chronology may lie in internal sapwood contamination effects. Moreover, there is the possibility that bristlecone pine wood exposed at high elevations may suffer *in situ* production of radiocarbon based on its nitrogen content over long periods of time (Rama 1969, personal communication). Neither of these effects in itself is appreciable but we do not know whether there does not occur a combination of the two.

There are a number of still unresolved uncertainties which have a bearing on the correlation of historically and isotopically based chronologies. First, early Egyptian history is not yet unequivocally certain and anchored in time. In order to improve our confidence radiocarbon measurements of well-dated contemporaneous Mesopotamian samples will be carried out to cross-check two major yet independent chronologies. Furthermore, attempts will be made in trying to locate ancient trees elsewhere which are suitable for dendrochronological studies, and which can be used for an independent comparison with the bristlecone calibration measurements of Suess. Another uncertainty is the actual half life of radiocarbon. Even though the best accepted value so far is 5730 ± 40 years (Mann, Marlow & Hughes 1961; Godwin 1962) there is no guarantee that future more refined determinations may not be forthcoming yielding a longer half life. An indication to this effect is the measurement by Schell, Fairhall & Harp (1965) of a radiocarbon half life of 5833 ± 127 years. Lastly, the question may be raised what the cause is for secular variations of radiocarbon. At the moment a coincidence is observed between dipole changes of the geomagnetic field and the major trend of radiocarbon date deviations (Bucha *et al.* 1970). If this coincidence amounts to an actual dependence, as the case may very well be, then the long-term deviation is due to geomagnetic field changes. By implication, the short-term variations might be caused by changes in the helio-magnetic field. Ultimately when all these questions are answered we shall know how to date with greatest accuracy the period of the third millennium B.C., a time range so important in Neolithic studies elsewhere.

In the meantime, conventional radiocarbon measurements of ancient Egyptian samples can be converted to dates coming close to fitting the presently accepted historical chronology by calibration against the bristlecone pine correlation. However, some dates appear to be more accurate using only the 5730-year half life.

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