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CALIBRATION OF MANGERUD'S BOUNDARIES

Adam Walanus

Department of Geoinformatics, AGH University of Science and Technology, al. Mickiewicza 30, 30-059 Kraków, Poland. Corresponding author. Email: walanus@geol.agh.edu.pl.

Dorota Nalepka

W. Szafer Institute of Botany, Polish Academy of Sciences, Lubicz 46, 31-512 Kraków, Poland.

ABSTRACT. The "calibration" of arbitrarily defined (in some sense, "conventional") ages, given in conventional radiocarbon years BP, is now becoming necessary because the term "radiocarbon age" is used less often in archaeological and Quaternary practice. The standard calibration procedure is inappropriate here because Mangerud's boundaries are not measurement results. Thus, another approach to the problem is proposed in order to model the natural situation of many, uniformly distributed, dated samples, which should be similarly divided by the original and "calibrated" boundary. However, the result depends on the value of the typical measurement error and is not unequivocal.

THE PROBLEM

From the early (precalibration) development era of the radiocarbon method, some well-established "dates" of global or regional events have existed in the literature. These "time horizons" summarize a considerable number of ^{14}C dates as well as lithological considerations. Mangerud's chronozone boundaries are probably the most important (Mangerud et al. 1974). Dates proposed as a summary of the cumulated knowledge on climate change in the Holocene and Late Glacial epochs have the sense of convention. But in fact, these are arbitrarily established dates, or "boundaries," to which individually recorded events should be referred. The notion of a "chronozone" is correct for the climate stage while its boundaries are set as the absolute age. However, when one considers the date of publication (1974) it is clear that the boundaries are given in ^{14}C years (Conv BP). A problem arises because Mangerud's chronozones have been used extensively up to the present day (Webb 2006; Anderson et al. 2007; Berglund et al. 2008; Haynes 2008; Rybníček and Rybníčková 2008; Sørensen 2008; Wanner et al. 2008; Niinemets and Hang 2009; Walker et al. 2009).

It should be noted that a "rounded-off" number is typical for any arbitrary reference value. The chronozones provide a good example here, with values such as 5000 or 10,000. Less round, however, are 8000, 9000, 11,000, 12,000, and 13,000 Conv BP. Even less so is 2500 Conv BP, but swift climate changes, ending with the Last Glacial, have forced the value of 11,800 to be referred to within a precision of hundreds of years.

"Calibrating" an arbitrarily defined age (e.g. 5000 Conv BP) is different from calibrating a typical ^{14}C date. The chronozone boundaries have essentially no error. In a sense, it is an arbitrary definition to give an unequivocal reference value.

For about half of Mangerud's boundaries, it is possible to simply determine the calibrated age from the calibration curve (second column in Table 1). The function $T_{conv} = f(T_{cal})$ is one-to-one in many cases, with a total duration of 27% of calendar time over the last dozen millennia. However, not only due to the fact that 2 boundaries (2500 and 8000 Conv BP) produce essentially many calibrated dates, the general "calibration" should be used here, and the longer parts of the calibration curve, particularly around the boundary, transformed to cal BC. Also, chronozones are long in duration in comparison to the typical time span of the calibration curve wiggle. The boundary between 2 chronozones reflects considerably slower climate changes (perhaps excluding the Preboreal/Younger Dryas). Calibrated boundaries should not depend on a ^{14}C concentration that is strictly local in time.

The "calibrated" age of the boundary has to reflect its original, ^{14}C conventional counterpart in as many aspects as possible.

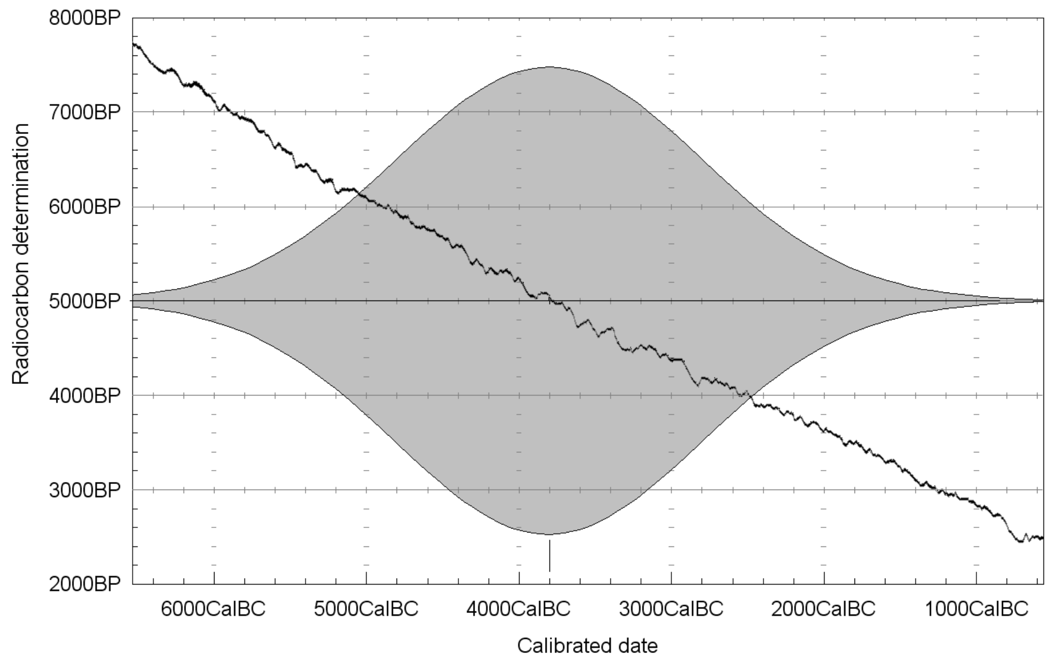

Figure 1 The general idea of "calibration" of Mangerud's boundary, exemplified by 5000BP - SB/AT one. For each (calendar) year, the responding ^{14}C age is taken from the calibration curve and the measurement Gaussian curve is calculated (Figure 2) and multiplied by the Gaussian weight presented for that figure. Then, all the measured Gauss are totaled, and the median of probability densities is calculated, for the given measurement error and central position of Gaussian weight for the samples (here 3800 cal BC). The obtained median values are plotted in Figure 3.

Table 1 Readouts from the plots (Figure 1) for selected σ, the proposal of the "general" value valid for any σ, and final proposal of "calibrated" values with "rounding off" applied (with one ambiguity at 7000 BC). The value σ = 0 refers to the simple transformation of the precise conventional age according to the calibration curve, which sometimes gives a unique value (neglecting calibration curve error) and sometimes not (then including that error). Calibration curve applied: IntCal09 (Reimer et al. 2009).

	BC					
Conv BP	σ = 0	σ = 20	σ = 50	σ = 100	"General" σ	Rounded off
2500	760–550	690	660	640	640	600
5000	3780	3780	3780	3780	3780	3800
8000	7400–6850	7000	6960	6940	6940	6950 (7000)
9000	8250	8250	8240	8220	8200	8200
10,000	9650–9420 (9450)	9470	9500	9520	9540	9500
11,000	11,120–11,000	10,965	10,970	10,980	10,980	11,000
11,800	11,740	11,740	11,730	11,715	11,720	11,700
12,000	11,880	11,890	11,900	11,900	11,900	11,900
13,000	13,570 (13,900–13,200)	13,560	13,580	13,600	13,600	13,600

PROPOSED SOLUTION

The method of defining (calibrating) Mangerud's boundaries, in terms of calendar age, is as follows. Let us assume a uniform distribution of samples at the calendar time axis. (It is worth mentioning that this is an assumption for *a priori* distribution of ages in the typical calibration procedure.) Since, at the moment, we are interested in one boundary (say 5000 Conv BP), we focus on samples distributed around the expected equivalent calibrated age, maybe 4000 or 3800 cal BC.

Let us take samples of true age equal to the consecutive years: … 4001, 4000, 3999, 3998 cal BC, …, one sample per year. However, its weight in the following calculations will diminish, according to the bell curve (Figure 1), with the distance from the assumed cal BC boundary (e.g. 3800 cal BC for 5000 Conv BP). Equally, the samples should be distributed Gaussially, more densely at 3800 cal BC, less densely at 2800 cal BC, even less so at 1800 cal BC, and so on. The choice of the bell curve for the weight is arbitrary here, and has no connection with the probability distribution of the conventional date. The σ of the Gaussian weight is also arbitrarily chosen to be 1000 yr. It has been checked that the final result does not depend heavily on that choice. (For the 2500 Conv BP boundary, the weights are cut symmetrically because of the AD 1950 limit.)

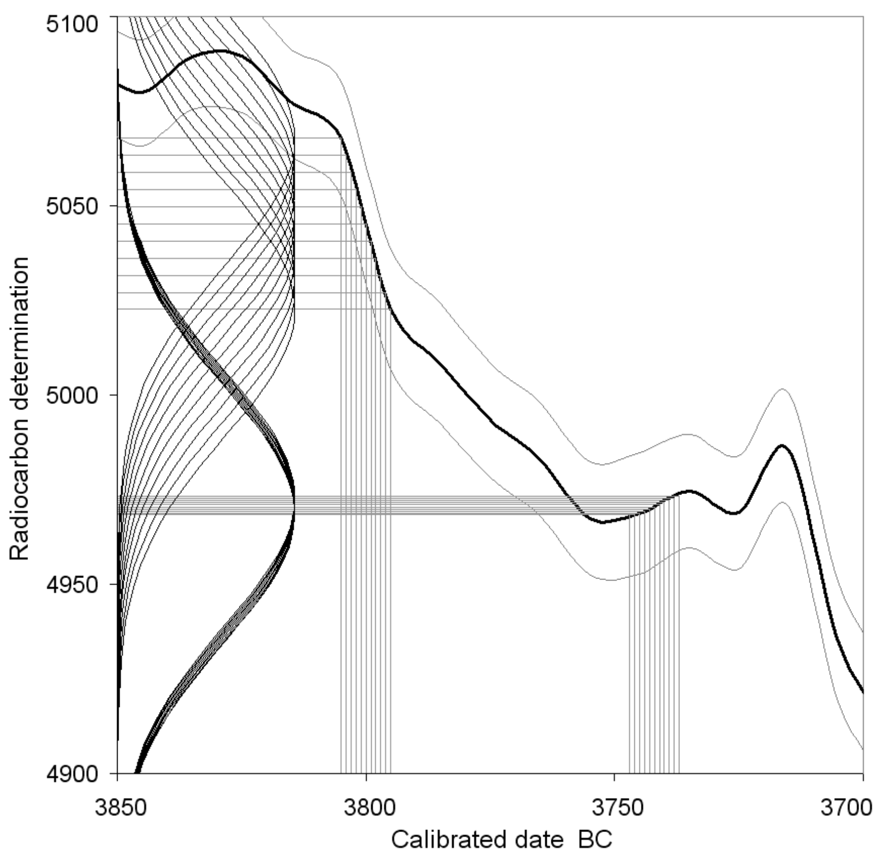

Figure 2 For each calendar year, the responding ^{14}C age is calculated and the Gaussian curve is obtained. All Gausses are totaled with the weight depending on calendar age (see Figure 1). Finally, the median of the sum is calculated. Only 2 groups of "samples" are presented for clarity (taken for extreme calibration curve slopes).

Each sample is recalculated from the cal axis to the ^{14}C axis (Figure 2). For each sample, the typical measurement Gauss is obtained, with some measurement error σ. The amplitude of the probability density function is scaled down according to the weight indicated in Figure 1. All (weighted) Gaussian curves are totaled, and for the obtained function the median is found. That median is the final result, at that stage. Note that the result (radiocarbon age BP) is obtained for the assumed potential cal BC value for the given boundary (e.g. the aforementioned 3800 BC), and for the assumed date error σ. Calculations are performed for 20 values of σ equally (logarithmically) distributed over 10 and 300 yr. The procedure is repeated for all sensible cal BC values for a 20-yr sequence (…3800, 3820, 3840 BC…).

Figure 3 shows the results of the calculations. Namely, the median Conv BP value is plotted as a function of the measurement σ, with the cal BC value representing the parameter of curves. According to the above, one median is recalculated to another median, which seems to be correct. The purpose of any boundary is to divide. If our aim is to recalculate Conv BP to cal BC, the samples equally divided in the sense of Mangerud's Conv BP should also be equally divided in exactly same manner when their real time is considered.

RESULTS

A feature of the result given in Figure 3 is the non-negligible dependence on σ (Walanus 2009). If the curves at the plot were flat, the final answer would be straightforward. Closest to that ideal is the Subboreal/Atlantic boundary at 5000 Conv BP, as well as that of the Older Dryas/Allerød at 11,800 Conv BP. Keeping in mind that the question of "rounding off" numbers is important here, the value of 3800 cal BC seems to be a very good candidate for the "calibration" of 5000 Conv BP.

For 9000 Conv BP, the situation is not as promising, especially in comparison with the normal calibration result for that value (assuming $\sigma = 0$, see Figure 3). In any case, despite the unique crossing of the calibration curve at 8246.5 cal BC, which should be "rounded off" to 8250 cal BC, the value 8200 cal BC seems to be a better solution. The "exact" value is valid only for a measurement error of zero and for very small errors. However, the realistic errors of ^{14}C determination (^{14}C concentration measurement in the sample's proper chemical fraction) are larger (Buck et al. 2003; Scott et al. 2007).

Figure 3 is a pure result of calculations, performed under the numerical assumption of a 1000-yr sigma for the Gaussian weight of the samples (Figure 1). However, plotted lines give no unique answer for the "calibration" of boundaries. Table 1 shows some values taken from the plots (Figure 3) as well as some generalizations, in the 2 far-right columns, separated from the objective values by a vertical line. The attempt to choose 1 value for the cal BC age, which would be universally accepted for any σ, is the most disputed point in the procedure. The subjective weights for different, practical, realistic values of σ were applied. The idea of a "realistic" measurement error is connected with any possible "gross" errors as well as, for example, archaeological difficulties with the sample context. The next step, given in the last column of Table 1, i.e. that of "rounding off" numbers, is not so doubtful.

Table 2 shows the final proposal for the "calibration" of Mangerud's chronozones. There is only one difference in relation to the last column of Table 1, i.e. the subjective, deeper "rounding off" of the Boreal/Atlantic border.

The ambiguity of the proposed values is clearly visible in Figure 3. The range defined in the columns "$\sigma = 20$" and "$\sigma = 100$" (Table 1) can be treated as error estimation for the given BC boundary.

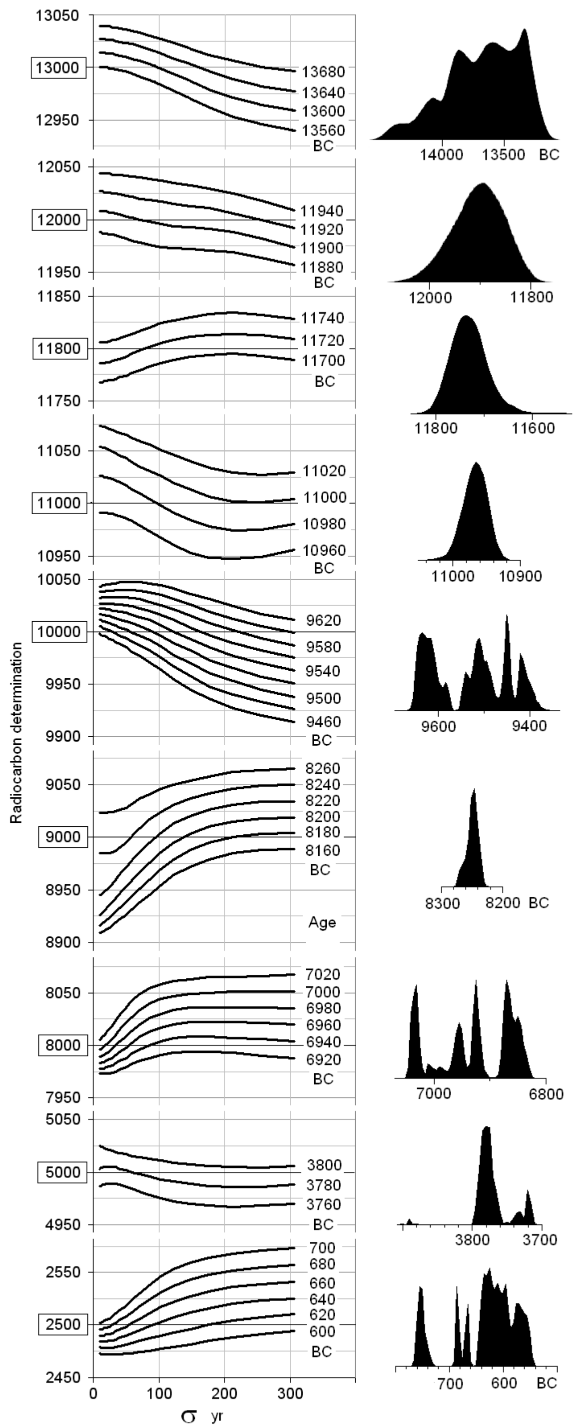

Figure 3 The ^{14}C (median) age as a function of the measurement error σ, for different calendar (BC) ages of the trial "center" of the large group of samples. Because lines are not strictly horizontal, the "calibration" of Mangerud's boundaries, in some cases only, is almost independent of σ. (The "conventional" description of the vertical axis is somehow incorrect here due to the different meanings of the word "determination.") Standard calibration (OxCal 4.1) of discussed boundaries, obtained with σ = 0, is given for comparison purposes.

Table 2 Final proposal for the "calibration" of Mangerud's chronozones.

Boundary	Conv BP	BC
Subboreal / Subatlantic	2500	600
Atlantic / Subboreal	5000	3800
Boreal / Atlantic	8000	7000
Preboreal / Boreal	9000	8200
Younger Dryas / Preboreal	10,000	9500
Allerød / Younger Dryas	11,000	11,000
Older Dryas/ Allerød	11,800	11,700
Bølling / Older Dryas	12,000	11,900
Middle Glacial / Bølling	13,000	13,600

A confidence interval should be attached to any given range, with the confidence level associated roughly with the frequency of dates of $\sigma > 100$ yr, in a given project. However, it should be repeated that the idea of error or any imprecision is inconsistent with the idea of an arbitrary value. It would only be the question of an arbitrary decision as to which strict "calibrated" numbers are to replace the conventional ^{14}C ages of the Holocene and Younger Dryas boundaries.

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