MODERN ASPECTS OF RADIOCARBON DATING METHOD: FUNDAMENTAL CONCEPTS AND ARCHAEOLOGICAL APPLICATIONS

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INTRODUCTION. Since fifties the radiocarbon dating technique has became a standard tool for the Quaternary geologists and archaeologists, as well as for specialists involved in studies of environmental processes. In the eighties an important progress has been achieved in the field of experimental techniques and methodical problems. The summary of important achievements of the last two decades is available in form of proceedings of the international radiocarbon conferences in Los Angeles and La Jolla in USA in 1976 (Berger, Suess, 1979), in Bern and Heidelberg in 1979 (Stuiver, Kra, 1980), in Seattle, USA, in 1982 (Stuiver, Kra, 1983), in Trondheim. Norway in 1985 (Stuiver, Kra, 1986) and in Dubrovnik, Yugoslavia, in 1988 (in print). Specific problems associated with archaeological applications of the radiocarbon dating method were discussed during two important meetings in Groningen, Netherlands, in 1981 and 1987 and the papers presented during these meetings were published as separate volumes of the PACT journal (Mook, Waterbolk, 1983, 1989). There are several hundreds important papers contained in theses proceedings volumes and it seems worthwhile to present a concise but comprehensive summary, reporting the most important topics to the reader interested in the state-of-the-art of the radiocarbon dating method. The aim of this paper is to give a brief review of fundamental concepts, technical problems and applications of the radiocarbon dating method at its mature age in the beginning of nineties. Special attention is paid to archaeological applications including discussion of suitability of various materials for solving specific chronologic problems, statistical interpretation of results of radiocarbon dating, and new possibilities offered by recent technical and methodical studies. Finally, one of the most important topics discussed in this paper, is relation between conventional radiocarbon dates and calendric time scale, including discussion of recently developed methods of probabilistic calibration of radiocarbon dates.

FUNDAMENTAL CONCEPTS. *Production and distribution of radiocarbon.* The natural carbon has two stable isotopes : ^{12}C and ^{13}C, with abundances 98.9% and 1.1%, respectively, and one radioactive isotope ^{14}C, called radiocarbon, with abundance ca 10^{-10} %. Radiocarbon is produced in the lower atmosphere in reactions between low energy cosmic neutrons and nitrogen ($n + {}^{14}N \rightarrow {}^{14}C + p$) and decays by emission of low-energy beta particles : ${}^{14}C \rightarrow {}^{14}N + \beta^-$ with the half-life of nearly 5,700 yr. The newly formed carbon is oxidized to CO_2 and mixes with atmospheric carbon dioxide, then enters living organisms by assimilation of with organic food. Most of ${}^{14}CO_2$ is adsorbed in the ocean where it becomes incorporated in the marine carbonates. The exchange of ^{14}C between atmosphere and biosphere is relatively fast compared with its half-life and these two reservoirs can be regarded as equilibriated and well mixed. All living organisms exchange ^{14}C with the surroundings and have approximately constant specific radiocarbon activity, equal to 13.5% $\pm$ 0.07 dpm/1gC. This means that one gram of carbon, separated brom living organism, produces about 13—14 beta particles per minute. There are some minor differences in specific ^{14}C activity of organisms living in different environments, known as the reservoir effects, which will be discussed in one of next chapters.

Assumptions of radiocarbon dating method. The exchange of ^{14}C with the surroundings ceases completely after the carbon fixation and ^{14}C content of a certain material decreases by the radioactive decay $A(t) = A(0)\exp(-\lambda t)$, where λ is the decay constant, and $A(0)$ is the initial ^{14}C activity of dated material. The value of $A(0)$ is, however, unknown, and the use of radiocarbon for absolute

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age determination is obviously associated with several assumptions, mainly concerned with establishing the best estimate for A(0).

With some simplifications, these assumptions may be listed as: 1. The production rate of ^{14}C has been essentially constant over a long period of time (over the last 100 kyr). 2. The main carbon reservoirs (i.e. the atmosphere, biosphere and the ocean) were in the steady state and were well mixed over this period of time. 3. There was no exchange of carbon between dated material and the surroundings after organic carbon fixation or carbonate deposition (the „closed system" assumption). Much research has been done in order to check these assumptions and to evaluate the influence of possible deviations on the reliability of radiocarbon dates. At present it is well known that the first two assumptions are not true. However, the differences between ^{14}C dates obtained under theses assumptions and the true ages are relatively well established for the period of the last 7 millenia and appropriate corrections may be introduced to radiocarbon dates from this interval of time basing on various calibration curves or tables (Damon et al, 1974; Ralph et al, 1973; Clark, 1975; Switsur, 1975; Suess, 1979; Damon et al, 1982; Stuiver, 1982; Stuiver, Pearson, 1986; Pearson, Stuiver, 1986; Pearson et al, 1986). The corresponding deviations are only approximately known for the period of 30—40 millenia (Olsson, 1970; Stuiver, 1978; Vogel, 1980; 1983). The closed system assumption may be seriously violated in the case of carbonate materials (shell, speleothem, travertine) but is regarded as realistic for most of organic materials (wood, charcoal, peat). Such materials often are mixed with both organic and inorganic matter of different origin and age, referred to as contaminants. In practice it is possible to eliminate the contaminants by appropriate laboratory treatment of dated samples and to develope criteria by which can be decided that this has been accomplished.

Conventional radiocarbon time-scale. In practice of radiocarbon dating it has been shown necessary to introduce the notion of the conventional radiocarbon dates in order to assure the comparability of results of different laboratories, produced in different time. It involves the following requirements (cf. Godwin, 1962; Stuiver, Polach, 1977; Stuiver, 1980; Mook, 1986): 1. The „old" value of the half-life of ^{14}C, determined by W. F. Libby (1952) and equal to 5568 yr, is used to calculate the age, instead of correct value of 5,730 $\pm$ 40 yr. 2. The zero point of conventional ^{14}C time scale is AD 1950. 3. The initial ^{14}C activity A(0) is determined from measurements of ^{14}C counting rate of the Oxalic Acid Standard Reference Material, produced and distributed by the National Bureau of Standards, USA, after appropriate normalization. 4. The measured ^{14}C activity of unknown sample is normalized for isotopic fractionation to $\delta_3 = -25$ per mil wrt PDB standard. Conventional radiocarbon age is calculated according to formula $T = 8033 \ln \{A(0)/A\}$.

TECHNICAL ASPECTS OF RADIOCARBON DATING. Low abundance of ^{14}C in natural samples, together with relatively long half-life and low energy of beta particles, imposes high requirements on the quality of equipment used for ^{14}C assay, first of all concerning the background value of counting system, the reproducibility and the long-term stability of counting conditions. The fundamental concept now employed in all counting systems, used for ^{14}C dating, is that the dated sample is used as an active medium of the nuclear radiation detector.

Three different methods of ^{14}C assay are actually used:
1. gas counting (GC); 2. liquid scintillation counting (LS); 3. accelerator mass spectrometry (AMS). The most relevant parameters of the modern counting systems are compared in Table 1.

In the *gas counting (GC) technique* the sample is converted to CO_2 (by combustion of organic samples or by acid treatment of carbonates). After careful purification the obtained CO_2 is introduced into the proportional counter directly for counting beta particles from ^{14}C decays. In some other GC techniques CO_2 obtained from sample is converted to methane or acethylene and this new gas is used as counting medium of proportional counter. The status of GC technique at the beginning of eighties has been summarized by Mook (1983).

Advantages: in the CO_2 technique the combustion (or acid treatment of carbonate) is the only chemical reaction involved in the whole process of preparation of counting medium; no catalysts, no other chemical reactions, no contact with atmospheric CO_2, which may introduce contamination with foreign carbon or may change initial carbon composition by isotopic fractionation.

Drawbacks: high purity of CO_2 is the necessary condition for good performance of proportional counter. Minute amounts of electronegative gases (O_2 or H_2O) seriously decrease counting efficiency and may cause significant errors of age determinations.

The most important achievements of the last decade include: 1) development of large-volume counting systems with CO_2 — filled proportional counters, dedicated to high-accuracy dating with overall error of ca $\pm$10 yr (Stuiver et al, 1979; Tans, Mook, 1979; Schoch et al, 1980) as well as improvement of the enrichment methods (Grootes et al, 1980), 2) development and introducing into routine operation miniature gas proportional counters for dating small samples, containing 20—100 mg of carbon (Harbottle et al, 1979; Currie et al, 1983; Sheppard et al, 1983; Jelen, Geyh, 1986; Otlet et al, 1986).

The *liquid scintillation (LS) technique* has been introduced in late fifties and now is fully compatible with the GC technique. About 50% of all active dating laboratories are using the LS technique. In this technique CO_2 is converted to C_2H_2, which is then trimerized to benzene. Obtained liquid benzene sample with small quantities of some chemicals added to enhance scintillations, is then used for counting of beta particles.

Advantages: Sample size is reduced to 5—25 ml volume, leading to significant simplification of construction of counting system. Commercially available counting system are manufactured by several companies (PACKARD, WALLAC, BECKMAN), some of them computerized and fully automated.

Drawbacks: process of benzene synthesis involves chemical reactions with some catalysts; there is a possibility of laboratory contamination of dated sample or fractionation of carbon isotopes. The presence of hydrogen atoms in benzene molecule may introduce additional radioactivity of tritium.

The accuracy of the LS technique was seriously improved (Eichinger et al, 1980), and some laboratories are able to achieve the status of high-accuracy dating with the overall error of ca ± 10 yr (Pearson, 1979). Recent research (Polach et al, 1988) has shown also the possibility of dating very small samples, containing less than 100 mg of carbon with satisfactory accuracy using special dedicated LS spectrometers supplied by the Wallac Oy company.

The *accelerator mass spectrometry (AMS) technique* is the new technique introduced in late seventies and at the present time it offers unique opportunity to date samples containing ca 1 mg of carbon with accuracy of ca 1%, i.e. from ± 50 to ± 150 yr for samples younger than ca 10,000 yr, i.e. associated with Upper Palaeolithic, or younger sites (Hedges, 1981; 1983; Kutschera, 1983). In this technique CO_2 obtained from dated sample is converted to graphite which forms a target used to produce beam of carbon atoms, then ionized and accelerated to energy of few MeV. In magnetic field the beams containing different carbon isotopes are separated and the intensity of ^{14}C beams of unknown and standard samples are compared to determine the ^{14}C concentration and age of sample to be dated. Recent international comparisons have shown that the results produced by AMS laboratories are in very good agreement with results of conventional dating methods (Burleigh et al, 1986). Actually there are more than ten active AMS dating laboratories producing a large number of radiocarbon dates, mostly for oceanographic and environmental studies; the Oxford AMS dating facility is used primarily for archaeological dating and the results are systematically published in the „Archaeometry" journal starting from 1984 (Gillespie et al, 1984).

Advantages: 1) very low mass of sample needed for dating expands significantly the possibility of applications of the radiocarbon method, 2) short counting time (ca 30 minutes) enables very high annual output of the AMS laboratory, exceeding 3000 datings per year.

Drawbacks: very high cost of the AMS facility (ca 2 millions $ US), sample may constitute a non-representative part of inhomogeneous material, the degree of archaeological association may be small.

Diversity of the experimental techniques used in radiocarbon dating and increasing number of radiocarbon dating laboratories as well as increasing annual production of radiocarbon dates imposes new requirements for international collaboration between radiocarbon laboratories to assure full comparability of results obtained with different techniques. Such interlaboratory comparisons were initiated several years before by British laboratories (cf. Otlet et al, 1980; Burleigh et al, 1986; Scott et al, 1986), indicating good agreement of results obtained with AMS and small proportional counters. First international collaboration was initiated by the International Study Group (1982) with limited participation of 20 laboratories and the results were summarizes by Baxter (1983), indicating some excessive scatter of radiocarbon dates obtained by different laboratories, as well as the tendency of laboratories to overestimate their dating accuracy. The presence of some bias was also shown in some of these results. There was also a common practice of radiocarbon laboratories to exchange samples to verify results of dating (cf. Pazdur et al, 1980; 1982). In recent years a new systematic research project has been initiated by the group of Glasgow University devoted to detailed study of accuracy of radiocarbon datings obtained by radiocarbon laboratories using different experimental techniques. The aim and scope of this project was presented by Scott et al (1986) during the radiocarbon conference in Trondhein, Norway, in 1985, and the first results were reported to the participants of the next radiocarbon conferences in Groningen in 1987 and in Dubrovnik in 1988 (cf. Scott, 1987; 1989). The results of three steps of this project with participation of almost 50 laboratories were summarized during the seminar „Radiocarbon Workshop", held in East Kilbride, Scotland, in September, 1989. The papers presented during this meeting will be published in form of separate issue of „Radiocarbon". It may be concluded that there is an excessive variability of results produced by different laboratories on same samples. It seems also that the GC laboratories using carbon dioxide show better reproducibility of results and slightly better overall accuracy than the LS laboratories.

PROBLEMS ASOCIATED WITH DATED MATERIALS. *Contamination and pretreatment.* Any dated sample must be free from contaminants if a reliable date is to be obtained. A sample which is suspected to be seriously contaminated must not be selected for accurate dating. Contamination of the sample may occur at different stages:

A. *Already before deposition.* This contamination is by fossil organic matter or fossil carbonate (eg lake sediments frequently contain material coprecipitated with autochtoneous organic matter, such as elemental carbon or graphite, charcoal from fireplace may contain charred pieces of much older wood; cf. Schoute et al, 1981). The contaminating organic matter is impossible to recognize and remove, but as a rule the contaminant consists of highly resistant fraction and dating of. a less resistant fraction (eg alkali soluble humic acid) may provide more reliable date (cf. Schoute et al, 1983).

B. *After deposition or sample formation.* a). *By penetration of rootlets.* This is a major problem, especially in dating peat. However, also many charcoal samples examined in our laboratory showed numerous rootlets, in some samples the rootlets were visible before treatment with the naked eye, in some sample the rootlets appeared visible after preliminary treatment with acid and alkali. This contaminant cause rejuvenation and is specially important for older samples, and may make the result of dating completely false.

b). *By organic matter infiltration.* This contamination is one of the main problems as it occurs for most of samples. Younger carbon from soils at lower depth may be transported in solution or in colloidal form by infiltrating with rain water to the layer to be dated and then adborded. The acid soluble fraction (fulvic acids) and alkali soluble fraction (humic acids) can be removed during chemical treatment in laboratory. The insoluble fraction of dated sample, consisting of sufficiently resistant organic fraction (lignin, cellulose, humins) is used for dating. The important condition is that the initial mass of sample submitted for dating is sufficiently large, as the loss of mass may be high (up to 70% for peat), especially during alkali treatment. This type of contamination present no problems when dating wood, charcoal, charred organic remains (charred grains), well preserved macroscopic remnants of plants (twigs, leaves, cones, grains, seeds, bark, etc.).

c). *By admixture of foreign organic matter.* Admixture of material of different age may result from activity of small animals (cf. Awsiuk et al, 1986) which transport the organic matter between cultural layers of form channels of holes which are then filled with foreign organic matter of different age. It seems that the only way to avoid errors caused by this type of contamination is to try to recognize this phenomenon in the field. Same effect may be introduced by natural or man-induced disturbance or reworking of original cultural layers with mixing of organic remnants (eg, falling trees, landslides, etc.).

C. *In field during excavation and sampling.* This contamination may result from physical admixtures of materials from different layers during sampling, or from wind-borne organic dust, carbonaceous particulate fallout, etc. Great care is required to avoid such admixtures which are impossible to recognize and remove in the dating laboratory.

D. *During storage.* Contamination is caused by insufficient packing or by contact with paper cover or labels, especially if sample is wet. The sample should be kept and submitted to laboratory in glass, plastic or aluminium foil.

E. *By preservatives.* Bones and wooden objects are sometimes treated with organic preservatives. Such samples should be avoided, or, if dating is necessary the preservatives should be removed using appropriately selected chemicals. Moreover, detaled description of the method of preservation (including list of chemicals used and type of treatment) and the method applied to extract the preservatives, should be given in sample information form required by dating laboratory.

F. *During processing in laboratory.* This contamination may be introduced by inappropriate chemicals used when sample is pretreated in laboratory or by contact with other samples of different age processed at the same time. Another important source or laboratory contamination is so-called memory effect, i.e. the residual amount of sample remaining adsorbed on walls of storage flask or counter which may cause an admixture to the next sample introduced to same flask or counter. This memory effect is to be avoided by the laboratory staff, but important factor is even approximate information about predicted age of the sample submitted for dating. Methods of pretreatment must be effective enough to remove most contaminants. Because of variety of sample materials and possible sources and mechanisms of contamination, many specific methods have been proposed and tested by radiocarbon laboratories. In any case, first step to be applied is careful visual examination of the sample, mechanical cleaning (including removal of visible rootlets, separation of appropriate mechanical fraction or selection of the most suitable part of sample for dating). In general, there are three different groups of pretreatment methods, applied to organic materials, bones and carbonates.

a). Organic matter — acid or AAA (Acid-Alkali-Acid) treatment to remove carbonates (with acid) and humic acids (with alkali). It is regarded that the soluble fractions are probably contaminated and, as a rule, are rejected. In some specific cases, however, they are also dated to have a check for the presence of different types of contamination.

b). Bones — collagen is commonly regarded as the most suitable fraction of bone. Extraction of collagen is usually performed according to the method described by Longin (1971) or modified version of this procedure (Brown et al, 1988).

c). Carbonates (shell, speleothem, travertine) — Acid treatment is applied to remove outermost carbonate layer, which may be affected by foreign carbon (Goslar, Pazdur, 1985).

Initial radiocarbon content. The second of fundamental assumptions of the radiocarbon dating method states that the main carbon reservoirs are equilibriated and well mixed. However, there is some delay in the transport of ^{14}C atoms from atmosphere to the ocean. In consequence, the ocean water has slightly lower ^{14}C concentration than the atmosphere and biosphere, and same concentration show marine organisms. Therefore, shells and bones of seals and whales seem to have some artificial „age", which is usually called „aparent age" or „reservoir age". The value of reservoir age of marine samples is close to 400 yr, and in higher latitudes, at the coasts of Spitsbergen, northern Norway and Arctic Canada, is even higher (Olsson, 1983 a, b ; Mangerud, 1972). In the fresh-water systems the situation is more complicated because inorganic carbon dissolved in water may contain significantly less radiocarbon than the atmospheric CO_2. Carbonate sediments deposited in fresh-water environment show therefore values of reservoir age ranging from several hundreds to several thousands years and there is no regularity in observed values. Same conclusion is valid for shell of fresh-water snails, which should not be used therefore for precise dating of archaeological sites. However, land snails do not show significant reservoir age. In lake marls the value of reservoir age may change with depth (i.e. age) in the profile (cf. Pazdur et al, 1987). Recent research on isotopic composition of carbon of fresh-water tufas (Pazdur et al, 1988 ; Pazdur, 1988) has shown the presence od some correlations between δ^{13} C, the type of tufa, and the value of reservoir age. Obtained phenomenological relations may be used to evaluate true ages of some tufaceous sediments. Speleothems show relatively constant value of the reservoir age, amounting to ca 1300 yr. There is also some evidence for very local effects, for example release of inactive carbon during volcanic eruptions or from fumaroles may cause significant local depletion of radiocarbon concentration in plants. There is a continuing discussion concerning dating of the excavations in Thera (Aitken et al, 1988 ; Betancourt, 1987) and the possible of volcanic emnations on obtained results of radiocarbon dating of some cultural levels. Also grass from the neighbourhood of artesian aquifiers, and plants growing on highly calcareous soils, show sometimes much lower ^{14}C activity than the normal atmosphere (Tauber, 1983).

Isotopic fractionation. The three isotopes of natural carbon show the same chemical behaviour, but because of their different masses the vibrational energies of $^{12}CO_2$, $^{13}CO_2$ and $^{14}CO_2$ molecules are slightly different. Therefore the reaction speeds and equilibrium constants for the listed molecules are different, causing natural fractionation of carbon isotopes : the enrichment of the heavier isotopes in the bicarbonate when carbon dioxide is dissolved in water, and the depletion of the heavy isotopes when CO_2 is assimilated by plants. The fractionation of ^{14}C is almost exactly twice that for ^{13}C. As the ^{13}C content does not change during the sample history than the value of $\delta^{13}C$ in dated sample may be measured by mass spectrometry and then used to introduce correction to the radiocarbon date. By definition, of the conventional radiocarbon age, the isotopic fractionation in all samples, irrespectively of environment, is taken into account by normalizing to $\delta_0 = -25$ per mill wrt PDB, i.e. to the postulated mean value of $\delta^{13}C$ of terrestrial wood. Values of $\delta^{13}C$ in most organic and inorganic samples used for dating cluster around some characteristic values (Stuiver, Polach, 1977 ; Burleigh et al, 1984 ; Goslar, Pazdur, 1985), listed in Table 2 (after Stuiver and Polach, simplified and modified by the author). These values may ne used to correct radiocarbon dates if direct determinations of $\delta^{13}C$ are not available.

CARBON VARIATIONS IN THE PAST. It has been known since many years that the ^{14}C concentration in the past was variable. The variations and their possible causes were discussed at the 12th Nobel Symposium in Uppsala (Olsson, 1970) and from that time these topics were included in the scientific programme of all next radiocarbon conferences (Berger, Suess, 1979 ; Stuiver, Kra, 1980 ; 1983 ; 1986). The observed variations are classified into three groups, basing on their characteristic time constants, as : a). *Long-term variations* ($\tau \cong 5000$ yr). These variations are caused by changes of the magnetic field of the Earth (Damon, Linick, 1986). The magnitude of deviation from normal ^{14}C concentration exceeds 10% at ca 6,000 BP. The changes of the ^{14}C concentration may be described by the third-order polynomial (Wendland, Donley, 1971) or by nearly sinusoidal curve with period of ca 9600 yr (Damon et al, 1974 ; 1978). b). *Medium-term variations*, called also secular variations, has time constant of ca 200 yr. These variations may be regarded periodical ; the 200-yr periodicity was well established (Neftel et al, 1981) and other authors have reported

also the evidence for other periodical patterns (Sonett, 1984). Medium-term changes of ^{14}C are probably controlled by climatic factors (Roedel, 1980; Sonett, Suess, 1984). c). *Short-term variations* with periods 11 and 22 yr and amplitude of ca 0.5% (Stuiver, 1978) are associated with corresponding cycles of solar activity (Baxter, Farmer, 1973; Burchyladze et al, 1980; Damon et al, 1973).

The variations of past radiocarbon content are of primary significance for correct interpretation of radiocarbon ages of archaeological samples, especially when radiocarbon dates are to be compared with other chronologic evidence, as for example written documents, coins, or if the relative local chronology is compared with absolute Egyptian chronology. The problems associated with dendrochronologic calibration of conventional radiocarbon dates will be discussed in a separate chapter.

APPLICATIONS IN GEOLOGY. *Quaternary geology and related disciplines,* as paleogeography, paleobotany, paleoecology, paleoclimatology constitute the most important field of application of the ^{14}C dating. With the advent of high-precision counting systems and improvement of the enrichment methods the range of dating was extended back in time to ca 75,000 yr BP. At present the chronostratigraphy of the middle and upper vistulian and holocene is based on conventional ^{14}C dates. Radiocarbon is used to date and correlate important catastrophic events as volcanic eruptions, landslides, earthquakes, etc. Correlation of ecological changes, reconstructed from pollen diagrams, is based on detailed dating of peat-bog profiles (cf. Pazdur et al, 1985). Dating of carbonate sediments associated with $\delta^{13}C$ and $\delta^{18}O$ determinations is useful for reconstruction of paleotemperatures (Pazdur et al, 1988). Global or regional reconstructions of environmental changes are frequently based on statistical analysis of large sets of ^{14}C dates of a specific class (cf. Geyh, Rhode, 1972; Pazdur, Pazdur, 1986; Goździk, Pazdur, 1987; Webb, 1986).

Applications in hydrolegological studies include dating of groundwater and determination of relative ages, which provide possibility of evaluation of groundwater flow directions and velocities (Mook, 1980; Geyh, 1980). These applications rely on a number of biogenic and chemical processes occuring in the top soil and during next stages of infiltration. For being able to interpret ^{14}C ages of groudwater samples it is necessary to perform also some chemical and stable isotope determinations and sometimes also to determine the content of other radioisotopes, as for example tritium. For more detailed review of those and other applications (eg oceanography, atmospheric and pollution studies, geochemistry, pedology) the readers should consult proceedings of the recent international radiocarbon conferences (Stuiver, Kra, 1980; 1983; 1986).

RADIOCARBON DATING AS A RESEARCH TOOL IN ARCHAEOLOGY. Applications of the radiocarbon dating method to archaeology were in recent years significantly improved due to progress achieved in four directions: a) improvement of dating accuracy to ca ± 10 yr; b) development in dating methodology, enabling direct dating of mortar (van Strydonck et al, 1986; Zouridakis et al, 1987) and potsherds (Gebasio et al, 1986), etc.; c) application of AMS techniques, enabling dating of a much larger class of artifacts, undoubtly associated with human activity (cf. Batten et al, 1986; Nelson et al, 1986); d) publication of high-precision calibration curves (Stuiver, 1982; Stuiver, Pearson, 1986; Pearson, Stuiver, 1986; Pearson et al, 1986) and development of computer programs for probabilistic calibration of conventional ^{14}C dates (Aitchison et al, 1989; Stuiver, Reimer, 1986; Michczyńska et al, 1989; Weninger, 1987; van der Plicht et al, 1989; Pazdur, Michczyńska, 1989).

Simultaneous application of ^{14}C dating and $\delta^{13}C$ analysis was proved as succesful tool for study of ancient diet (Johansen et al, 1986; Lovell et al, 1986). For detailed discussion of specific problems associated with application of the radiocarbon dating method to archaeological research the readers should consult proceedings of the Groningen meetings in 1981 and 1987 with important review papers by H. T. Waterbolk (1983), W. G. Mook and H. J. Streurman (1983), and J. Evin (1983). Application of the histogram methods were presented by Geyh and de Maret (1982); the suitability of various materials to dating archaeological sites was discussed by Gillespie and Polach (1979), Awsiuk et al (1986), Haas et al (1986). Important general comments concerning collaboration between archaeologists and radiocarbon dating laboratories were given by Ottaway (1986) and by Waterbolk (1983 a).

Selection of samples for radiocarbon dating. It seems obvious truth but it should be clearly stated that reliable dates may be obtained only when „good" samples are used for dating. The aim of this chapter is to present an explanation of the notion of „good" sample and to formulate some practical recommendations which would help the excavator to achieve the best result with the real samples collected during field work. In selecting samples for radiocarbon dating the following three criteria should be taken into account:

1. *Certainty of association between sample and event to be dated.* The real samples available for radiocarbon dating show great variation in the degree of certainty with which they are associated with the prehistoric event they are intended to date. This topic was excellently discussed in details

in a series of papers by H. T. Waterbolk (1983 a, b, c) and his classification will be repeated here without any significant modifications. According to Waterbolk (1983 a, b) samples could be divided into the following groups:

A. *Full certainty:* the archaeological object itself furnishes the dated sample. Examples: part of treetrunk canoe or other constructional materials of ancient ship (cf. Awsiuk et al, 1986), post of house, papyrus, organic backing material in pottery, ancient mortar (cf. van Strydonck et al, 1986; Zouridakis et al, 1987).

B. *High probability:* there is a direct functional relationship between the organic material selected for dating and the object or event to be dated. Examples: charcoal in an urn, carbonized grains in rubbish pit, carbonized coffin in a grave, hearth in floor of house.

C. *Probability:* there is no directly demonstrable functional relationship between sample collected for dating and the associated archaeological material, bur the quantity and amount of organic material, including size of fragment and their relation to other findings, may be used as arguments in favour of a relationship. Examples: concentration of charcoal in a rubbish pit or cultural layer.

D. *Reasonable possibility*: as before, but the fragments observed during excavations are small and scattered. Example: particles of charcoal or pieces of bone dispersed in occupation layer.

2. *Amount of sample material available for dating.* Quality of radiocarbon date, determined by the dating error quoted by dating laboratory, depends strongly on the mass of carbon available for radiocarbon activity determination. Undersized samples which are counted after dilution with inactive carbon yield results subjected to significantly greater errors. Only large samples may be used for dating with high-accuracy systems (cf. Table 3). Moreover, if only very limited amount of datable material is available it is necessary to reduce or even abandon the laboratory treatment of the sample and the result of dating may be influenced by possible contaminants.

3. *Type of sample, including evaluation of*: a) *age of sample before human use or incorporating in the sediment.* Every radiocarbon sample has a date older than that at which it was buried in the cultural layer and became associated with other objects. This is an obvious conclusion resulting from the basic assumptions of the radiocarbon dating. The radiocarbon method gives date of carbon fixation by the living organism. In the history of organic remnants used for dating in form of radiocarbon sample the following events can be distinguished: carbon uptake — death of organism — use of organic matter fragments by ancient man — incorporating in a certain cultural context. These events may be separated by highly different intervals of time, ranging from few weeks to many years. For correct interpretation of the radiocarbon date obtained with certain sample it is important to evaluate the time elapsed between first and last event. The following four possibilities can be distinguished: A. The difference is so small that may be regarded as negligible (less than 10 years). This situation is expected in case of dating the so-called short-living samples as grains, leaves, twigs, leather, bone of small animals, outermost tree-rings. B. The time difference can amount to several decades (up to 100 years). It should be expected that for most charcoal obtained by combustion of wood species of relatively short life-span (pine, spruce, etc.) the age difference is of order of 10—50 years. C. The time difference may amount to several centuries (more than 100 years), for example if charcoal from wood species with a long life-span is dated, or if there is a possibility that dated wood was subject to re-use. D. Undetermined time difference — this case occurs when the nature of dated sample is not precisely known, as for example when dating samples described as „dark earth", „ash".

b) *possibility, type and degree of contamination.* Practically every sample is contaminated or mixed with younger and/or older organic and/or carbonate material. The possible sources and mechanisms of contamination were discussed in one of previous chapters. It is also to be expected that the contaminants can be more or less completely removed by appropriate mechanical and chemical pretreatment if they are chemically different from the material to be dated. There is no way to separate the original sample from the contaminant of same chemical nature. The excavator should bear it in mind and decide whether there is a chance of such admixture. The quantitative effects of contaminants are summarized in Table 4, which gives magnitude of errors caused by recent and infinitely old (i.e. not containing radiocarbon) contaminants for samples of different age. The following conclusion may be drawn from data listed in this table: 1). Contamination with infinitely old carbon has same effect on samples of any age. If the amount of contaminant is below 0.5% the effect of contamination can be regarded negligible even for young (Iron Age or even Medieval) samples. 2). For young samples contamination with recent carbon is insignifiant. 3). For old samples, collected during excavations of Palaeolithic sites, the effects of contamination with recent carbon are critical and may seriously falsify the result of age determination.

Interpretation of radiocarbon dates. Dating error and related concepts. The conventional radiocarbon date is calculated according to the formula $T = 8033 \ln\{A(0)/A\}$. Both A and A(0) values are determined experimentally with some errors, estimated by accounting for all recognized laboratory sources of uncertainty. It is important to note that only laboratory errors are included in the final

value of the error ΔT of conventional radiocarbon date T. It is commonly accepted that the quoted value of error is calculated so that it represents the so-called 1σ (one-sigma) uncertainty. In consequence, this value has relatively simple probabilistic interpretation in terms of confidence interval and confidence level. The value T of conventional radiocarbon age together with its error Δt determine the interval (T−ΔT, T + ΔT) which is sometimes called uncertainty or confidence interval of conventional radiocarbon date. The probability that the true date is confined in this interval, i.e. that it is greater than T−ΔT and less than T + ΔT, is equal to ca 68%. Moreover, the probability that the true date is confined in the doubled interval (T−2ΔT, T + 2ΔT) is equal to ca 95%, and in tripled interval (T−3ΔT, T + 3ΔT) — is equal to ca 99%.

Comparing and averaging radiocarbon dates. It is a frequent task to compare two or more radiocarbon dates of same sample, object, or cultural layer, i.e. the dates which are obtained on materials of same age. As a rule, because of statistical nature of the processes involved in dating, the dates obtained are different. The question therefore arises if they can be regarded as consistent or not and if there is any single value which may be taken as representing the true date. Strict mathematical formulation of the answer to this question is the subject of mathematical statistics. Detailed discussion of specific problems encountered in statistical evaluation of radiocarbon dates of archaeological sites was given by Ward and Wilson (1978) and Long and Rippeteau (1974). Wilson and Ward (1981) have discussed the three most important cases and developed set of appropriate statistical procedures. The readers should consult these papers for detailed and strict discussion of related problems. However, it is recommended to consult specialists in dating and statistical treatment of data in case of any problems. Here I will give only some very simplified rules, referring to previously introduced interpretation of the dating error. Four simple cases of comparing the radiocarbon dates are shown in Figure 1, a. In cases A and B the 1σ error bars of the dates overlap and the dates can be regarded as consistent, or indistinguishable. In case C the two dates differ by 300 years and because the errors are very small the dates should be refarded as representing different events, significantly separated in time. In case D the dates also differ by 300 years as in case C, but the dating errors are much larger and the error bars overlap and completely cover the time span separating the dates. These dates cannot be used to support the hypothesis that the two dated events really differs in time. In Figures 1, a and b are shown two sets of four dates representing same cultural layer. Dates in Fig. 1, b may be regarded as highly consistent and the single value can be assigned to represent the age of the layer. There are two ways of calculating the average value, namely a) arithmetic mean, b) weighed mean. In the first way the differences in the accuracy of individual radiocarbon dates, measured by values of dating errors, are neglected. In the second way appropriate weights are given to all dates to account for the fact that dates with small errors are more significant. The weights are usually defined as inverse squares of dating errors. The situation shown in Figure 1, c is more common; there are three dates which form a consistent set with mean date equal to 5200 ± 25 BP and one much younger date 5050 ± 30 BP. This younger date from the statistical point of view should be treated as outlier which is not related with the main set. In evaluation of such set all additional knowledge concerning the nature of dated samples and the cultural context dated should be taken into account. There are several possibilities which should be considered: a) contamination of one sample, b) intrusion of younger sample into the layer, c) real difference of age between organic materials forming the cultural layer. In the last case the conclusion that the dated cultural layer was formed during some 200—300 years is justified.

Calibration of radiocarbon time scale. The radiocarbon dating relies on the fundamental assumption that the biospheric inventory of ^{14}C has remained constant during the past 100,000 years. This assumption was tested 40 years ago by Arnold and Libby (1949) with the accuracy of ca 10% by dating known-age Egyptian samples. However, with the improvement of the accuracy it was realized that this assumption is not precisely true. Systematic studies of discrepancies between ^{14}C and calendric dates, based on accurate ^{14}C determinations in dendrochronologically dated tree-ring samples have led to publication of numerous versions of calibration curves and tables (Suess, 1970; 1979; Damon et al, 1974; Ralph et al, 1973; Switsur, 1973; Clark, 1975; Klein et al, 1982). All these versions of calibration of the radiocarbon time scale were based on dendrochronologically dated American trees (*Pinus longaeva* and *Sequoia gigantea*). Dendrochronological background of these investigations was founded by C. W. Ferguson (1969; 1970; cf. also Ferguson and Graybill, 1983). There are several reasons which were raised against the early results obtained in the study of calibration of radiocarbon time scale by both archaeologists and physicists. The listed versions of the calibration have actually the historical value and this important discussion will not be considered here. The real breakthrough in the calibration was achieved in the last decade and was stimulated by the progress in dendrochronology of the European fossil oak in West Germany (Becker, 1980; 1988; Becker, Kromer, 1986) and in Ireland (Baillie, 1982; Baillie et al, 1983) and by important improvements of the accuracy of radiocarbon dating (cf. chapter on technical problems). The continued international collaboration between radiocarbon dating laboratories in Belfast (directed by G. W. Pearson) and

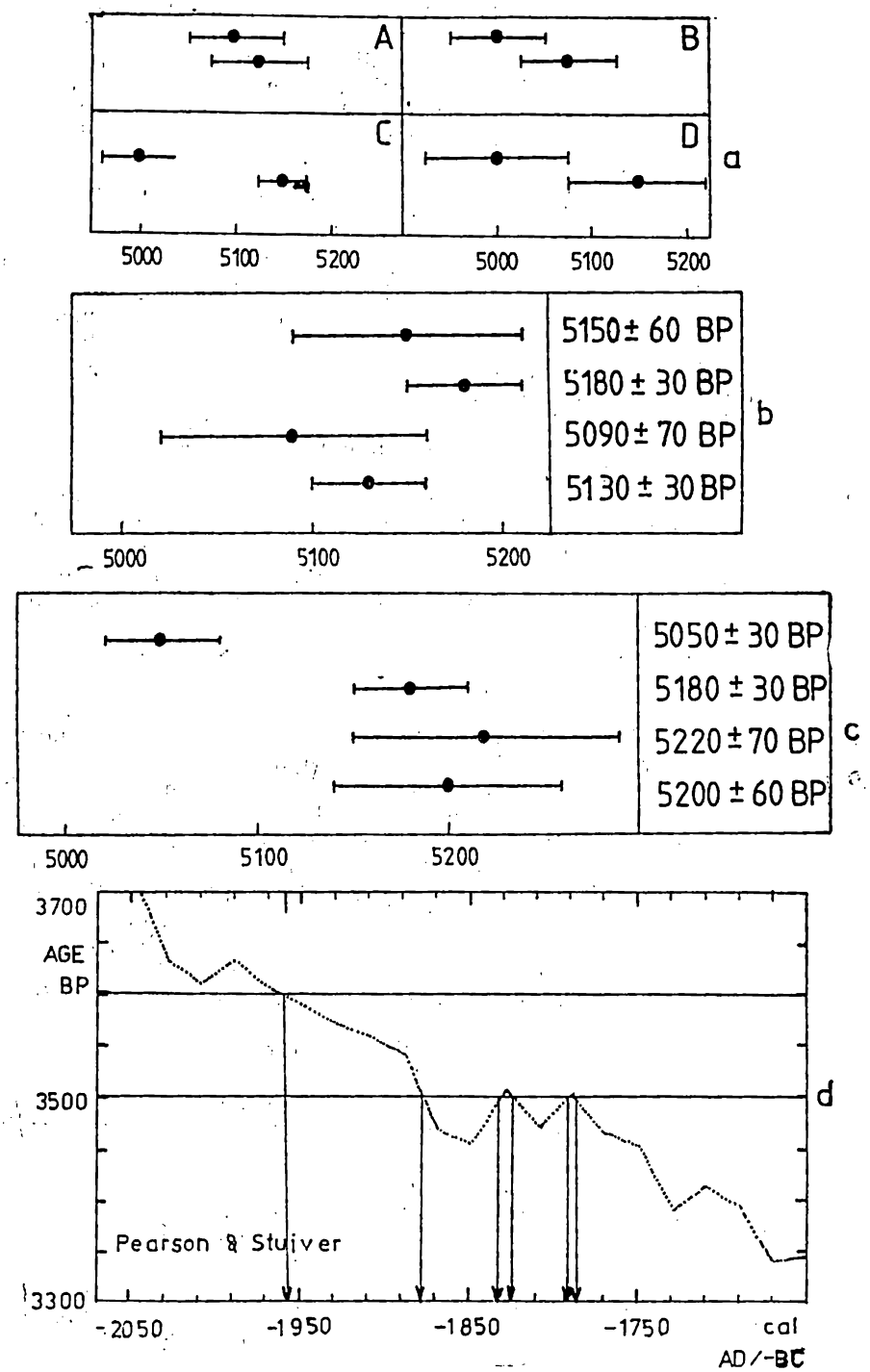


Fig. 1. a, examples of different cases encountered in comparing radio-carbon dates. A, B — error bars are overlapping, dates can ne regarded as consistent; C — two dates representing really different moments of time; D-same dates as in C, but subjected to much larger dating errors; b, consistent set of four dates; c, set of four dates with one result outlying; d, example of multiple values of calendric ages resulting from multiple intercepts with calibration curve.

in Seattle (directed by M. Stuiver) has led to elaboration of the first high-precision calibration curves based on measurements verified by two mentioned laboratories using different high-accuracy techniques (GC in Seattle and LS in Belfast). This research was also supported by several other laboratories (Groningen, Heidelberg and Pretoria) and the results obtained, after detailed discussion were accepted by the participants of the 12th International Radiocarbon Conference in Trondheim in 1985. The decision of this conference was the publication of the „Calibration Issue" of „Radiocarbon", with three high-precision calibration curves by Stuiver and Pearson (1986), Pearson and Stuiver (1986) and Pearson et al (1986). Continuing collaboration between European and American dendrochronologists and dating laboratories has led to the extension of calibration data back to more than 13,000 years BP (Stuiver et al, 1986). However, these data are preliminary and need to be confirmed before they can be recommended as a practical tool for conversion of conventional radiocarbon dates of Upper Palaeolithic and Mesolithic sites to calendric-time scale. Practical application of those high-precision calibration curves is, however, not simple, and the interpretation of obtained calendric ages is not straightforward. Because of numerous wiggles of calibration curve the correspondence between conventional ^{14}C dates and calendric ages is not equivocal, and, as a rule, there are several values of calendric age corresponding to a given ^{14}C date. For example, calendric age corresponding to ^{14}C date 3,600 BP may be easily read as equal to 1970 BC, but for ^{14}C date 3,500 BP we obtain five values of calendric age, equal to 1780, 1795, 1820, 1835 and 1880 BC (Fig. 1, d). Similarly, if the error of conventional ^{14}C date is taken into account, we have the problem of multiple intervals. For example, for ^{14}C date 4,200$\pm$ 50 BP, we obtain three intervals of calendric age : 2700—2725 BC, 2770—2810 BC, and 2865—2890 BC.

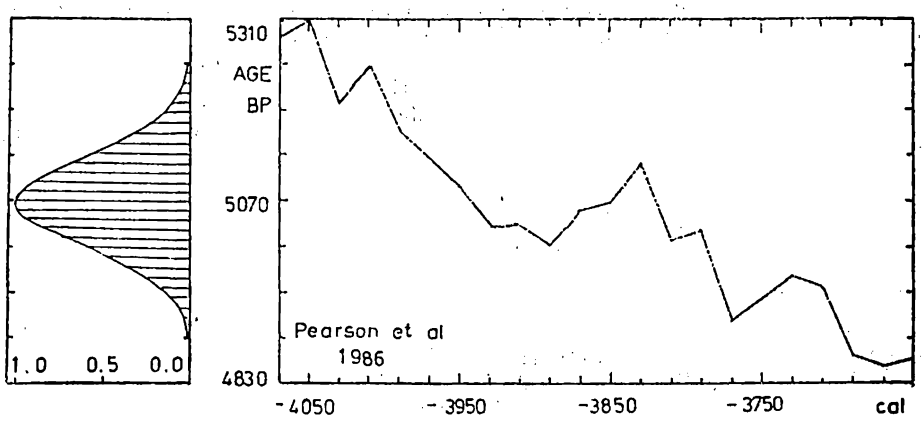
Probabilistic calibration of radiocarbon dates. In order to overcome the difficulties caused by multiple intercepts with calibration curve we have introduced the concept of probabilistic calibration of radiocarbon dates and developed a set of appropriate computer procedures. The idea of probabilistic calibration consists of transforming initial probability distribution of conventional ^{14}C date into calendric time scale and selecting appropriate parameters of resulting probability distribution as the measures of calendric age and its uncertainty.

Description of the computer procedure. The idea of probabilistic calibration was first introduced by Robinson (1985) and applied by Hassan and Robinson (1986) to calibration of a series of dates from Egypt, Nubia and Mesopotamia. The critique of this approach (Michczyńska et al, 1989) has led to more strict mathematical formulation of the algorithm of calibration, and the first version of calibration procedure was presented during the 2nd Symposium „Archaeology and ^{14}C" in Groningen, September 1987, and the improved version was presented during the 13th International Radiocarbon Conference in Dubrovnik (Pazdur and Michczyńska, 1989, in print). The system of calibration procedures was designed taking into account the specific tasks of archaeological application ; and includes three main options : 1. calibration of single date ; 2. calibration of a set of arbitrary dates, representing same or different cultures/phases/objects ; 3. calibration of a set of related dates obtained from a series of samples representing well-defined culture or phase.

Input data include : sample identifier (laboratory code and number, conv BP date and its error) ; calibration output is presented on screen in form of graphs and numeric data. By pressing special function key ⟨Prt Sc⟩ it is possible to obtain hard copy the screen on printer. In options 2 and 3 input data can be entered from diskette file. Printed report including list of conventional and calibrated dates is also available. Calibration is performed according to recently published high-precision calibration curves of Stuiver and Pearson (1986), Pearson and Stuiver (1986) and Pearson et al (1986) ; range of conventional ^{14}C dates extends back to 6,210 BP. Number of dates in series of input data for options 2 and 3 is limited to 50 dates. Results can be presented in either BP or AD/BC scale.

Examples. The possibilities offered by the developed set of computer procedures and some difficulties involved in interpretation of results of calibration will be illustrated on several examples of real or artificial ^{14}C dates. First we will present problems connected with calibration of single ^{14}C dates. Two specific cases are selected for this purpose, first we consider calibration of medium-accuracy ^{14}C dates (i.e. ^{14}C dates quoted with error of $\pm$ 50 to $\pm$ 100 yr), which, in general, do not cause significant interpretational difficulties. Second example presents the calibration of high-accuracy ^{14}C date (dating error of ca 30 yr or less), and illustrates typical difficulties with interpretation of calendric ages of high-accuracy dates. Next examples consider calibration of groups of ^{14}C dates, obtained on same or different sites or cultures, and show several ways of presentation of results of ^{14}C dating in terms of calendric ages.

1.a. *Calibration of single medium-accuracy date.* As an example we will consider a date obtained on charcoal sample from the Nagadian level in El Tarif site : (Gd-689 ; 5,070 $\pm$ 60 BP), quoted by Ginter and Kozłowski (1984). The results are presented in Figures 2, a and b. Figure 2, a is a hard copy of the first screen of calibration output. Relevant input data (site and sample name, lab. code and number, conv BP date with 1σ error, range of calibration) are listed at the left-hand side. Plots



a

b

⟨F1⟩ Help
⟨F2⟩ BP
⟨F3⟩ Next Scr
⟨Esc⟩ Exit
⟨PrtSc⟩

El Tarif

Gd-689
D=5070 conv BP
Sigma=60

Analysed interval:
[D−3*Sigma, D+3*Sigma]
Max. probability for dates:
−3850, −3942, −3820, −3790
Interval of cal age:
[−3695, −4038]

⟨F1⟩ Help ⟨F2⟩ BP
⟨F3⟩ First Scr ⟨Esc⟩ Exit
⟨PrtSc⟩

D=5070 BP Sigma=60 yr

P(T< To)	To cal. AD/-BC
0.01	−3996
0.05	−3975
0.10	−3962
0.25	−3932
0.50	−3876
0.75	−3826
0.90	−3792
0.95	−3750
0.99	−3712

Ranges

0.50	[−3932, −3826]
0.95	[−3985, −3725]
0.98	[−3996, −3712]

Fig. 2. a, typical result obtained in calibration of single medium-precision date, part one (copy of the first screen of calibration output). The date considered was obtained on sample from Nagadian level in El Tarif site, Egypt, excavated by B. Ginter and J. K. Kozłowski. For detailed explanations see text; b, typical result obtained in calibration of single medium-precision date, part one (copy the second screen of calibration output). Underlined are values of median and interquartile range.

how probability distribution of conventional ^{14}C date (upper left-hand side), appropriate part of alibration curve (upper right-hand side) and resulting probability distribution of calendric age lower plot). Negative values of calendric age denote BC dates. Because of wiggled shape of calibraion curve in the considered interval of conventional ^{14}C dates (4,890—5,250 BP) also the shape of esulting probability distribution of calendric age shows several peaks of approximately same height, vith two small peaks at the tails of probability distribution, which can be regarded insignificant. From the time scale we can estimate that the calendric age of dated sample should be confined with pproximately constant probability within 3780 BC and 3950 BC. Strict statistical measures are given n Figure 2, b which shows plot of cummulative probability (upper plot) and tables of selected quaniles and interquantiles. The centroid of probability distribution (the median) can be regarded as the nost appropriate measure of calendric age. This value, equal to 3876 BC, is underlined in Fig. 2, b. As the measure of uncertainty of calendric age can be chosen the interquantile range (underlined). This range indicates the interval of calendric age which contains the real value of calendric age with probability 50%. It is obvious, that the probability of finding true age out of this interval is also equal to 50%. After rounding the numbers listed in Fig. 6 to the 10 years we can state that the calendric age of calibrated sample is equal to 3880 $\pm$ 50 BC.

1.b. *Calibration of single high-accuracy date.* As an example will be considered calibration of an artificial date equal to 5,010 $\pm$ 15 BP. Calibration output is presented in Figures 3, a and b. The resulting probability distribution of cal age reveals the presence of two pronounced peaks of approximately the same height. Their exact location on the calendric time scale are given at the left-hand side; calendrid age covers two intervals separated in time (exact limits of these intervals are listed in brackets). The total range of time covered by probability distribution of cal age is greater than 250 years. Figure 3, a shows the hard copy of the second screen of calibration output. The most important value, i.e. the median (center of probability distribution, underlined), equal to 5,825 cal BP, is indicated by bold vertical line in Fig. 3, b. As can be easily seen, this value is close to the minimum of probability, between two prominent peaks in lower plot, and therefore cannot be accepted as the measure of calendric age. It should be also noted that the interquartile range is equal to 5,844—5,748 BP, i.e. it is close to the distance between the two peaks. The limits of the interquartile range are shown as dashed vertical lines in Fig. 3, b. This means that standard characteristics of probability distribution (median and interquartile range) cannot be accepted in this specific case as giving adequate value of calendric age. Therefore, it should be concluded that the real calendric age of dated sample corresponds to the value of maximum probability, i.e. it is equal either 5,840 cal BP or ca 5,740 cal BP. Exact values of probable intervals of calendric age can be obtained by interpolation. The most probable calendric age of considered date can be evaluated by using special option of the calibration program. Introducing the marker, shown by arrow at the lower part of Fig. 3, a it is possible to cut out the insignificant tails of the probability distribution of the calendric age. The limits corresponding to probability of 95% are shown by bold vertical arrows in Fig. 3, a. Finally, it may be concluded that with probability equal to ca 95% the calendric age of considered conventional radiocarbon date is confined either in interval from 5,870 to 5,830 cal BP, or from 5,770 to 5,730 cal BP. The readers should note that the quoted probable intervals of calendric age differs by 100 years. This example is an illustration of the limits of accuracy of the radiocarbon method, as the question of the true age of dated object cannot be solved on the grounds of radiocarbon dating, even if more accurate radiocarbon date was available on same sample of charcoal. It may appear possible to solve this question by dating another sample of short-living material (eg. grains) or by combined usage of radiocarbon and dendrochronologic dating.

1.c. *Special difficulties in calibration.* In some periods of time the radiocarbon concentration was disturbed in such a way that the resulting shape of the calibration curve is relatively flat with some minor wiggles. This is the situation of the beginning of the Iron Age (ca 800—400 cal BC). In this period of time the calibrated radiocarbon dates cover several centuries irrespectively of their accuracy. An example is provided in Figures 4, a and b, showing calibration output obtained for charcoal sample from Texel Den Burg site (GrN-7,457; 2,480 $\pm$ 35 BP). The shape of appropriate part of calibration curve, shown in upper plot of Fig. 4, a is practically flat in time period from ca 720 BC to 420 BC. Obtained probability distribution of calendric age covers more than two centuries without any significant peaks and shows no similarity to initial Gaussian probability distribution of the conventional radiocarbon date (left plot at top of Fig. 4, a). In such a case the median of obtained probability distribution (underlined, equal to 626 cal BC) may be used as the correct measure of calendric age. The uncertainty of calendric date, determined by the interquartile range, is however, much larger that those of conventional radiocarbon date, and extends from 690 cal BC to 560 cal BC. Final conclusion is that the calendric date is equal to 630 $\pm$ 60 cal BC. It should be noted that the error of calendric date is two times greater than that of conventional date.

2. *Calibration of a set of arbitrary dates.* This option was designed to show the results of calibration of any set of individual dates on common time scale of calendric age. The number of dates in

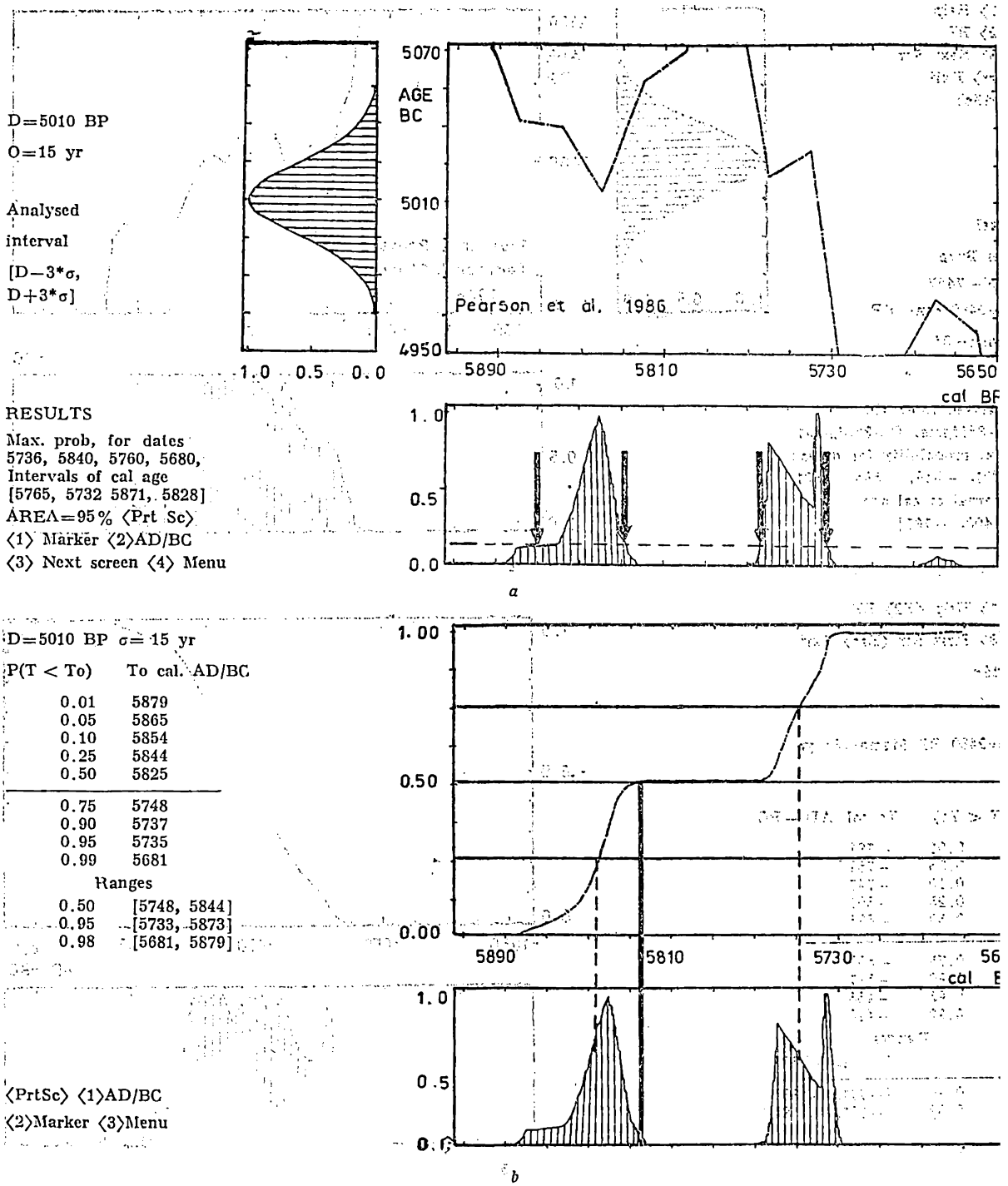
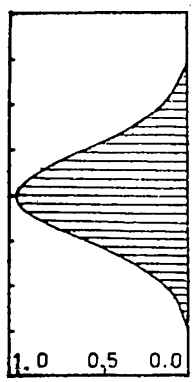
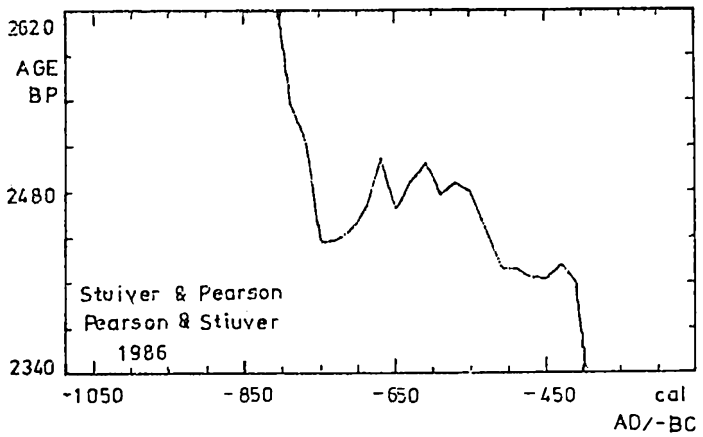


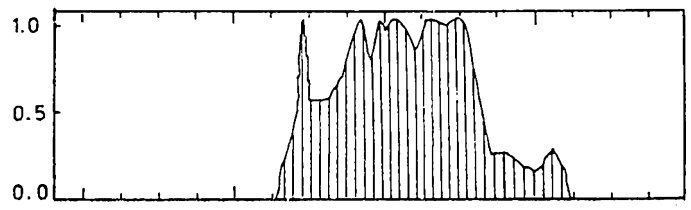
Fig. 3. a, typical result obtained in calibration of single high-precision date, part one (copy of the first screen of calibra output). An example is based on artifical result, 5010 ± 15 BP. For explanations see text; b, typical result obtained in bration of single high-precision date, part two (copy of the second screen of calibration output). Underlined values (Fig. cannot be regarded as appriate measures of calendric age and its uncertainty.

<F1> Help
<F2> BP
<F3> Next Scr
<Esc> Exit
<PrtSc>





Texel
Den Burg
GrN—7457
D=2480 conv BP
Sigma=35



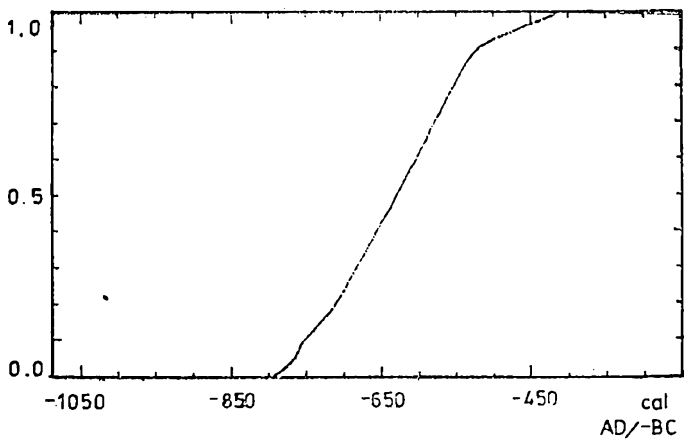
Analysed interval:
D—3*Sigma, D+3*Sigma1
Max, probability for dates:
—637, —549, —585, —591
Interval of cal age:
[—403, —797]

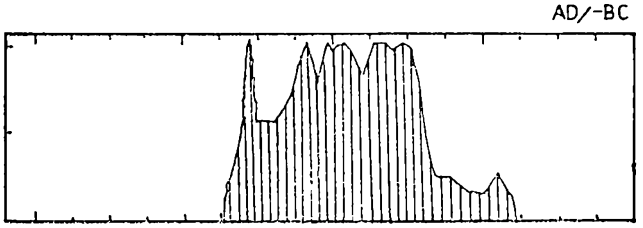
a

<F1> Help <F2> BP
<F3> First Scr <Esc> Exit
PrtSc

D=2480 BP Sigma=35 yr

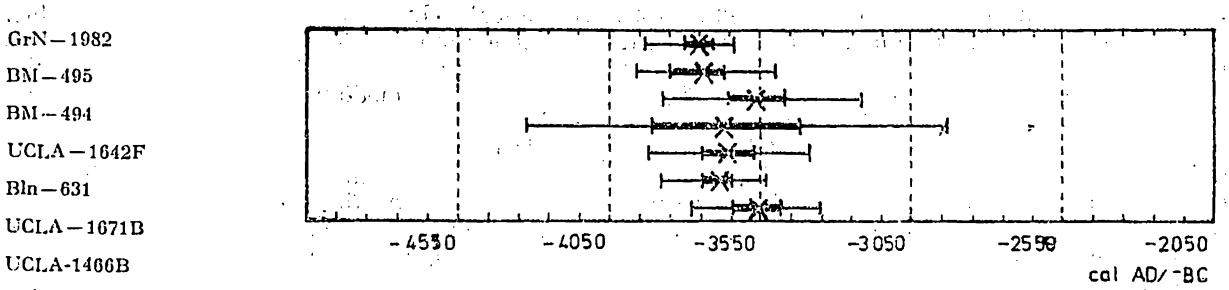
P(T < To)	To cal. AD/—BC
0.01	—781
0.05	—762
0.10	—747
0.25	—691
0.50	—626
0.75	—562
0.90	—517
0.95	—466
0.99	—418
Ranges	
0.50	[—691, —562]
0.95	[—771, —433]
0.98	[—781, —418]





b

Fig. 4. a, illustration of calibration output obtained for typical dates of the Hallstatt period. Copy of the screen of calibraftion output. For detailed explanation see text; b, calibration of single date of the Hallstatt period. Copy of second screen ocalibration output. For detailed explanation see text.



⟨F1⟩ Help ⟨F2⟩BP
⟨F4⟩Prt Report ⟨Esc⟩ Exit
⟨DrtSc⟩
Name of data set:
Cucuteni B
7 dates were calibrated

P(T < To)	To cal. AF/-BC
0.01	—4196
0.05	—3931
0.10	—3888
0.25	—3764
0.50	—3680
0.75	—3564
0.90	—3436
0.95	—3381
0.99	—3049

Ranges

0.50	[—3764, —3564[
0.95	[—3997, —3218]
0.98	[—4196, —3049]

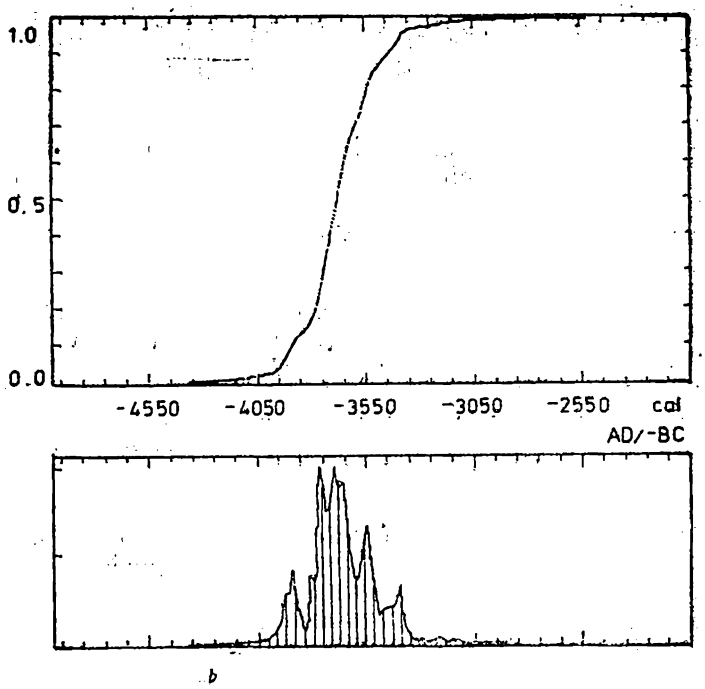


Fig. 5. a, results of calibration of a set of seven radiocarbon dates representing the Cucuteni B culture of Romanian Eneolithic (Monah, 1987), showing median (dots), interquartile ranges (bold lines) and 95% confidence intervals of calendric age; b, example of calibration output obtained with option for calibrating of a set of related dates (7 dates representing culture Cucuteni B of Romanian Eneolithic; Monah, 1987).

analysed series is not limited, but only 22 dates can be presented simultaneously in a single separate picture on the screen. Longer series of ^{14}C dates are presented in groups of 22 successively on the screen. Three versions of presentation of calibration output are available in this option. First version shows the so-called „cut-out" calibration, i.e. the intervals of calendric age which are cut out of calibration curves by bands of width $[D-\sigma, D+\sigma]$, where D is conventional ^{14}C age and σ is its error. The results on the screen shows the intervals of probable calendric age of dated samples. Second version gives interquartile ranges of calendric age, third version, which seems to be most useful, gives the almost complete information about probability distributions of calendric age of all considered samples. In this version the plot shows values of centroid (median) and 50% and 95% confidence intervals of calendric age of all considered samples. Numerical values are available in form of table. As an illustrative example of this option we will consider calibration of the set of seven ^{14}C dates representing the Cucuteni B culture of the Romanian Eneolithic, quoted by Monah (1987). The results obtained using third version are shown in Fig. 5, a with indicated median values (dots), interquartile ranges (bold lines) and 95% confidence intervals of calendric age.

3. *Calibration of a set of related dates.* This option is useful for calibration of groups of dates obtained on samples from a definite site or culture. The result is presented as composite probability distribution of all dates in form similar to second screen produced by first option for calibration of a single date. An example of calibration output of a group of 7 dates of the Cucuteni B culture (same as in Fig. 5, a) is shown in Fig. 5, b. The composite probability density function shows the presence of main well-distinguished peak, which can be interpreted as resembling the floruit of this culture. Time limits determining this period are determined as interquartiles of composite probability distribution of calendric age of this set of dates.

Final remarks and conclusions. In the beginning of the radiocarbon dating the known-age Egyptian samples were used by W. F. Libby to test his idea. Now, after 40 years, almost all users of ^{14}C dates are aware of discrepances between (conventional) ^{14}C time scale and calendric chronology. However, it seems that the need for comparing both ^{14}C and calendric chronology remains unchanged, and, moreover, such comparisons are of crucial importance for studies of the prehistory of Egypt and adjacent regions.

Described set of computer procedures is far from perfection, but, in spite of this, it enables presentation of results of ^{14}C dating in terms of calendric ages, using strict statistical concepts such as median, interquartile range, etc. The examples discussed in the text of this article show that there are no general rules for interpretation of calibration output. Therefore we developed a system of related procedures which can be used in various ways, enabling different ways of presentation of calibration output. The possibility of working with single ^{14}C dates, with groups of dates, and sets of groups of dates connected with different sites or cultures, seems to be the main advantage of the developed system. Practical limitation is connected with the range of calibration curves, which extend back to 6,200 BP.

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B. *IMPORTANT BOOKS AND CONFERENCE PROCEEDINGS*

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Appendix A

PRACTICAL RECOMMENDATIONS

1. During excavations try to collect more samples than necessary and collect a greater amount of sample than necessary for one dating to provide material for additional check dating. Estimate whether the amount of sample is sufficient to provide the required dating precision.

2. Try to recognize the nature of an archaeological deposit or natural section in order to evaluate possibilities of contamination according to classification presented in chapter dealing with sample and contamination problems (possibilities of humic acid infiltration from higher layers, root penetration, visible traces of animal activity, visible traces of human activity from other periods than the sample, geological complications, etc).

3. Pack the samples in double plastic cover or plastic or glass container. Attach immediately the appropriate label indicating name of the site, sample serial number date and name of collector. Warning: Do not use paper or cloth to pack the samples. Do not attach paper labels to organic samples. Do not insert paper labels to the bottles containing organic samples.

4. Realise that botanical or zoological identification of the sample material will not be possible after treatment in the radiocarbon dating laboratory.

5. Send sample to the radiocarbon dating laboratory as originally packed and enclose complete information requested by laboratory using appropriate laboratory information form. Complete the form carefully providing all information requested. If some information is not available please state it clearly. Do not leave empty fields in the sample information form.

6. Store the samples for radiocarbon dating in a cool, dry and dark place. Dry the samples carefully to avoid contamination in an oven at ca 50°C.

Appendix B

List of active European laboratories involved in radiocarbon dating of archaeological samples

Lab. code	Institution	Director
ANT W	Antwerp University, Belgium	Prof. R. Vanhorne
B	Universität Bern	Prof. H. Oeschger
Bln	Berlin	Dr. G. Kohl
BM	British Museum	Dr. S. Bowman
Deb	ATOMKI Debrecen	Dr. E. Csongor
Gd	Technical University Gliwice	Dr. M. F. Pazdur
Gif	Gif-sur-Yvette	Dr. M. Fontugne
GU	SURRC	Prof. M. S. Baxter
Hel	University of Helsinki	Dr. H. Jungner
Hv	Hannover	Prof. dr. M. A. Geyh
K	Copenhagen	Dr. H. Tauber
KN	Universitat Köln	Dr. J. C. Freundlich
Lu	University of Lund	Mr. G. Skog
Lv	Louvain la Neuve	Mr. E. Gilot
Ly	University of Lyon	Mr. J. Evin
Q	University of Cambridge	Dr. V. R. Switsur
R	University of Rome	Dr. F. Bella
SRR	NERC East Kilbride	Dr. D. D. Harkness
T	Trondheim University	Dr. R. Nydal
U	University of Uppsala	Dr. I. U. Olsson
VRI	Universität Wien	Dr. E. Pak
Z	Institut „Ruder Boskovic" Zagreb	Dr. D. Srdoc
	AMS laboratories	
ETH	ETH/AMS Facility, Zürich	Prof. W. Woelfli
Gif	CFR Gif-sur-Yvette	Prof. J. C. Duplessy
OxA	Oxford Radiocarbon Accelerator Unit	Dr. R. E. M. Hedges
Ua	Uppsala Tandem Accelerator Lab	Dr. G. Possnert
UtC	Utrecht Van de Graaff Lab	Dr. K. van der Borg

Table 1

Comparison of techniques used for radiocarbon dating

	GC			LS		AMS
	ST	MC	HA	ST	HA	ST
Mass of C	5 g	50 mg	25 g	5 g	20 g	2 mg
Counting time	48 h	14 d	5 d	48 h	10 d	20 min
Counting vol	2,5 l	30 ml	6 l	5 ml	25 ml	—
Dating range	45 kyr	40 kyr	60 kyr	45 kyr	55 kyr	45 kyr
Age error	50 yr	100 yr	10 yr	60 yr	15 yr	100 yr

ST — standard version, MC — microcounters, HA — high accuracy.

Table 2

Summary of isotopic fractionation effects

Material	δ^{13} C per mil wrt PDB	Age correction and error
Marine carbonates	0±4	410±70
Lake carbonates	−4±6	340±100
Speleothems	−8±3	275±50
Tufa, travertine	−8±5	275±80
Grains, seeds (maize, millet)	−10±3	245±50
Marine organism (whale, seal)	−15±4	160±70
Succulents (cactus, pineapple)	−17±8	130±130
Bone collagen	−22±2	50±35
Grains (wheat, oats, rice)	−23±4	30±70
Wood, charcoal	−25±5	0±80
Peat, humus	−27±6	−35±100

Table 3

Typical carbon content of various types of sample used for radiocarbon dating and amount of dry material (in grams) needed to obtain 1 gram of carbon

Type of sample	%C	Treatment			Recommended[a] mass of sample
		without	A	AAA	
Wood	50	2	3	6	15/30
Charcoal	75	1.5	2.5	4	5/10
Peat	50	2	3	10	10/50
Soil/humus	0–10	50	100	200	500
Bone	0–5	–	50[b]	–	300
Charred bone	0–5	–	50[b]	–	200
Carbonate	12	10	15	–	15/40
Charred grain	50	2	3	4	5/10

a) recommended mass of sample for dating on small/large counter with standard accuracy equal respectively to ± 50/80 yr, respectively.
b) pretreatment according to method of Longin (1971).

Table 4

Effects of contamination with infinitely old and recent carbon on radiocarbon dates

Sample age yr BP	Percentage of contaminant					
	0.1%		1%		10%	
	old	recent	old	recent	old	recent
500	+8		+80	−5	+850	−50
1000	+8	−1	+80	−10	+850	−110
2500	+8	−3	+80	−30	+850	−290
5000	+8	−7	+80	−70	+850	−670
7500	+8	−12	+80	−120	+850	−1150
10000	+8	−20	+80	−200	+850	−1780
15000	+8	−45	+80	−440	+850	−3500
20000	+8	−90	+80	−840	+850	−6000
25000	+8	−170	+80	−1560	+850	−9200
30000	+8	−330	+80	−2750	+850	−13100
40000	+8	−1100	+80	−7200	+850	−22000