AUTOMATIC RADIOCARBON CALIBRATION: ILLUSTRATIVE EXAMPLES

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ABSTRACT: A PC-based computer program for automatic calibration of radiocarbon dates has been developed. It uses a calibration curve, generated along the calibration data points as published in the Trondheim (12th Radiocarbon Conference) proceedings. The program produces a calendar age probability distribution. Well-chosen example calibrations are discussed to aid the non-specialist in interpretation of the obtained probability distributions.

KEYWORDS: Radiocarbon, ^{14}C, calibration, computer.

1. INTRODUCTION

Age determination by ^{14}C (radiocarbon) is based on measurement of the residual amount of ^{14}C. The isotope ^{14}C is continuously produced in the earth's atmosphere by cosmic radiation.

The radioactive carbon isotope enters the global carbon cycle and finally decays with a half life of 5730 years. A stationary state of production, distribution and decay results in a constant ^{14}C concentration in atmospheric CO_2. ^{14}C is taken up by photosynthesis and (less directly) by other organisms. The carbon exchange with the environment ceases after death, whereupon the ^{14}C is subject to radioactive decay. Thus the age of carbon-containing matter can be determined by measuring the ^{14}C left in the sample.

Radioactive decay follows an exponential law, so that the age can be calculated by

$$T = -\frac{1}{\lambda} \ln \frac{A}{A_0}$$

where λ is the decay constant, which is related to the half life by $\lambda = \ln 2/T^1/_2$, A and A_0 are the measured and original specific activity, respectively. The ^{14}C laboratories always report the so-called conventional age, which is defined as follows (Mook & Streurman, 1983; Mook & Waterbolk, 1985):

1. The natural specific ^{14}C activity has always been equal to a value defined by a standard, NBS Oxalic Acid.
2. The half life is 5568 years (the so-called Libby value).
3. The ^{14}C activity is corrected for isotope fractionation by bringing the measured $^{13}\delta$ value to -25‰.
4. The age T is expressed in years BP (Before Present), i.e. before 1950 AD.

The true half life of ^{14}C is 5730±40 years (Godwin, 1962), but the older value is preferred in order to avoid confusion with earlier reported dates. Also, the ^{14}C content in the atmosphere has not been constant in history. The effect of these natural ^{14}C variations and the erroneous half life are both taken into account by means of calibration of the radiocarbon time scale.

2. THE ^{14}C CONTENT OF THE ATMOSPHERE

In the early days of radiocarbon, ages were calculated based on the formula given above. The relation between ^{14}C ages (years BP) and calendar years was simply taken as AD = 1950 - BP, and BC = BP - 1949 (the year '0' does not exist in chronology).

It was discovered soon that serious errors were made, because the ^{14}C content of the atmosphere has not been constant in the past (de Vries, 1958). This effect was discovered by measuring the ^{14}C content of tree rings, which are also dated dendrochronologically. In some cases (for example, around 7000 years BC) corrections of 800 years have to be applied.

By plotting the ^{14}C ages in BP versus the dendroyears of tree rings, sets of calibration points were obtained, which are not located on the line AD = 1950 - BP because of variations in the atmospheric ^{14}C content. The first calibration curve more or less connecting the individual points was published by Suess (1967). Later curves also became in use (Ralph et al., 1973; Clark, 1975; Klein et al., 1982). Since the original work of de Jong et al. (1979), several series of calibration data were produced with higher precision than the original data from La Jolla, Pennsylvania and Arizona. At present, the recommended high-precision calibration data are published in the special issue of *Radiocarbon* (Stuiver & Kra, 1986). The accepted calibration data are those of Stuiver & Pearson (1986) and Pearson & Stuiver (1986) for the period 1940 AD to 2490 BC. The points are given in 20 (sometimes 15) year intervals. These series are usually extended to 5210 BC using data from Pearson et al. (1986). There is also a set with higher precision (decadal, 1950 AD-2500 BC) from Stuiver & Becker (1986). Furthermore, high-precision data are presented by Vogel et al. (1986) (1935-3099 BC), de Jong et al. (1986) (3930-3230 BC), Linick et al. (1986) (6549-6089 BC and 5815-5355 BC), Kromer et al. (1986) (7207-5858 BC and 5321-4429 BC) and Stuiver et al. (1986) (7197-6474 BC). The data from de Jong were recently corrected (Mook & Becker, 1989). We ignore here the so-called marine curve which is theoretically derived from the atmospheric data and spans a range back to 7000 BC (Stuiver, Pearson & Braziunas, 1986). The calibrated age ranges of all these data sets are plotted in figure 1.

A plot showing all calibration points and - for illustrative purposes - the Libby line (AD = 1950 - BP) is shown in figure 2. We distinguish three types of natural variations:

1. The long-term trend of the calibration points is like an oscillation. The data can be fitted to a polynomial function yielding the relation between BP and AD/BC (Ralph et al., 1973). This trend can be explained by changes in the earth's magnetic field, which follow the same trend (Bucha, 1970).

2. On a time scale of a few hundred years, one can recognize medium-term variations, the so-called wiggles (Suess, 1970; de Jong et al., 1979) which are due to solar fluctuations (de Jong & Mook, 1980).

3. For precise measurements, even the well-known 11 year sunspot cycles are reflected in atmospheric ^{14}C production (Stuiver, 1978; Tans et al., 1979).

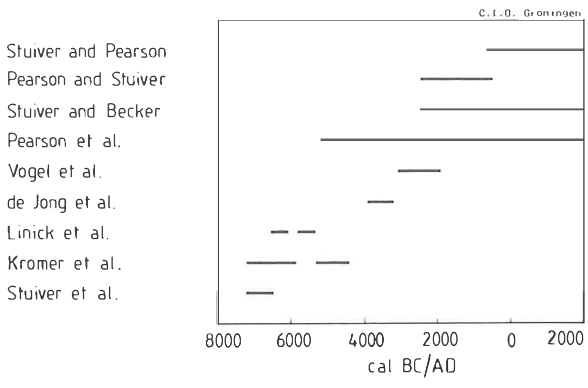

Fig. 1. Time span for age calibration data points, as published in the 12th International Radiocarbon Conference Proceedings (Trondheim, 1986).

It is the wiggly shape of the calibration data that makes calibrating of ^{14}C ages into calendar dates complicated. For instance, wiggles can cause a ^{14}C age to correspond to more than one calendar date. Furthermore, horizontal parts of the calibration curve cause clustering of ^{14}C ages if frequency diagrams are applied (de Jong & Mook, 1981). Also, the ^{14}C sample and the calibration data should have the same time width (growth period) in order to avoid ambiguities (Mook, 1983).

In this paper, we present a method of calibration of ^{14}C ages using the data from the special issue of *Radiocarbon* (Stuiver & Kra, 1986). A computer program has been developed for this purpose (van der Plicht et al., in press; van der Plicht & Mook, in press).

3. CALIBRATION

In this chapter, we discuss the consequences of the non-constancy of the atmospheric ^{14}C content for calibration. In figure 3:a, a typical wiggle is drawn. If we suppose that the ^{14}C age is y years BP, it is obvious that this results in 3 possible calibrated calendar dates (x_1, x_2 and x_3). The ^{14}C age results from a radioactive decay measurement, which usually has a Gaussian probability distribution with a well-defined standard deviation σ. This is illustrated in figure 3:b. The age is expressed as $(y \pm \sigma)$ BP, which - statistically - means that there is a 68% probability that the true age lies between $y + \sigma$ and $y - \sigma$. If we consider the range $y \pm \sigma$, the calibration age ranges will be Δx_1, Δx_2 and Δx_3.

The situation becomes even more complicated if we want to take into account the uncertainty in the calibration curve as well (fig. 3:c). This would result in larger calibrated ranges Δx_1, Δx_2 and Δx_3.

The problem is how to formalize this calibration procedure, illustrated graphically in figure 3, in correct mathematical expressions, or how to express the ^{14}C age $y \pm \sigma$ in one or more calibrated dates, including a measure for the uncertainty.

One approach is to add σ's of the ^{14}C age and the calibration curve quadratically ($\sigma_{tot} = \sqrt{[(\sigma_{date})^2 + (\sigma_{curve})^2]}$) and determine the points along the calendar axis where $y \pm \sigma_{tot}$ is meeting the calibration curve. This method is explained in Mook & Waterbolk (1985), and a worked-out example can be found in Pearson (1987). Also a computer program performing this task automatically has been distributed (Stuiver & Reimer, 1986). The final results are expressed in calibrated calendar age ranges.

This method of calibrating is proven to be useful but in fact is mathematically not correct and does

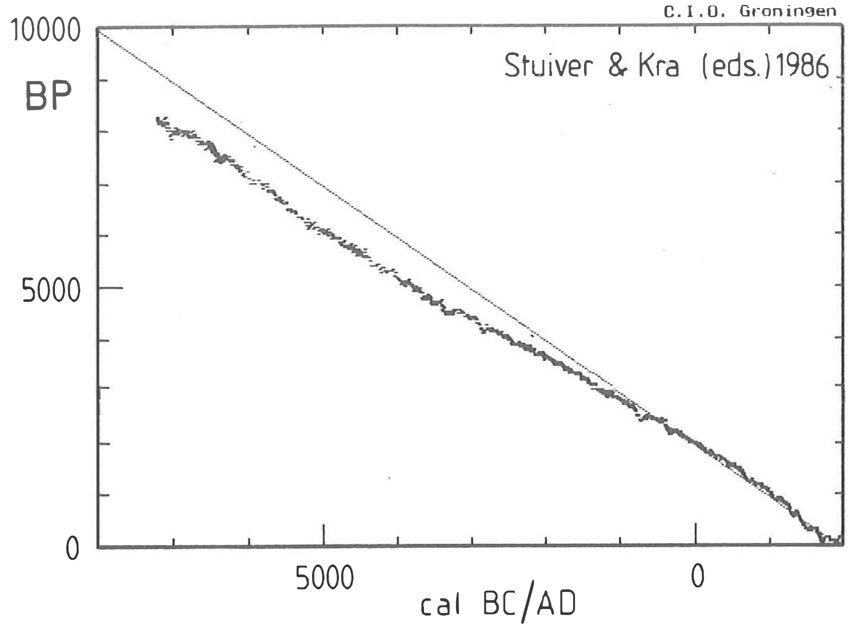

Fig. 2. Plot of the Trondheim calibration data points in BP (vertical) versus cal BC/AD (horizontal). The solid line represents BP = 1950 − AD.

not provide all the information possible. For instance, within the resulting calibrated ranges, all dates have an equal probability which is not true. The correct calculation of the probability of calibrated date ranges is where recently developed computer programs are made for, instigated by the special calibration issue of *Radiocarbon* (Stuiver & Kra, 1986) and the increasing use of microcomputers in the last years. The results of the various programs were compared at the 13th International Radiocarbon Conference in Dubrovnik (Aitchison et al., in press).

One may have noticed that all existing calibration programs yield slightly different results, even if all programs use the same calibration points as published in the special calibration issue of *Radiocarbon* (Stuiver & Kra, 1986). The reasons are to be found in mathematical details. Firstly, the calibration points are to be connected to form a calibration curve, which can be done in a variety of ways. Secondly, the uncertainty in the ^{14}C age has been taken into account using one, two or three standard deviations. Thirdly, the resulting calendar date probability distribution can be interpreted by different approaches.

However, the differences between the programs

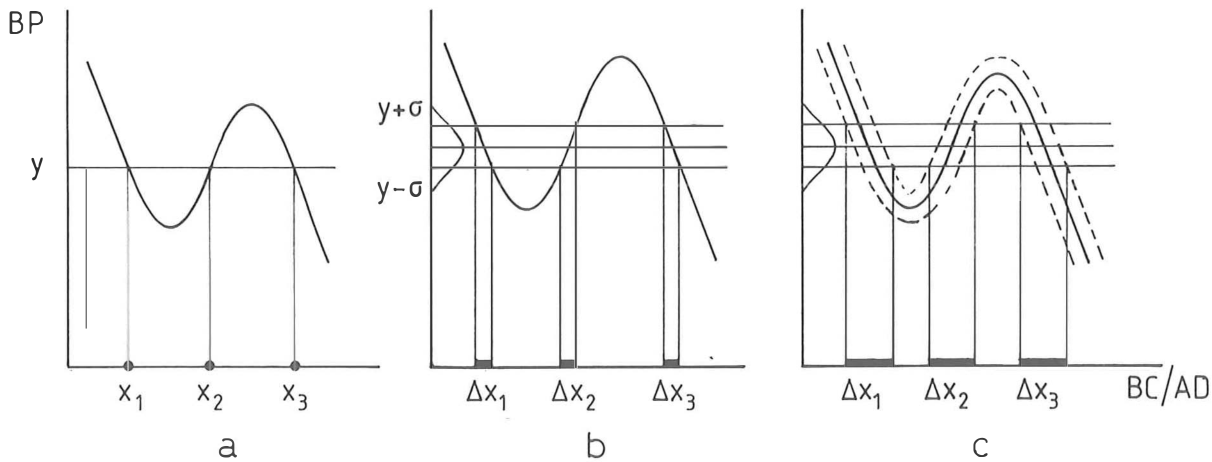

Fig. 3. Illustration of the effect of a wiggle in the calibration curve on the calibration of a ^{14}C age: a. calibration of age y (BP); b. effect of the error associated with y; c. effect of introducing also the error in the calibration curve.

developed independently at several laboratories turn out to be negligible in most cases. For details we refer to Aitchison et al. (in press).

We concentrate here on the program developed at the C.I.O. in Groningen, which is widely distributed (van der Plicht et al., in press; van der Plicht & Mook, in press). Our goal in this paper is to make the calibration procedure as developed on microcomputers transparent for the non-specialist. We try to accomplish this goal by means of discussing well-chosen example calibrations.

4. A SHORT DESCRIPTION OF THE PROGRAM

The Groningen computer program is developed for use on an IBM-XT/AT or compatible PC. It is completely written in Turbo-Pascal (version 4.0) (Borland, 1987). Three graphics modes are supported: CGA, EGA and Hercules. Great care is taken to make the program user friendly. One only has to enter the age (in BP), its error (sigma-BP) and an identification label at user's choice (for instance, a GrN number). All other data necessary for the calculations are read in from the appropriate data files automatically. The graphs such as shown in this paper will then automatically appear on the screen, and can be printed as wish. Only for special options one has to set some parameters.

In order to perform the calibration procedure, a calibration curve has to be calculated first which represents the calibration points. We have chosen to calculate a so-called spline function through the calibration points, following a procedure described by Reinsch (1967). For details we refer to van der Plicht & Mook (in press).

The program first selects, via the calibration curve, those points on the calendar axis corresponding to $y \pm 3\sigma$, where y is the ^{14}C age in BP and σ its standard deviation. This means that we use 99.7% of the Gaussian probability distribution. Next, we calculate the probability along the calendar axis within this range, which – for each point – depends on the local value of the corresponding Gaussian probability distribution of the ^{14}C age and the calibration function value. Finally, the calendar axis probability distribution is properly normalized so that the total probability is 1 or 100%. Again, for details we refer to van der Plicht & Mook (in press).

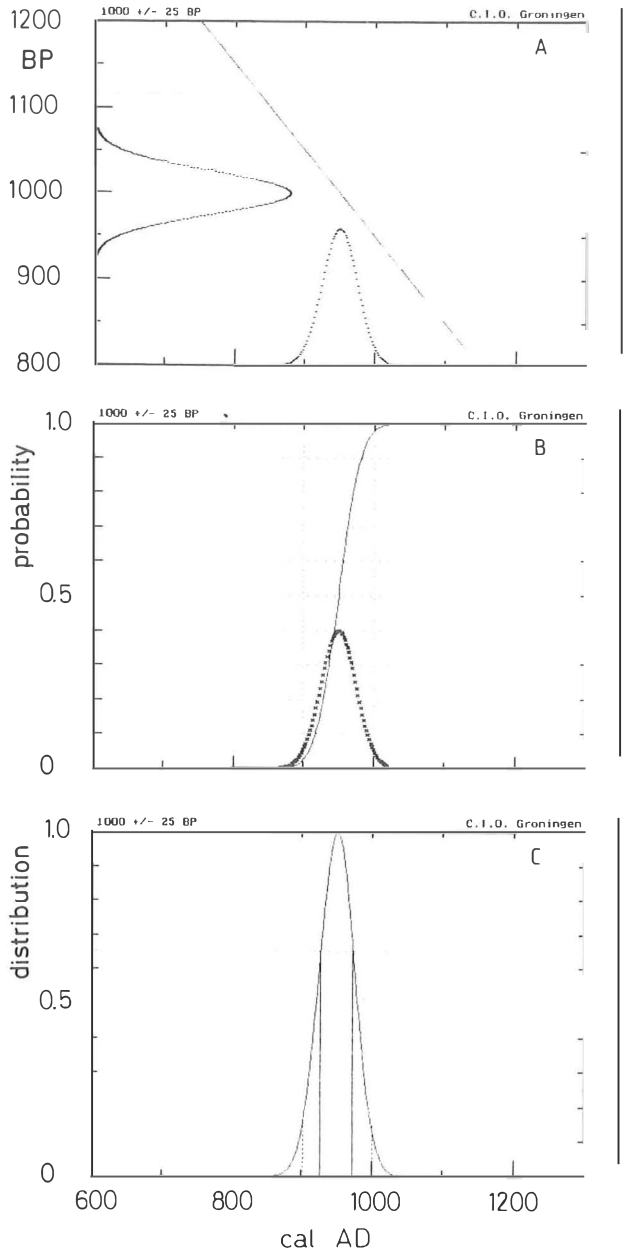

Fig. 4. Results of calibrating the age 1000±25 BP using a straight line (BP = 1950 – AD) as a calibration curve. Figure 4:a shows the calibration curve, the Gaussian probability distribution corresponding to the ^{14}C age (along the y-axis) and the calibrated calendar age distribution (along the x-axis). Figure 4:b shows the same calendar axis probability distribution and the normalized cumulative probability distribution (solid line). Figure 4:c shows the calendar axis probability distribution with levels corresponding to 1- and 2-confidence levels (dotted lines).

5. ARTIFICIAL EXAMPLES OF CALIBRATION

In order to fully appreciate the results of the calibration program, we first show some illustrative examples. In figure 4, where we calibrate a ^{14}C age of 1000±25 BP, the calibration curve is taken as a straight line corresponding to AD = 1950 - BP. This means in fact that there would be no secular variations (the Libby model). Since the calibration curve is a straight line with a slope of 45°, the calibrated distribution is also a Gaussian with the same standard deviation as the non-calibrated distribution and the result can be stated as 950±25 cal AD. In figure 4:a, the Gaussian probability distribution of the radiocarbon age is plotted along the vertical (y) axis. The calibrated calendar date probability distribution is plotted along the horizontal (x) axis. This distribution is also a Gaussian, with a maximum value at 950 cal AD (i.e. 1950-1000) and the same standard deviation (25). Also the selected part of the calibration curve (in this case the straight line) is plotted. Note that the calibration curve is plotted according to the convention that was agreed on at the 12th Radiocarbon Conference in Trondheim (Mook, 1986).

A plot of the integrated (cumulative) and normalized probability distribution is shown in figure 4:b (the solid line). From this plot we can read the mean value at the probability of 0.5 (or 50%), which is again at 950. The standard deviation corresponds to a probability of 0.16 (16%) or 0.84 (84%) so that the total probability range (from 0.16 to 0.84) is 0.68 (68%), which in turn corresponds to 2 times σ. An alternative plot is shown in figure 4:c, where the top horizontal dotted line indicates the date range with a total probability of 68%. Also from this plot we can infer the so-called 1-σ range. A second bottom dotted line indicates the 2-σ range. This means that the area (or probability) under the curve between 925 and 975 is 68% (1-σ) and between 900 and 1000 95% (2-σ).

In the following examples (figs 5 and 6) we will complicate the calibration procedure by introducing aberrations from the straight line.

In figure 5:a an artificial horizontal range of 100 years is introduced in the calibration curve. In this case, the calibrated probability distribution is of course no longer a Gaussian. Again, we calibrate an age of 1000±25 BP (fig. 5:b). The calibrated probability distribution is symmetric so that we can assign a median (mean) value at a probability of 0.5 (or 50%), which is of course at 950. The 68% probability range inferred from figure 5:b at 16 and 84%, or from figure 5:c as indicated by the top dotted line is 895-1005. This can be called the 1-σ range, but it is wrong to state the result as (950±55) since the resulting calendar age probability distribution is not Gaussian.

In figure 6 we have artificially introduced a wiggle in the calibration curve consisting of straight lines. The calibration yields a probability distribution with three isolated peaks. Since the calibration curve is still symmetric, each of the three calibrated

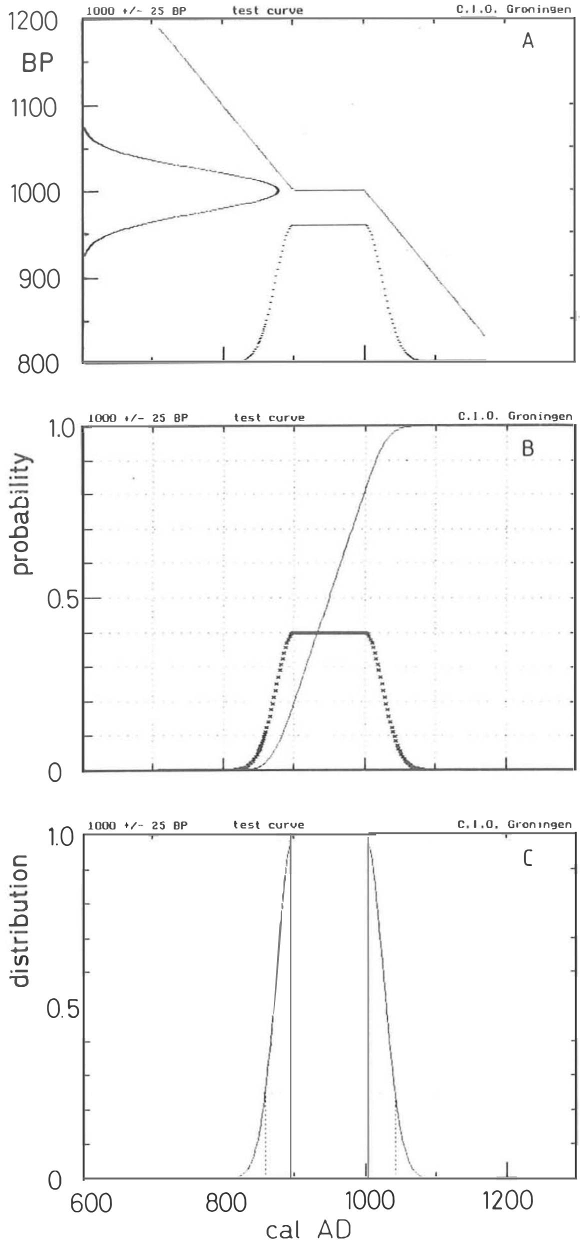

Fig. 5. Results of calibrating the age 1000±25 BP using a straight line with a horizontal stretch as a calibration curve.

peaks is also symmetric. From figure 6:b we read that the two outer peaks (at 800 and 1100 cal AD) each have a probability of 40% and that the middle peak (located at 950 cal AD) has a probability of 20%. The 68% (1-σ) probability range can again be read from the bottom part of figure 4:c, and is 775-825, 938-962 and 1075-1125. It is important to note that the three peaks in figure 6 (or, equivalently x_1, x_2 and x_3 in fig. 3:a) do NOT have the same probability, in contradiction with what one might expect at first sight.

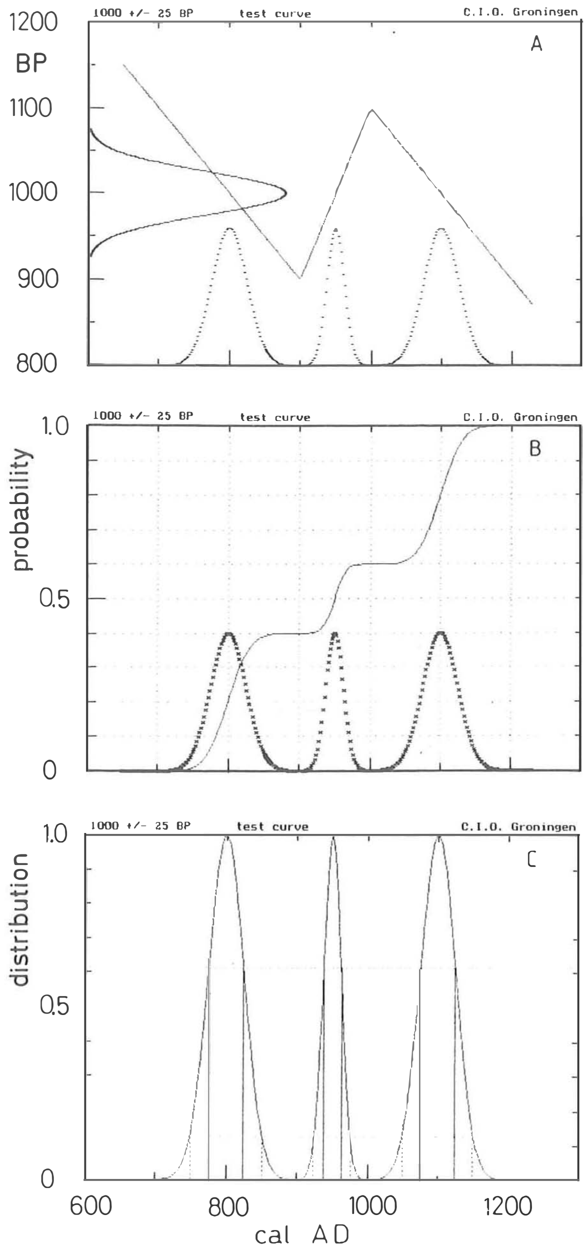

Fig. 6. Results of calibrating the age 1000±25 BP using a straight line with a wiggle as a calibration curve.

6. REALISTIC EXAMPLES OF CALIBRATION

In this chapter, we discuss the outcome of calibrations of selected radiocarbon datings. We have chosen 6 examples ranging from the 18th century AD to the 3rd millennium BC. These examples represent a variety of calibrated probability distributions.

The first example we discuss is the dating of wood from the tomb of King Djoser, the 1st king reigning from the 3rd dynasty of Egypt. Hassan & Robinson (1987) report a ^{14}C age of 4097±25 BP, which is an average of 8 separate datings and a historical date of 2686 BC. This is a more recent (and apparently better, as will be shown) value than the date given by Säve-Söderbergh & Olsson (1970). The result of the calibration of 4097±25 BP is shown in figure 7. Along the vertical (y) axis, the Gaussian probability distribution of the ^{14}C age is plotted. The computer program selects the part of the calibration curve that corresponds to the ^{14}C age plus/minus three sigma, i.e. 4022 (= 4097 - 3x25) to 4172 (= 4097 + 3x25). Within this range, the probability distribution along the calendar (x) axis is calculated. This distribution is shown as dotted lines, whereas the calibration curve is the solid line. The latter is the spline function, calculated through the calibration points (van der Plicht & Mook, in press). The calibration points, with their error bars as given in the special *Radiocarbon* issue (Stuiver & Kra, 1986) are also plotted. The data points are taken from Stuiver and Pearson (1986), followed by those of Pearson et al. (1986).

The calibration curve is rather wiggly in the region considered here. The effect of the wiggles can be easily recognized in the calibrated probability distribution. The general trend of the curve is almost horizontal (albeit modulated by the wiggles), so that the calibrated range is rather broad (2510-2870 cal BC) despite the relatively small error in the ^{14}C age. The plot of figure 7:a can only be regarded qualitatively. Quantitative results should be obtained from properly normalized curves, such as shown in figures 7:b and 7:c. The plot in figure 7:b represents a method developed in Groningen (van der Plicht et al., in press), and the plot in figure 7:c a method developed in Seattle (Stuiver & Reimer, 1988). It was agreed at the 13th International Radiocarbon Conference in Dubrovnik (1988) to include both analysis methods in the program (van der Plicht & Mook, in press).

The Groningen method is basically graphical. In figure 7:b the probability distribution along the calendar axis is plotted again, now together with the so-called integrated probability distribution (solid line), which indicates the probability between 0 and 1 (or 100%). Analogous to the artificial example shown in figure 6, we can state that the peak between 2870 and 2810 cal BC has a probability of 31%, the peak between 2775 and 2720: 14%, between 2700 and 2670: 11%, between 2670 and 2575: 42%, and the small peak around 2525 cal BC: 2%. It is absolutely wrong to use a mean (or median) value corresponding to a probability of 0.5 (or 50%) located at 2685 cal BC!

The Seattle method is shown in figure 7:c. The same calendar axis probability distribution as before is again plotted, although with a different scale.

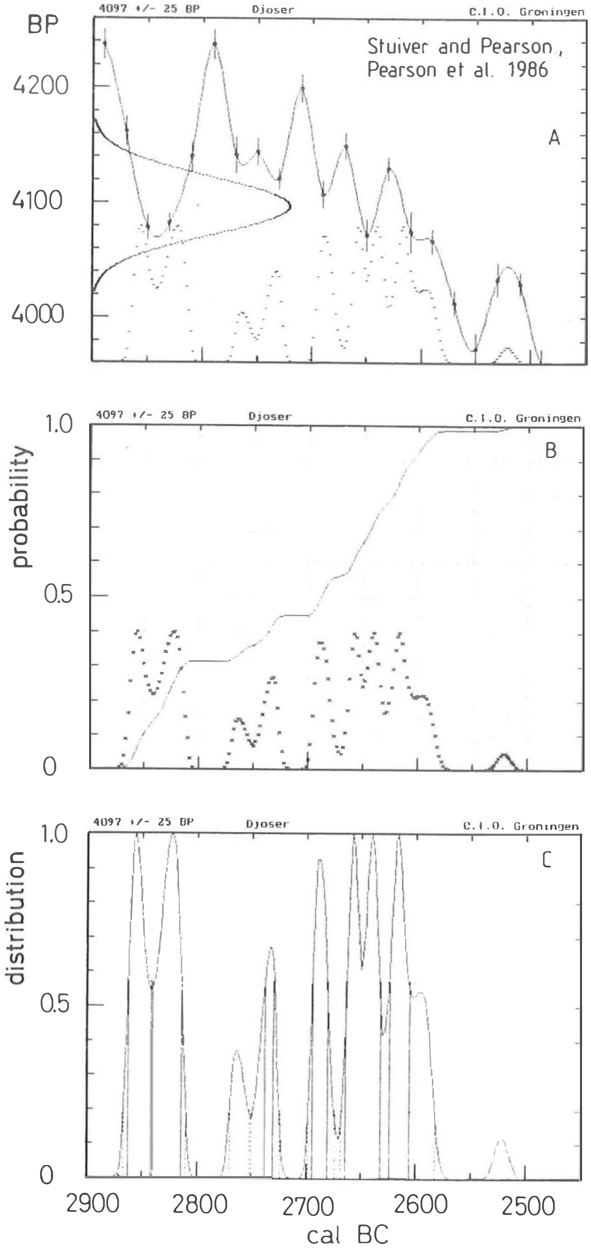

Fig. 7. Results of calibrating 4097±25 BP (wood from the tomb of King Djoser, 3rd dynasty of ancient Egypt).

The two dotted lines correspond to a 68% and 95% confidence level. The intercept of these dotted lines and the probability distribution can then be taken as the calibrated ranges just as shown in the examples of figures 4, 5 and 6. For the example considered here, 4097±25 BP, the results are: 2862-2842, 2840-2814, 2738-2730, 2694-2680, 2664-2632, and 2624-2606 cal BC for the 68% (1-σ) confidence level, and 2866-2810, 2770-2752, 2750-2724, 2698-2674, and 2668-2582 cal BC for the 95% (2-σ) confidence level.

The historical date of 2686 cal BC as quoted by Hassan & Robinson (1987) agrees better with the calibrated ^{14}C age than the earlier date (2590±40 cal BC) quoted by Säve-Söderberg & Olsson (1970). The latter date is, however, still within the accepted range. We emphasize that the fact that the historical date (2686 cal BC) coincides with the median of the probability distribution (at a probability of 0.5 or 50%) is a coincidence, and not a generally valid conclusion.

The second calibration example we will discuss is the calibration of 3010±30 BP (GrN-6507), the dating of a wood sample from Egypt with an expected date in the range of 1309-1290 cal BC (19th dynasty, King Seti I). The three resulting plots of the calibration program are shown in figure 8. Also in this time span, the curve has many wiggles as can be seen from figure 8:a. From the cumulative probability distribution in figure 8:b, we conclude that the peak between 1400 and 1335 cal BC has a probability of 24%, the peak between 1330 and 1250: 53% and between 1250 and 1210 cal BC: 16%. The small peaks at around 1175 and 1140 cal BC are ignored. We conclude that the expected date range agrees very well with the calibrated date. Note that in this case, the mean probability (0.5 or 50%) coincides with a minimum in the calendar date probability distribution, as an illustration that the median here is certainly not the most probable calibrated result. From figure 8:c, we conclude that the 68% (1-σ) calibrated date ranges are 1370-1350, 1314-1258 and 1236-1222 cal BC. For the 95% (2 σ) confidence level, the numbers are 1392-1336, 1326-1208 and 1188-1164 cal BC.

The third example is shown in figure 9. In this case the radiocarbon age has an unusually small error. It is the dating of an oak sample from Abcoude, the Netherlands, with an expected date of 6 cal AD. The result from the ^{14}C measurement is 1989±8 BP (GrN-13852). From figure 9:a we see that – because of the small error – only a small part of the calibration curve is relevant; only 5 calibration points fall within this range. The main part of the Gaussian probability distribution of the radiocarbon age intercepts the calibration curve where it almost can be considered to be a straight line, so that the resulting calendar date probability distribution also closely resembles a Gaussian curve (just as in figure 4:a). The tail between 35 and 10 cal BC may very well be ignored. Since the calibrated probability distribution is one peak, the use of the median of the probability distribution is justified. The calibrated peak is only slightly asymmetric. From figure 9:b we read that 50% (or 0.5) probability corresponds to a calibrated ate of 8 cal AD and that 16 and 84% correspond to 2 cal AD and 12 cal AD, respectively. Here we may state that the ^{14}C age of 1989±8 BP is calibrated into 8 (+4/-6) cal

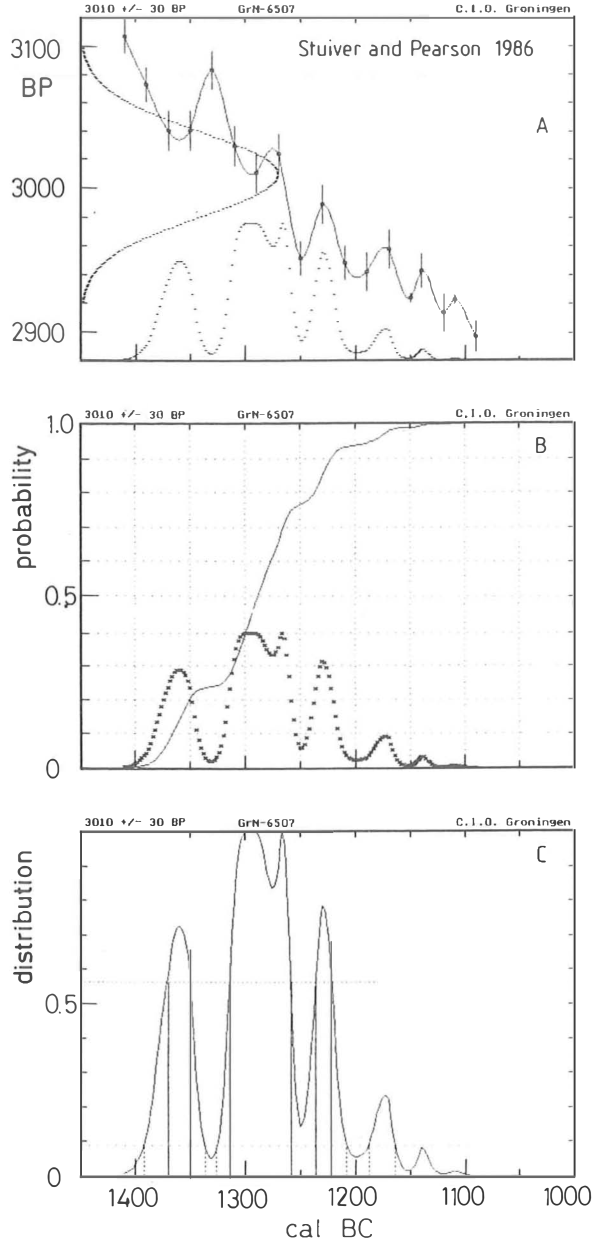

Fig. 8. Results of calibrating the ^{14}C age 3010±30 BP (wood sample from Egypt, GrN-6507).

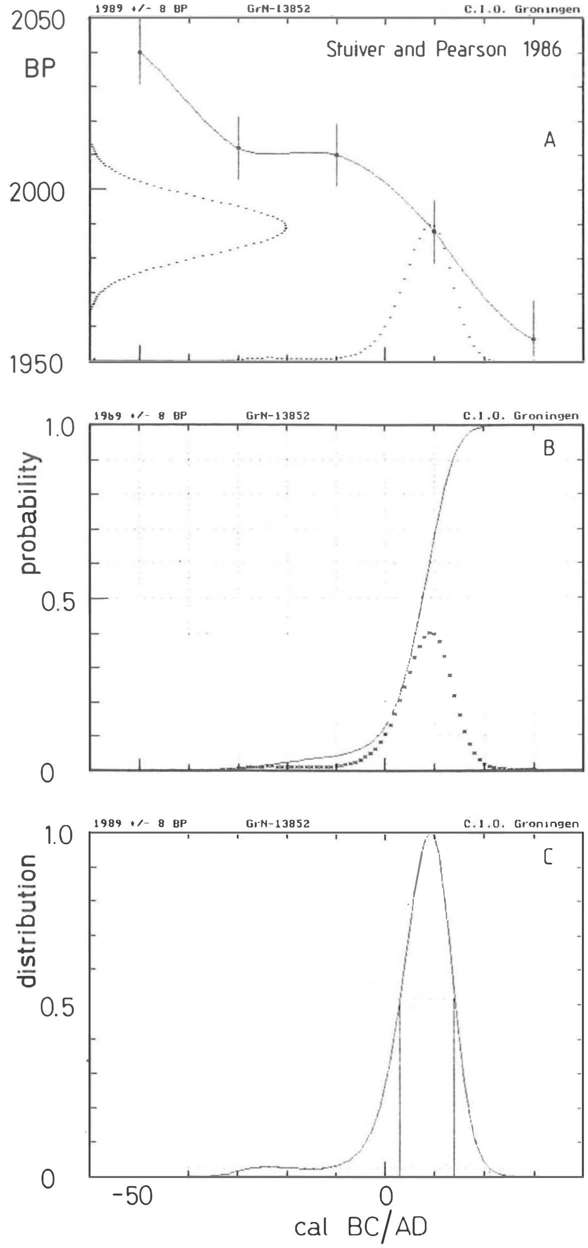

Fig. 9. Results of calibrating the ^{14}C age 1989±8 BP (oak sample from the Netherlands, GrN-13852).

AD. Again, we may only apply this procedure for calibrated distributions which consist of a single peak which – theoretically – is asymmetric. Or, in other words, if the ^{14}C age intercepts the calibration curve in a region with no wiggle. From figure 9:c, the 68% confidence level yields a range of 3-14 cal AD. The small difference with the method explained before (fig. 9:b) can be explained by errors due to finite step size integration and rounding-off in the computer program.

The final calibration example is shown in figure 10, where we consider a relatively recent ^{14}C measurement: 230±55 BP (GrN-4233). The material was bone from a grave in London. The historical date was expected to be 1782 cal AD. In this case we hit upon a mathematical problem, since the 3-σ range of the radiocarbon age intercepts the curve near its end (which is 1940 AD). Adding calibration points from dates after 1940 is in principle possible but does not help because of the increase of

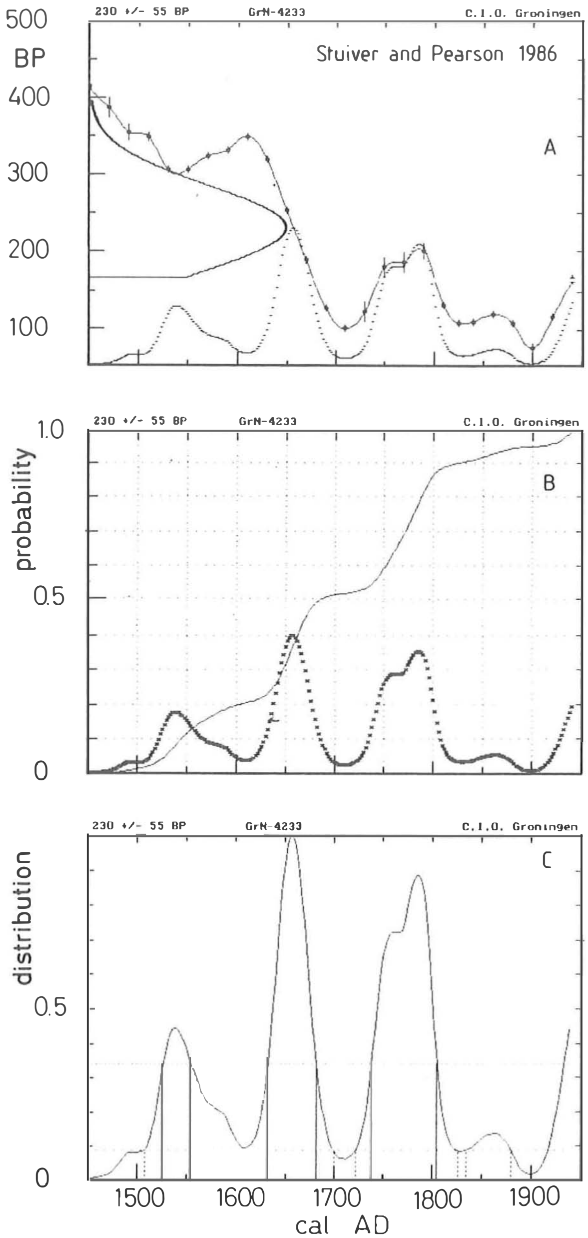

Fig. 10. Results of calibrating the ^{14}C age 230±55 BP (bone from a grave in London, GrN-4233).

atmospheric ^{14}C content due to nuclear test explosions resulting in a maximum value of about 180% in 1963. Therefore, the Gaussian probability distribution of the ^{14}C age is artificially truncated at 1940 AD. From figure 10 we conclude that the peak between 1480 and 1610 cal AD has a probability of 20%, between 1610 and 1710: 31% and between 1710 and 1850: 39%. We ignore the shoulder at around 1850 and truncate the part of the curve between 1900 and 1940. From figure 10:c, we read that the 68% confidence level (1-σ) corresponds to 1526-1554, 1632-1682 and 1738-1804 cal AD. The 95% (2-σ) confidence level corresponds to 1508-1700, 1722-1826 and 1834-1880 cal AD. The historical date of 1782 cal AD is well within the probability and calibration peak ranging from 1710 - 1850 cal AD, but the result of ^{14}C dating and calibration is certainly not positively conclusive.

7. CONCLUSIONS

We developed a PC-based computer program for automatic calibration of ^{14}C ages. A calibration curve is generated through calibration points which are published in the Trondheim (12th International Radiocarbon Conference) Proceedings. However, as a standard the calibration data from Stuiver & Pearson and Pearson & Stuiver are used, going back to 2490 cal BC, extended by the curve of Pearson et al. which goes back to 5210 cal BC.

The program is designed to be user-friendly; one only has to enter the age to be calibrated (in BP), the associated error (sigma-BP) and a text label, either interactively or by entering these data in an input file. One has to be slightly familiar with Turbo-Pascal (version 4.0).

The calibrated results are given to the user mainly in graphical form. Conclusions on calibrated ages or ranges can in general best be drawn by analyzing the calibrated probability distribution. We offer two ways for this analysis.

First, one can use the normalized cumulative probability distribution to obtain quantitative results. From this cumulative probability, which is the area under the calendar calibrated age distribution, one can directly determine the probability of a calibrated age range or a peak. It does not seem possible to provide an automatic procedure, which works correctly in all possible cases.

Secondly, the program produces optionally an extra plot of the same probability distribution, with indications of the 68.3 (1-σ) and 95.4 (2-σ) confidence levels. The calibrated age ranges corresponding to these levels are printed out. This analysis follows the procedure developed in Seattle.

In this paper, we presented examples in order to explain the principle of the calibration method in a clear way to the non-specialist.

Firstly, we attempted to do this by showing the calibration procedure for artificial calibration curves, such as the straight line BP = 1950 – AD which was used before the discovery of ^{14}C variations in the atmospheric CO_2. Next, deviations from this straight line are introduced, and resulting effects on the calibrated probability distribution are discussed.

Secondly, we have worked out 4 examples of real calibrations, ranging from the 18th century AD to the 3rd millennium BC. These examples represent a variety of possible shapes of calibrated probability distributions. Suggestions for interpretation of the calibrated results are presented for each example. Aided by these examples, the user of the program can easily interpret the meaning of a particular calibration of his ^{14}C age.

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