



A numerical approach to ^{14}C wiggle-match dating of organic deposits: best fits and confidence intervals

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Abstract

^{14}C wiggle-match dating (WMD) of peat deposits uses the non-linear relationship between ^{14}C age and calendar age to match the shape of a sequence of closely spaced peat ^{14}C dates with the ^{14}C calibration curve. A numerical approach to WMD enables the quantitative assessment of various possible wiggle-match solutions and of calendar year confidence intervals for sequences of ^{14}C dates. We assess the assumptions, advantages, and limitations of the method. Several case-studies show that WMD results in more precise chronologies than when individual ^{14}C dates are calibrated. WMD is most successful during periods with major excursions in the ^{14}C calibration curve (e.g., in one case WMD could narrow down confidence intervals from 230 to 36 yr).

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1. Introduction

The approach of ^{14}C wiggle-match dating has made it possible to construct precise chronologies of organic deposits (van Geel and Mook, 1989; Clymo et al., 1990; Kilian et al., 1995, 2000; Pilcher et al., 1995; Oldfield et al., 1997; Speranza et al., 2000; Mauquoy et al., 2002a,b; van der Plicht et al., submitted; van de Plassche et al., 2002). Although WMD often appears to result in more accurate and precise chronologies than can be obtained while calibrating individual ^{14}C dates, some issues still need to be clarified.

The width of confidence intervals gives an indication of the precision of a chronology. Whereas calibration of individual ^{14}C dates provides us with confidence intervals, such measures have not yet been implemented successfully in the procedure of WMD of organic deposits. Therefore, to compare the precision of WMD with that of calibration of individual ^{14}C dates, a methodology that determines confidence intervals for

WMD is required. Pearson (1986) and Bronk Ramsey et al. (2001) discuss numerical approaches to WMD of deposits of known accumulation rate such as tree-rings.

During periods of the Holocene with less-pronounced wiggles in the ^{14}C calibration curve (INTCAL98, see; Stuiver et al., 1998a), there are occasionally many ways to wiggle-match a sequence to the calibration curve. Here, objective methods to find the best wiggle-match solution would be very welcome. It is important to know if in these cases, WMD can still provide a chronology superior to one constructed from calibration of individual ^{14}C dates. Even more, it remains to be assessed whether WMD *does* result in a better chronology than if ^{14}C dates are calibrated individually, even during periods of major wiggles.

In this paper, we present a numerical approach to WMD. With this method, the best wiggle-match solutions can be found in an objective way, and confidence intervals for calendar age determinations can be constructed. We apply the methodology to the new peat cores Eng-XV and MSB-2K, both from raised bog deposits in the Netherlands, and to two ^{14}C wiggle-match dated peat cores that were recently published by Mauquoy et al. (2002a).

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2. A numerical approach to ^{14}C wiggle-match dating

The method we use for ^{14}C wiggle-match dating peat sequences will be explained in detail here. It could be used for other sediments with unknown accumulation history as well. All calculations can be made in a spreadsheet program (e.g., Microsoft Excel; files can be obtained from the first author).

In essence, the method is as follows: (i) the ^{14}C -dated levels of a sequence are translated from their accumulation measure (such as depth, mass accumulation or pollen concentration) directly to calendar ages, using two parameters (see following paragraph), (ii) the resulting calendar chronology of the ^{14}C dates is plotted together with the ^{14}C calibration curve INTCAL98 (Stuiver et al., 1998a), (iii) by changing the two parameters, the translation of depths to calendar ages is adapted such that the ^{14}C ages of the sequence match those of the calibration curve as precisely as possible, (iv) measures for the ‘goodness-of-fit’ are calculated.

2.1. Translation of depths into calendar ages

Because a peat sequence does not show annual lamination, its accumulation history is unknown. In the method proposed here, initially linear accumulation over time is assumed (see discussion). Such a linear relationship between depth and (calendar) age can be described by two parameters: the slope of the curve (accumulation rate in yr cm^{-1} , α) and its intercept (β). Instead of the intercept, we choose an alternative ‘anchor point’:

$$\text{Calendar age} = \alpha \times (\text{depth} - \text{depth}_{\text{average}}) + \text{calendar age}_{\text{average}} + \beta. \quad (1)$$

Here $\text{calendar age}_{\text{average}}$ is the calendar age for which the calibration curve has the same ^{14}C age as the average ^{14}C age of all ^{14}C dates of the sequence, and β is the parameter with which the sequence can be shifted on the calendar axis.

For long sequences of ^{14}C dates, assuming a constant accumulation rate for the entire sequence often results in an unsatisfactory wiggle-match. In these cases, the sequence needs to be divided into subsets that can be assumed to have accumulated at more or less constant rates. These subsets are then wiggle-match dated individually. Divisions of the subsets should be supported by events in the stratigraphy: e.g., charcoal peaks could indicate a gap in the record, and changes in the macrofossil composition of the peat, degree of humification, C/N ratio, pollen concentration or bulk density could point to a change in accumulation rate. There can be some uncertainty or subjectivity involved in deciding how to split the entire set into subsets.

To adapt the match of the ^{14}C dates of the sequence to those of the calibration curve, using a computer the parameters α and β are changed automatically and systematically in small steps (tens of thousands of combinations are tried; chosen values of the parameters include all realistically possible matches, e.g., $5 < \alpha < 35$, $-200 < \beta < +200$). An increase in α results in a lower accumulation rate, and therefore will expand the sequence on the calendar axis. In the same way, a decrease in α results in compression of the sequence on the calendar axis. A higher β results in a shift to the right on the calendar axis, and a lower β will move the sequence to the left (Fig. 1).

2.2. Comparison with the ^{14}C calibration curve

By choosing certain values of α and β , the depths of the sequence at which ^{14}C dates have been taken are translated into calendar ages (Fig. 1a and b). The resulting graph of ^{14}C ages against calendar ages of the sequence is overlaid on the ^{14}C calibration curve (Fig. 1c and d). This calibration curve consists of a ^{14}C age for every calendar year (linearly interpolated when necessary), constructed using the decadal INTCAL98 data (Stuiver et al., 1998a), and using higher-resolution calibration curves where available (for the period 3904–1936 BC: Vogel and van der Plicht, 1993, and for the period after AD 1511: Stuiver et al., 1998b).

2.2.1. Erroneous ^{14}C dates

Radiocarbon dates of a sequence could be erroneous due to sample composition, contamination or handling (e.g. Kilian et al., 1995, 2000; Shore et al., 1995; Speranza et al., 2000; Nilsson et al., 2001). If a reservoir effect on either all or a part of the ^{14}C dates of the sequence is suspected, this can be corrected for (Kilian et al., 1995).

2.2.2. Deposition period of samples

Because every sample has been deposited over a certain period (from the estimated calendar age— $[(1/2 \text{ thickness sample}) \times \alpha]$ up to the estimated calendar age + $[(1/2 \text{ thickness sample}) \times \alpha]$), the measured ^{14}C age is assumed to reflect the average ^{14}C age of this period. Therefore, while testing the fit of a wiggle-match (see later), the measured ^{14}C age is compared with the average ^{14}C age of the calibration curve during the assumed sample deposition period.

2.3. Computing the goodness-of-fit

For every combination of α and β , the goodness-of-fit with the ^{14}C calibration curve is measured. This can be done in different ways. Here weighted least squares (WLS) (Pearson, 1986; Kilian et al., 2000; Bronk

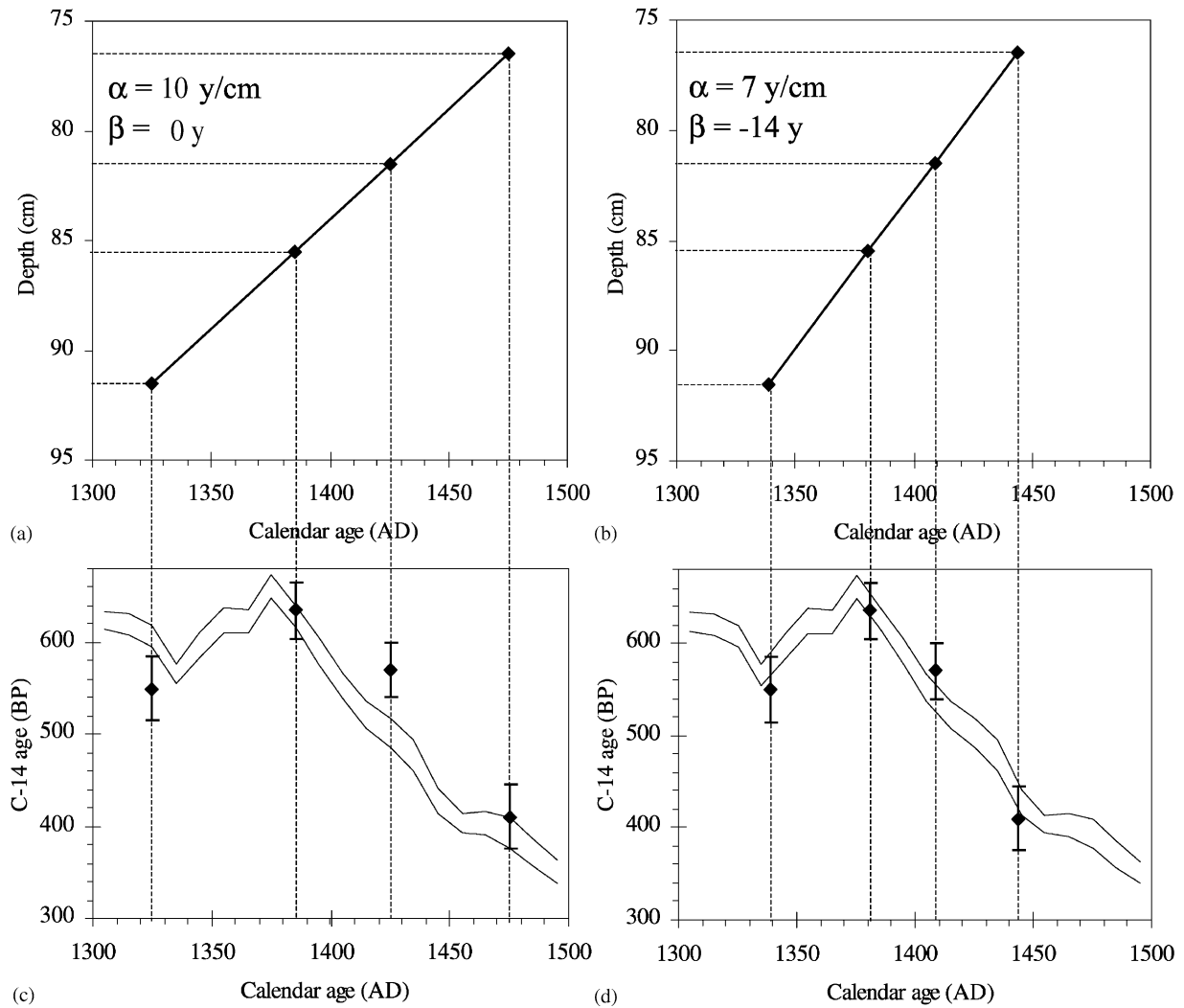


Fig. 1. Schematic explanation of how the numerical approach to WMD assigns calendar ages to ^{14}C dated levels of a sequence. With a certain combination of parameters α and β , depths are translated into calendar ages (a). The resulting wiggle-match is shown in (c). With a different combination of α and β (b), a different wiggle-match occurs (d). Thin lines in (c,d) show the 1 standard deviation (σ) error envelope of the INTCAL98 calibration curve (Stuiver et al., 1998a). Vertical error bars show the 1σ confidence intervals of the ^{14}C ages of the sequence.

Ramsey et al., 2001) and maximum likelihood (MLH) are used.

2.3.1. Weighted least squares

When we match a sequence to the calibration curve, we want the (squared) deviations between the ^{14}C ages of the sequence and those of the calibration curve to be as small as possible:

$$SS = \sum_{i=1}^n ({}^{14}\text{C}_{\text{sample},i} - {}^{14}\text{C}_{\text{calcurve},i})^2 = \text{minimal}, \quad (2)$$

where SS is the sum of squares, n is the number of dated samples, ${}^{14}\text{C}_{\text{sample},i}$ is the ^{14}C age of sample i , and ${}^{14}\text{C}_{\text{calcurve},i}$ is the average ^{14}C age of the calibration curve belonging to the assumed deposition period for sample i . We square the deviations because we do not want negative differences to cancel out positive ones.

Because ^{14}C ages are not exactly known quantities, but are the result of a measurement with limited precision, they follow a probability distribution. Therefore, error bars or standard deviations (σ) can be associated with both the samples and the calibration curve, and these are now included in the criterion to be minimised (see Bennett, 1994 or Stuiver et al., 1998a for a discussion on how to deal with error bars). Thus rather than minimising Eq. (2), we aim to minimise the weighted sum of squares (WSS):

$$WSS = \sum_{i=1}^n \frac{({}^{14}\text{C}_{\text{sample},i} - {}^{14}\text{C}_{\text{calcurve},i})^2}{\sigma_{\text{sample},i}^2 + \sigma_{\text{calcurve},i}^2} = \text{minimal}. \quad (3)$$

The combination of parameters α and β that gives the lowest WSS, yields the WLS estimates of α and β , and thus yields the optimal wiggle-match.

If we assume that a ^{14}C measurement follows a Gaussian distribution and that the errors in ^{14}C measurements are mutually independent, WSS will follow a χ^2 distribution with $n - 2$ degrees of freedom (the 2 parameters α and β need to be estimated from the data and this reduces the degrees of freedom by 2):

$$\text{WSS} \sim \chi_{(n-2)}^2. \quad (4)$$

Values of α and β that result in a WSS above a given threshold χ^2 value (derived from a statistical table) indicate a highly unlikely deviation between the ^{14}C ages of the sequence and the calibration curve, and therefore a highly unlikely match. Fig. 2 gives a schematic explanation of the WLS method.

2.3.2. Maximum likelihood

A ^{14}C date can be assumed to follow a Gaussian distribution on the ^{14}C age axis. However, because of the non-linear relationship between ^{14}C age and calendar age, projection of a ^{14}C date on the calendar axis results in a non-Gaussian probability distribution along the calendar axis (calibration, e.g., Dehling and van der Plicht, 1993). The calendar age that corresponds to the maximum of the probability density could be considered as the most likely calendar age, but often additional local maxima show other likely calendar ages (Fig. 2).

For the MLH measure of goodness-of-fit, we first determine the probability densities on the calendar axis of all individual ^{14}C dates of a sequence. A given combination of parameters α and β of the linear depth-age model Eq. (1) will assign a calendar age to every dated level. Now, the height of the probability density at this calendar age is determined for every ^{14}C dated level, and the product of all these values is calculated (P). Assuming independence, P represents the joint probability density for the sequence of ^{14}C dates. The MLH estimates for α and β are now obtained by maximising P for α and β . These values may be interpreted as those values for α and β under which the observed ^{14}C ages are most likely to occur (Hastie et al., 2001, p. 229).

The probability densities of the ^{14}C dates on the calendar axis are calculated as follows. For every calendar age, the ^{14}C value of the calibration curve at that calendar age is compared with the measured ^{14}C age. A radiocarbon date is assumed to have a Gaussian distribution on the ^{14}C axis:

$$p_x = \frac{1}{\sigma\sqrt{2\pi}} e^{-[(x-\mu)^2/2\sigma^2]}, \quad (5)$$

where p_x is the probability density at value x , σ is the standard deviation (the standard deviations of ^{14}C date and calibration curve are combined: $\sigma = \sqrt{[\sigma_{\text{sample}}^2 + \sigma_{\text{cal.curve}}^2]}$), and μ is the measured ^{14}C age. Filling in the appropriate numbers in Eq. (5), the height of the probability density on the calendar axis is found for

every ^{14}C date and calendar age. A schematic explanation of MLH is given in Fig. 2.

2.4. Presentation of results

The combinations of the parameters α and β translate depths (e.g., ^{14}C dated depths or levels of changes in stratigraphy) into calendar ages. For every calendar age assigned to a depth, the WLS and MLH values (the combination of α and β that gives the optimal solution for the specific calendar age) are plotted. The lowest WLS and the highest MLH give the optimal solution. Confidence intervals of a dated level are calculated by measuring the distance in calendar years between the minimum calendar age and the maximum calendar age where WLS is below the threshold χ^2 value.

3. Case studies

3.1. Core Eng-XV

The deposits of the raised bog Engbertsdijksvenen (Eastern Netherlands) have been investigated extensively (e.g., van Geel, 1978; Middeldorp, 1982; Dupont and Brenninkmeijer, 1984; van Geel and Dallmeijer, 1986; Kilian et al., 1995, 2000). In December 1998, from a vertical wall of a hole dug in the peat bog, a 1.5 m sequence was taken (Eng-XV), using 3 metal boxes of $50 \times 15 \times 10$ cm. One metre of the sequence was subsampled at 0.5–1 cm-resolution and analysed for microfossils, macrofossils, LOI, %C and %N (details of the record will be published elsewhere). Fifty-six samples of carefully cleaned above-ground macrofossils were AMS ^{14}C dated (Blaauw et al., submitted). One ^{14}C date, at 123 cm depth, turned out to be an outlier and was not used in the analysis. See Fig. 3a and b for ^{14}C dates, arboreal pollen concentration and stratigraphic information of the core.

The entire sequence of ^{14}C dates of core Eng-XV was plotted together with the ^{14}C calibration curve INTCAL98 with the assumption of continuous, linear accumulation (Fig. 3a). Whereas parts of the ^{14}C sequence appear to match the calibration curve rather well (correct translation of depths to calendar ages by parameters α and β), at other parts the ^{14}C dates show large offsets (incorrect α and/or β). Indications of hiatuses or accumulation rate changes thus had to be looked for.

Indications of hiatuses and accumulation rate changes were accounted for as follows: starting from the bottom of the core, the ^{14}C dates were matched to the calibration curve. At depths where the ^{14}C dates started to deviate from the calibration curve, the sequence was divided into subsets that were matched to the calibration curve individually (Fig. 3c). Care was taken to divide at

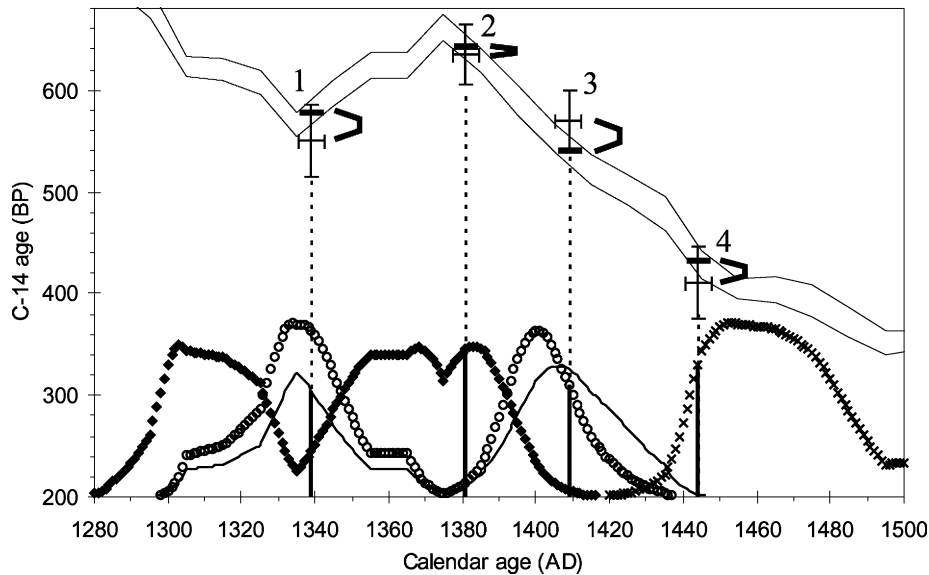


Fig. 2. Schematic explanation of weighted least squares (WLS) and maximum likelihood (MLH). Four ^{14}C dates of a sequence are matched to the calibration curve, giving a calendar age to every ^{14}C dated level (see Fig. 1, hatched vertical lines). WLS: the sum of the squared vertical distances between the sequence of ^{14}C samples and the calibration curve (distances are indicated by \triangleright 'brackets') is minimised, taking the error bars of samples and calibration curve into account. MLH: Calibration results of the ^{14}C dates are shown on the calendar axis (date 1: black line, date 2: closed diamonds, date 3: open circles, date 4: crosses). Thick vertical lines show heights of the probability densities of the chosen wiggle-match. The product of the four heights of the probability densities of all ^{14}C dated levels is maximised.

depths where the lithology indicated evidence for a hiatus or accumulation rate changes. The following subsets were decided upon (Fig. 3b; hatched lines in Fig. 3c):

Subset 1 (150–118 cm): layers of *Eriophorum vaginatum*, *Scheuchzeria palustris* and occasionally *Sphagnum*.

At about 117 cm depth the ^{14}C dates started to deviate from the calibration curve, indicating an accumulation rate change and/or hiatus. At this point therefore, a division was made. This was justified by the fact that here the vegetation composition of the core changed considerably, and arboreal pollen concentration peaked.

Subset 2 (117–91 cm): layers of *Sphagnum* sect. *Acutifolia* and *S. papillosum*.

From approximately 90 cm depth on, the ^{14}C dates started to deviate from the calibration curve again. At 91 cm a charcoal peak was found, indicating a hiatus and thus justifying subdivision.

Subset 3 (90–51 cm): phase of mainly *S.* sect. *Acutifolia* (relatively dry local conditions), later taken over by *S. imbricatum* (humid conditions).

Fig. 3c shows the proposed wiggle-match of core Eng-XV, based on the best MLH fits of the three individual subsets to the calibration curve. In the lower part of Fig. 3c, WLS and MLH results of selected levels are shown. WLS curves are concave-shaped; minimum WLS indicates best match (most probable calendar age for a level) and highest plotted WLS values indicates wiggle-match solutions that are at the border of statistical significance at 1σ level. The deeper the WLS 'concavity', the better a subset fits the calibration curve.

MLH curves are convex-shaped; maximum indicates best match. Local optima are more pronounced in MLH than in WLS. When instead of MLH the best WLS fits of the individual subsets would have been used, the neighbouring subsets 1 and 2 would have overlapped by 55 calendar years, which is unacceptable for constructing a chronology (data not shown). In Fig. 3d, the MLH chronology for all depths is shown. The thickness of the lines indicates the MLH value; the thicker the line, the higher the MLH value at that calendar age.

Accumulation rates as proposed by the optimal MLH wiggle-match of core Eng-XV are 17.50, 30.48 and 14.98 yr cm^{-1} for subsets 1, 2 and 3, respectively. As the bog has been drained, this could have caused secondary compaction of peat layers. Therefore, the reconstructed accumulation rates are not directly comparable with those of undisturbed bogs.

WLS and MLH measures of goodness-of-fit of subset 1 (150–118 cm) show several local optima (several ways to match the sequence to the calibration curve, Fig. 4) and relatively large confidence intervals (large statistically allowed (1σ) range of calendar ages for every depth, 204 yr on average). The wiggle-match of subset 2 (117–91 cm) is more successful than that of subset 1: 1σ confidence intervals are 114 calendar years on average in subset 2. There is a hiatus of 24 calendar years between subsets 1 and 2. Subset 3 (90–51 cm) is situated at a period of a major wiggle in the calibration curve, and a successful wiggle-match is possible. There is only one local optimum, and 1σ confidence intervals measure 36

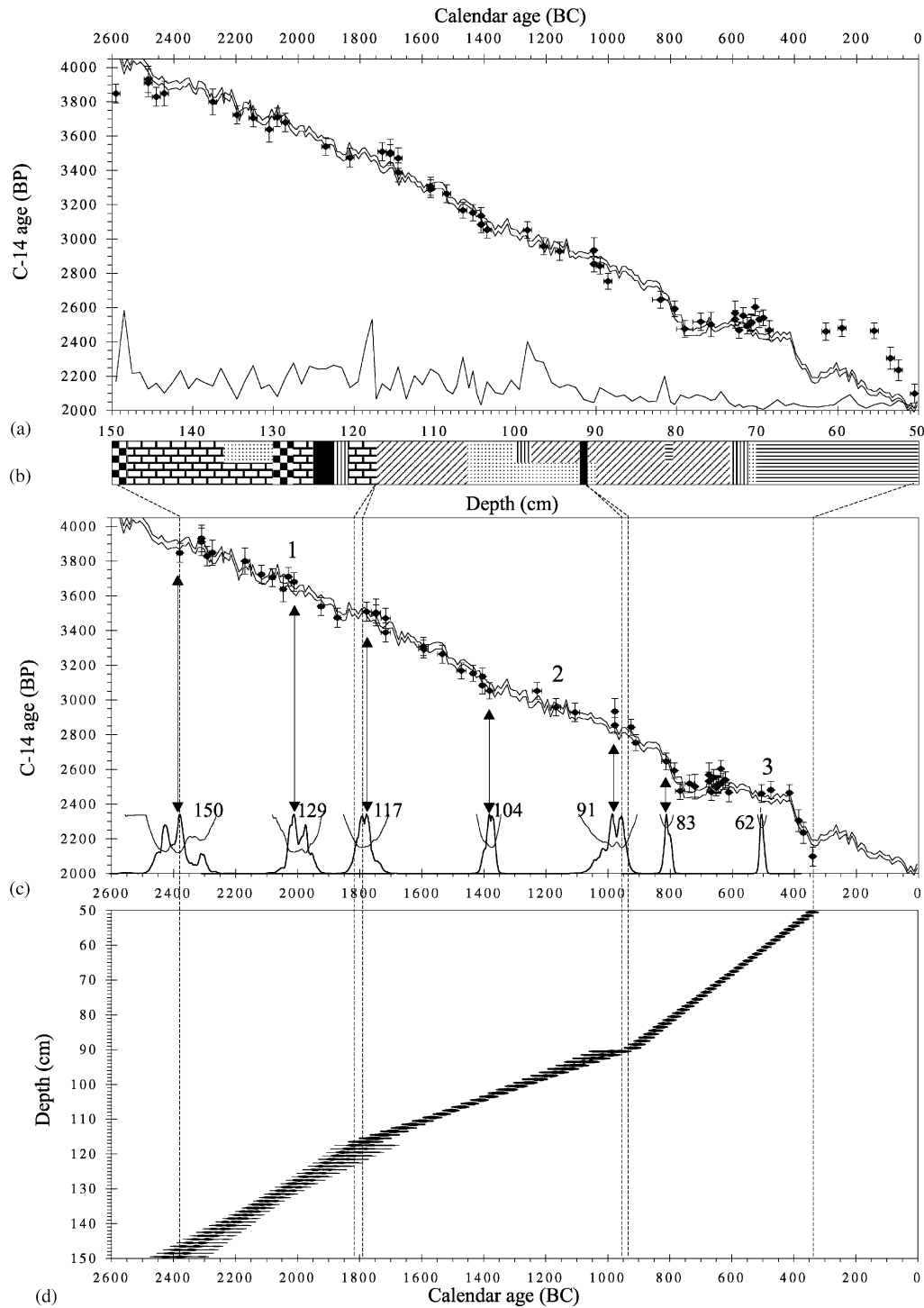


Fig. 3. ^{14}C AMS dates, pollen concentration, lithology and ^{14}C wiggle-match dating result of core Eng-XV. (a) ^{14}C AMS dates are plotted together with the calibration curve. Vertical bars of the ^{14}C samples show 1σ error bars, horizontal bars show thickness of samples. The line on the calendar axis shows the pollen concentration; the vertical scale is arbitrary. (b) Lithology shows domination by vegetation types: squares: *Eriophorum vaginatum*, 'bricks': *Scheuchzeria palustris*, dots: *Sphagnum papillosum*, vertical stripes: *S. cuspidatum*, diagonal stripes: *S. sect. Acutifolia*, horizontal stripes: *S. imbricatum*, black: charcoal peak. (c) The final wiggle-match dating solution. The sequence is divided into subsets 1–3 (hatched lines show levels of division), and the individual subsets are wiggle-matched to the calibration curve, as proposed by optimal MLH. Small hiatuses between the subsets are visible. On the calendar axis, WLS (weighted least squares; concave-shaped, thin lines, only $<1\sigma$ values) and MLH (maximum likelihood; convex-shaped, thick lines) values of selected ^{14}C dated levels are shown (arrows connect WLS and MLH curves with corresponding ^{14}C dated levels, labels indicate depth of levels). The vertical scale of WLS and MLH is arbitrary. (d) MLH confidence intervals for every cm of the core. The vertical thickness of the lines shows the MLH value.

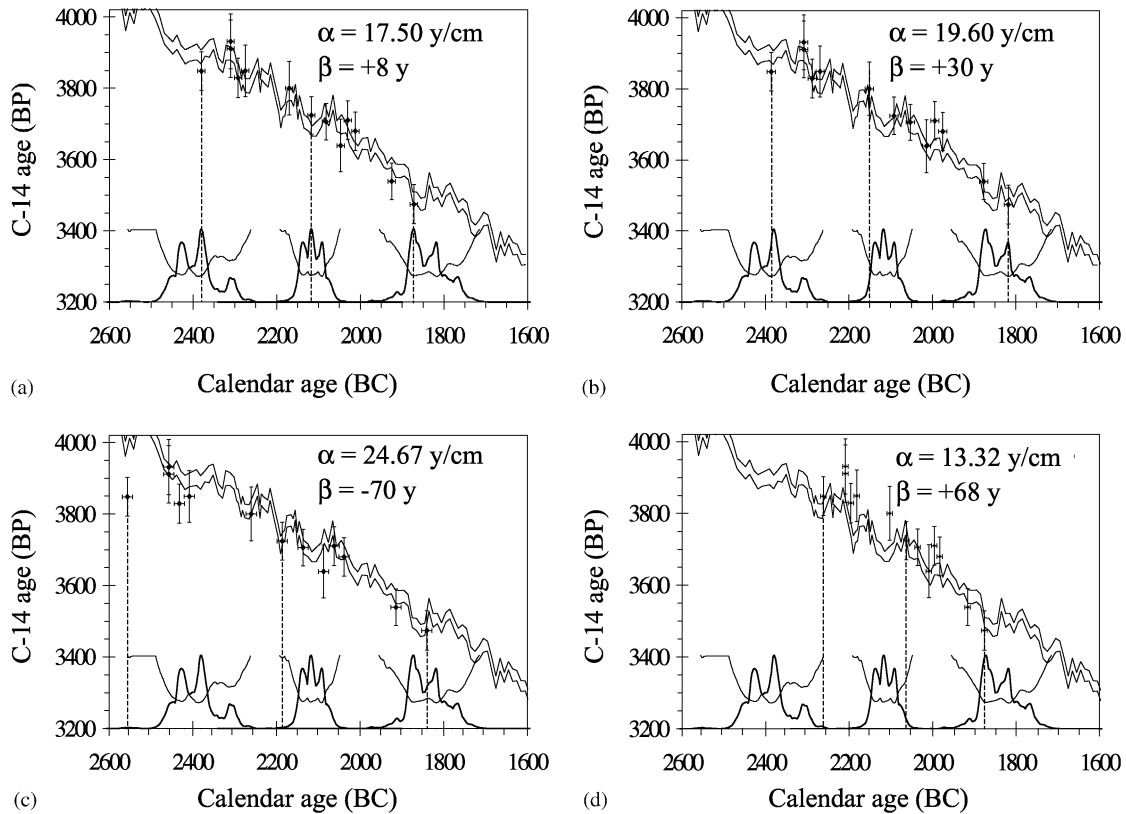


Fig. 4. Several solutions for ^{14}C wiggle-match dating subset 1 of core Eng-XV. Symbols as in Fig. 3, except: hatched lines show where the highest and lowest ^{14}C dates fall on the calendar axis. Values of the parameters α and β are given. The optimal MLH (maximum likelihood) solution is shown in (a), (b) shows optimal WLS (weighted least squares) solution. Solutions that are on the border of being statistically allowed (1σ values of WLS) are shown in (c,d).

calendar years on average. A hiatus of 29 calendar years is apparent between subsets 2 and 3.

To assess the validity of the above choice of subsets, alternative subsets were constructed and wiggle-matched to the calibration curve. It was not always clear where to subdivide, as lithology changed at several occasions besides those at the chosen division points. For example, based on lithology it would have appeared possible to split subset 2 (117–91 cm) into two subsets (117–100 and 99–91 cm), because ^{14}C dates from 99 cm and above appeared to float slightly above the calibration curve (within the limits of ^{14}C age error bars at 1σ , Fig. 3c). However, wiggle-match solutions based on these subsets did not place the ^{14}C dates at a much different calendar age, and moreover, it does not make sense to wiggle-match a small subset of only 5 ^{14}C dates on a relatively flat part of the calibration curve.

Also at another level in the core, from ca 90 to 72 cm depth, changes in lithology would propose accumulation rate changes, whereas the wiggle-match of the ^{14}C dates to the calibration curve does not support this. Lithology suggests relatively dry local conditions (*S. sect. Acutifolia*, and large concentrations of *Calluna vulgaris*), whereas from 71 cm on *Sphagnum imbricatum* took over (indicating wetter conditions). Accumulation rate changes could be expected here. At this point however,

there was no indication of changed accumulation rate on the basis of the wiggle-match of the ^{14}C dates to the calibration curve. Indeed, a further subdivision at 71 cm depth resulted in an unsatisfactory wiggle-match of both subsets, as a large overlap was apparent (data not shown). As overlaps in calendar ages are not acceptable for chronologies, alternative wiggle-match fits for both subsets would have had to be used, essentially resulting in the same wiggle-match result as that of the original subset (subset 3, 90–51 cm, Fig. 3c).

Instead of assuming a linear depth-time relation (depth as chronology), a chronology was constructed based on the assumption of constant arboreal pollen influx (compare Middelborg, 1982). Using this chronology, the sequence was wiggle-matched to the calibration curve (Fig. 5). As this did not improve the wiggle-match (compared with a supposed linear peat accumulation), arboreal pollen influx was no longer used (see discussion below).

In Table 1 and Fig. 6, WLS confidence intervals obtained by ^{14}C wiggle-match dating of core Eng-XV are compared with those obtained by calibration of the individual ^{14}C dates. Particularly around the ^{14}C age plateau at calendar ages 700–400 BC, WLS confidence intervals are much smaller than those of calibration of individual ^{14}C dates. As an illustration of how successful

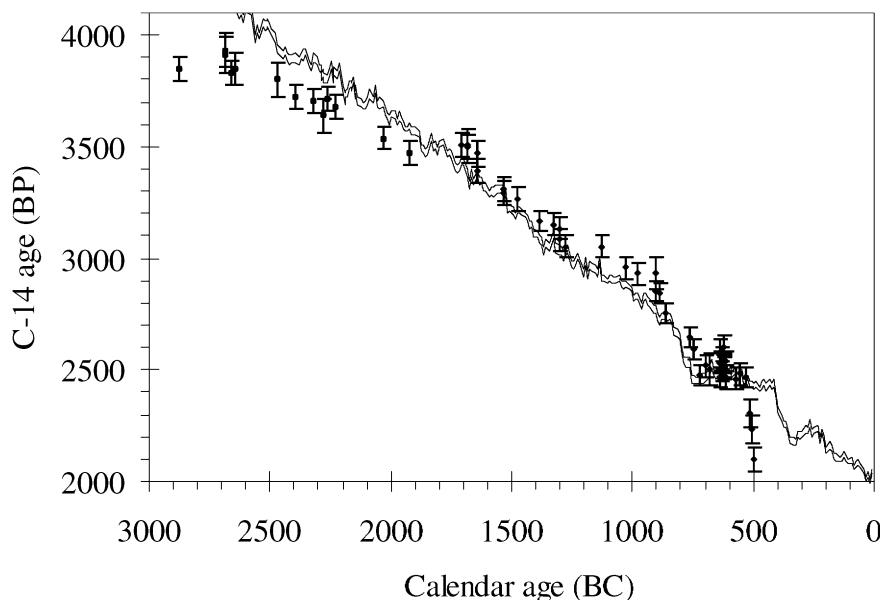


Fig. 5. ^{14}C Wigggle-match dating result of core Eng-XV when constant arboreal pollen influx is assumed instead of linear accumulation. Symbols as in Fig. 1.

Table 1

Comparison of confidence intervals between calibration of individual ^{14}C AMS dates and wigggle-match dating result of these dates (WLS; weighted least squares) of cores Eng-XV and MSB-2K

	Calibration	WLS	Ratio cal/WLS
Eng-XV subset 3	230	36	6.4
Eng-XV subset 2	155	114	1.4
Eng-XV subset 1	234	204	1.1
MSB-2K subset 3	263	86	3.1
MSB-2K subset 2	221	99	2.2
MSB-2K subset 1	176	52	3.4

See Figs. 6 and 9. Calibration: average confidence interval in calendar years at 1σ level for calibration of individual ^{14}C dates. WLS: average confidence interval in calendar years at 1σ level for WLS. Ratio cal/WLS gives an indication of the size of confidence intervals of WLS when compared with those of calibration of individual ^{14}C dates (precision-gain).

WMD can be during periods with major wiggles in the ^{14}C calibration curve, in Fig. 7 the WMD results of two of the ^{14}C dates of subset 3 of core Eng-XV are compared with calibration of the individual ^{14}C dates.

3.2. Core MSB-2K

In December 2000, core MSB-2K (Meerstalblok, the Netherlands) was taken from a vertical wall of a hole dug within a few metres from the site of Dupont (1985), using metal boxes of $50 \times 15 \times 10$ cm. One metre of the core was analysed for macrofossils, C, N, C/N, LOI and tephra at 1 cm resolution (details of the record will be published elsewhere), and 40 samples of carefully cleaned above-ground macroremains were AMS ^{14}C

dated (Table 2). Lithology and ^{14}C dates are shown in Fig. 8a and b.

As was the case for core Eng-XV, it was not possible to obtain a satisfactory wigggle-match of the ^{14}C dates with the calibration curve while assuming constant linear accumulation for the entire core (Fig. 8a). Indeed, lithology suggests that changes in accumulation rate had taken place (Fig. 8b). Subsets were distinguished, based on where ^{14}C dates started to deviate from the calibration curve and where at the same depth lithology suggested accumulation rate changes:

Subset 1 (80–54 cm): layers of mainly *Eriophorum vaginatum*, Ericaceae (mainly *Calluna vulgaris*) and *Sphagnum* sect. *Acutifolia*.

Subset 2 (53–23 cm): dominance of *Scheuchzeria palustris*, together with varying quantities of *Sphagnum cuspidatum*.

Subset 3 (22–2 cm): *S. cuspidatum* dominant (with *Scheuchzeria palustris*), later replaced by *Calluna vulgaris*.

Fig. 8c shows the wigggle-match result of the subsets of core MSB-2K (80–2 cm). Subset 1 comprised 80–54 cm depth only and not 100–54 cm depth: between 99 and 81 cm no levels were ^{14}C dated, resulting in a too low resolution of ^{14}C dates for a reliable wigggle-match of this part of the core. WLS and MLH show similar optima (and therefore similar wigggle-match results) and confidence intervals. In Fig. 8d, the MLH chronology for all depths is shown. Thickness of lines indicates the MLH value; the thicker the line, the higher the MLH value at that calendar age. Between the subsets hiatuses are apparent (75 yr between subsets 1 and 2, 222 yr between subsets 2 and 3). Outcomes of 1σ confidence intervals for WMD (WLS) and calibration of individual dates are

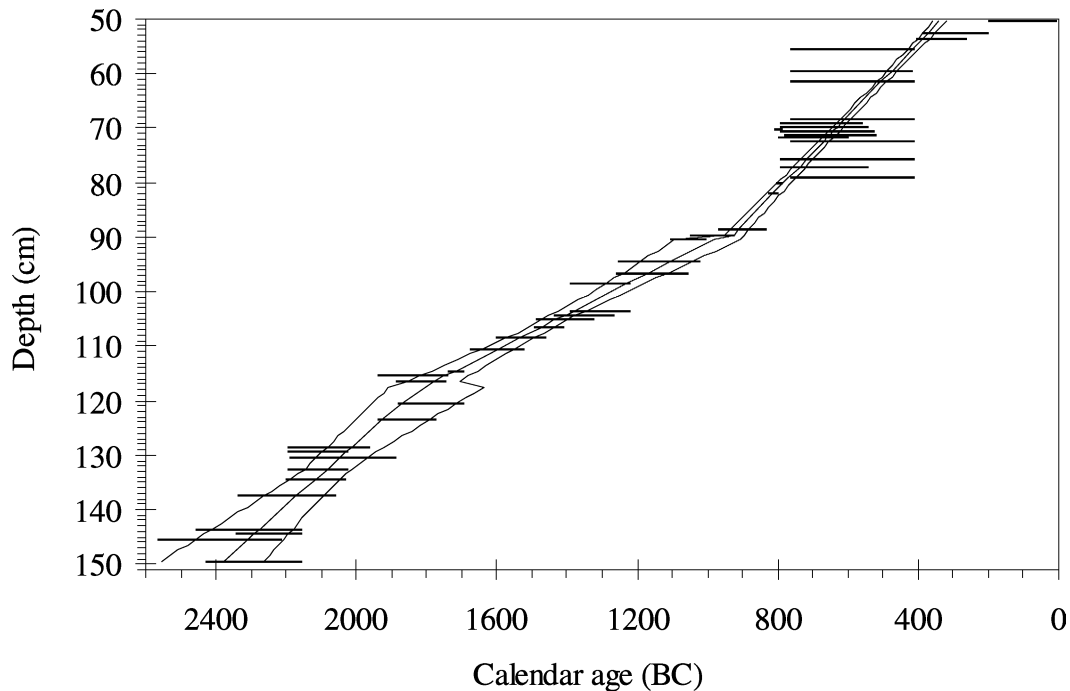


Fig. 6. A comparison between calibration of individual ^{14}C dates (thick horizontal lines, 1σ) and WLS (weighted least squares; thin connected lines; middle line shows proposed MLH [maximum likelihood] chronology, outer lines show 1σ confidence intervals WLS) of core Eng-XV.

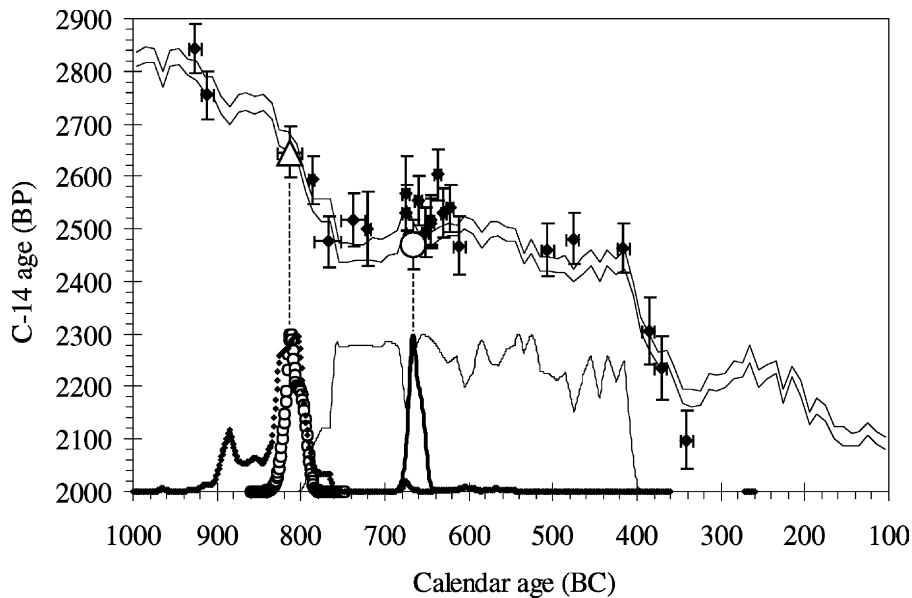


Fig. 7. Possible calendar age ranges resulting from calibration of individual ^{14}C dates and WMD (MLH; maximum likelihood) of these dates in subset 3 of core Eng-XV. The vertical scale of the calibration and MLH results is arbitrary. Symbols are as in Fig. 1, except: large triangle: AMS ^{14}C date of 2646 ± 49 BP at 83–81 cm depth, closed diamonds: calibration result of the same dated level, curve with open circles: MLH result of 83–81 cm depth; large circle: AMS ^{14}C date of 2469 ± 47 BP at 72.5–72 cm depth, thin black line: calibration result of 2469 ± 47 ^{14}C BP, thick black line: MLH result of the same dated level.

compared in Table 1 and Fig. 9. Average 1σ confidence measure 52 calendar years for subset 1, 99 yr for subset 2 and 86 yr for subset 3. For all subsets, calibration of individual ^{14}C dates results in larger 1σ confidence intervals than is the case for WMD (WLS).

Accumulation rates as proposed by the optimal MLH wiggle-match of core MSB-2K are 17.40, 25.10 and 13.10 yr cm^{-1} for subsets 1, 2 and 3, respectively. As with core Eng-XV, core MSB-2K was sampled from a bog that has been drained, which could have caused

Table 2
AMS ^{14}C dates of core MSB-2K

Depth (cm)	Composition	^{14}C age (BP $\pm \sigma$)	$\delta^{13}\text{C}$ (‰)	C content (%)	GrA no.
1.5	c,fl,r,s	4128 \pm 65	-27.88	54.2	19478
4.5	a,fl	4106 \pm 60	-27.66	52.4	19143
8.5	fl	4046 \pm 59	-27.45	52.1	19144
12.5	a	4184 \pm 58	-27.86	53.7	19146
14.5	r	4076 \pm 62	-24.97	49.4	19147
14.5	s	4107 \pm 61	-22.50	49.4	19148
14.5	a	4097 \pm 58	-27.40	54.3	19141
17.5	s	4177 \pm 53	-20.80	47.7	18675
20.5	a,c,e,fl,r,s,sch	4220 \pm 59	-24.76	49.9	19151
21.5	s	4281 \pm 64	-23.45	49.0	19476
21.5	a	4374 \pm 64	-26.57	51.8	19475
22.5	a	4493 \pm 62	-27.37	55.2	19152
28.5	r	4452 \pm 52	-24.43	46.9	18323
31.5	a,c,e,r,s,sch	4616 \pm 64	-25.91	54.1	19474
32.5	a,c,e,r	4662 \pm 64	-25.99	49.9	19473
33.5	a,c,e,r,s,sch	4743 \pm 67	-25.59	51.8	19509
34.5	a,r,s,sch	4638 \pm 67	-23.88	52.6	19480
37.5	r,s,sch	4810 \pm 67	-22.61	52.5	19483
38.5	fl	4757 \pm 82	-26.70	49.8	18674
41.5	a	4839 \pm 59	-27.46	52.0	19153
43.5	c	4913 \pm 65	-28.86	59.2	19484
46.5	c	4880 \pm 57	-28.95	52.0	19154
47.5	c	4989 \pm 70	-28.78	58.4	19485
48.5	a,c,e,fl,r,s,sch	5070 \pm 66	-25.05	52.9	19486
49.5	a,c,r,s	4993 \pm 67	-25.05	52.4	19488
50.5	r	5115 \pm 79	-25.48	48.4	17626
52.5	r	5026 \pm 51	-23.20	47.0	18682
53.5	c,e,fl,o	5242 \pm 64	-28.73	55.9	19489
54.5	fl,o	5159 \pm 50	-25.50	52.0	18679
55.5	c,fl,o,r	5130 \pm 66	-27.83	57.0	19490
58.5	s	5238 \pm 65	-26.00	44.9	19492
59.5	s	5293 \pm 38	-27.01	46.5	17501
64.5	s	5293 \pm 54	-26.06	41.7	18320
70.5	fl	5368 \pm 51	-25.70	50 ¹	18678
71.5	fl	5498 \pm 69	-28.38	55.1	19494
73.5	e	5588 \pm 55	-28.33	56.0	18319
75.5	c	5514 \pm 57	-28.98	56.0	18318
77.5	fl	5535 \pm 52	-27.30	52.9	18688
79.5	fl,o	5644 \pm 77	-28.74	54.2	17627
99.5	s	5885 \pm 45	-29.67	3.2 ²	17508

All samples were taken from 1 cm slices, and consist of AAA pre-treated, thoroughly cleaned above-ground plants remains. (a) *Andromeda polifolia*, (c) *Calluna vulgaris*, (e) *Erica tetralix*, (fl) Ericales flowers, (o) *Oxycoccus palustris*, (r) *Rhynchospora alba*, (sch) *Scheuchzeria palustris*, (s) *Sphagnum* spec. ^{14}C ages are given in BP (before 1950) with 1σ confidence intervals. (1) value estimated, (2) value probably incorrect.

secondary compaction of peat layers. Therefore, the reconstructed accumulation rates are not directly comparable with those of undisturbed bogs.

To assess whether ^{14}C ages of various macrofossils (e.g., *Sphagnum*, Ericaceae) showed any systematic error, from 14 levels pairs of various different above-ground macrofossils were ^{14}C dated (dates from Table 2 and Blaauw, submitted). No systematic difference was found in ^{14}C ages of macrofossils of various origin. All but one of the pairs of ^{14}C dates fell within their

common 1σ error bars. In core Eng-XV (Blaauw et al., submitted), a pair of samples was dated of above-ground remains of *Calluna vulgaris*. One of these samples contained abundant visible fungal contamination, whereas the other sample was thoroughly cleaned of fungal remains. Also in this case, no significant offset in ^{14}C age was found.

3.3. Cores LVM and WLM-19

Mauquoy et al. (2002a) ^{14}C wiggle-match dated two peat sequences (Walton Moss (WLM-19) from England, and Lille Vildmose (LVM) from Denmark) spanning the last millennium, in order to come up with precise calendar age estimates of wet-shifts in these cores. We re-assessed both chronologies, and inferred confidence intervals for the calendar age estimates of the major wet-shifts (^{14}C dates 16 from LVM and 20 from WLM-19 were outliers and rejected).

As can be seen from Fig. 10, statistically possible calendar age intervals for the starts of the wet shifts in core LVM as suggested by MLH and WLS, actually are wider than one would probably expect (based on the ‘wiggly’ nature of the calibration curve from ca AD 1700 to AD 1950). Historical evidence however can help to narrow the confidence intervals. Mauquoy et al. (2002b) cite several historical sources to obtain independent dating for certain levels in their cores. An example is shown in Fig. 10, where pollen evidence ‘anchored’ a level at a certain calendar age, whereas WLS and MLH suggested a much wider range of possible calendar ages. Local optima in WLS and MLH that did not correspond to the historically known calendar age for a certain level, could be ruled out as possible wiggle-match solutions. These rejected solutions were not used during WMD-analysis of other levels. In this way, the calendar age confidence interval for the wet-shift found at 67.5 cm depth in core LVM could be narrowed down from ca 80 to ca 40 yr. (Fig. 10, Table 3). Moreover, some wiggle-matches as proposed by WLS or MLH would have been difficult to accept, as with these solutions the accumulation rate would have been unrealistically high, and the above-lying acrothelm would have had to accumulate very slowly to obtain recent (and not ‘future’) calendar ages for the surface of the bog. It should be noted that in cores WLM-19 and LVM, sample resolution for pollen analyses was low (5 cm sampling intervals), and pollen sums were also low (300–350).

In the same way, historically known events explaining pollen changes in core WLM-19 could be used to narrow down WMD calendar age confidence intervals for the wet-shifts during the Little Ice Age (Table 3). The wiggle-match of the upper subset of core WLM-19 as suggested by WLS and MLH differs much from what historical evidence would suggest. Indeed, the fit of the

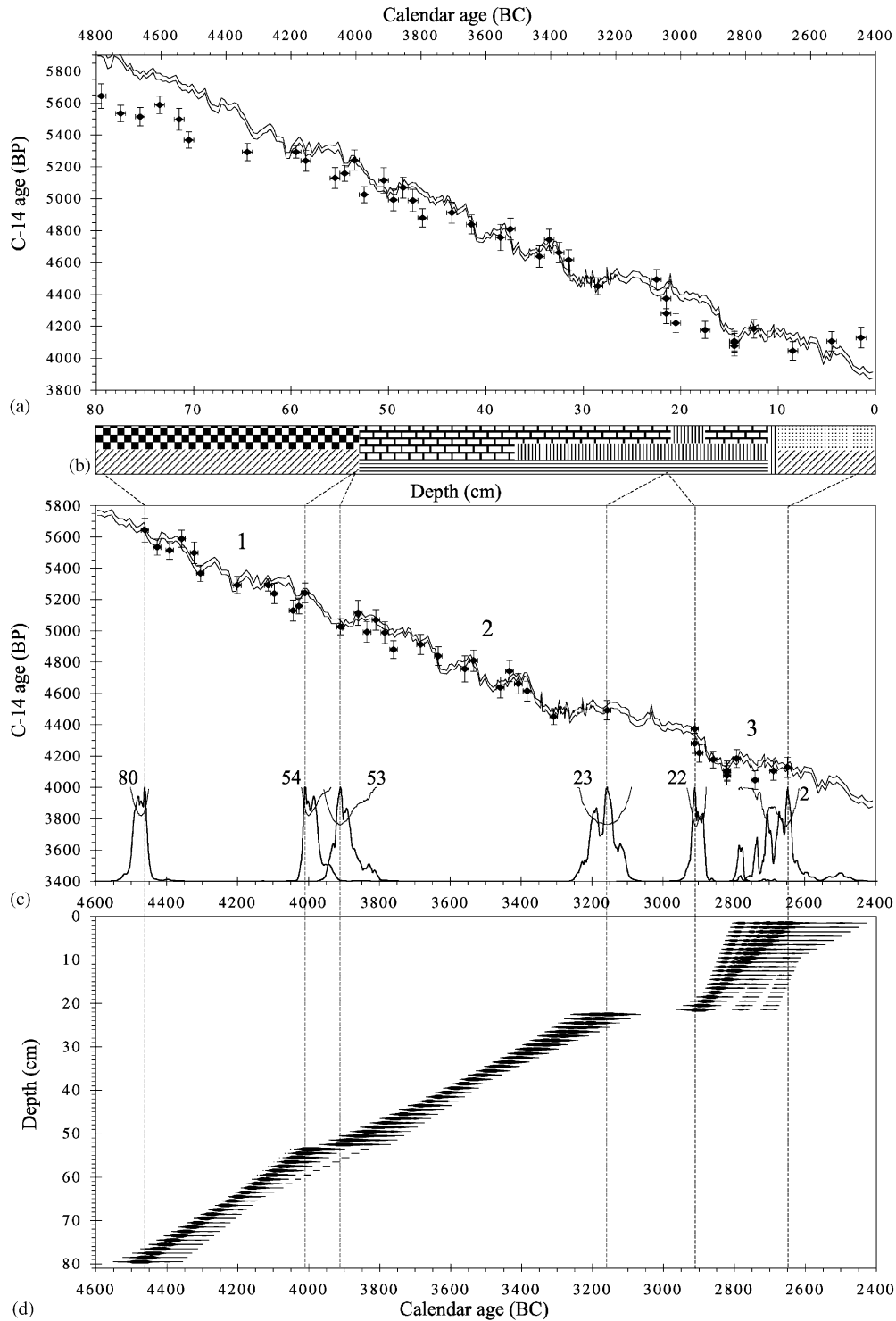


Fig. 8. ^{14}C AMS dates, lithology and wiggle-match dating result of core MSB-2K. (a) ^{14}C AMS dates are plotted together with the calibration curve INTCAL98 (1σ error envelope). The vertical bars of the ^{14}C samples show 1σ error bars, the horizontal bars show thickness of samples. (b) lithology shows domination by vegetation types: squares: *Eriophorum vaginatum*, 'bricks': *Scheuchzeria palustris*, vertical lines: *S. cuspidatum*, diagonal lines: *S. sect. Acutifolia*, horizontal lines: *Rhynchospora alba*, dots: *Calluna vulgaris*. The final wiggle-match dating solution is shown in (c). The sequence is divided into subsets 1–3 (hatched lines show levels of division), and the individual subsets are wiggle-matched to the ^{14}C calibration curve. Placements of subsets are as proposed by optimal MLH (maximum likelihood). Hiatuses between the subsets are visible. On the calendar axis, WLS (weighted least squares; concave-shaped, thin lines, only $<1\sigma$ values) and MLH (convex-shaped, thick lines) values of selected levels are shown (labels indicate depth of levels). The vertical scale of WLS and MLH is arbitrary. (d) MLH confidence intervals are shown for every cm of the core. The vertical thickness of the lines shows the MLH value.

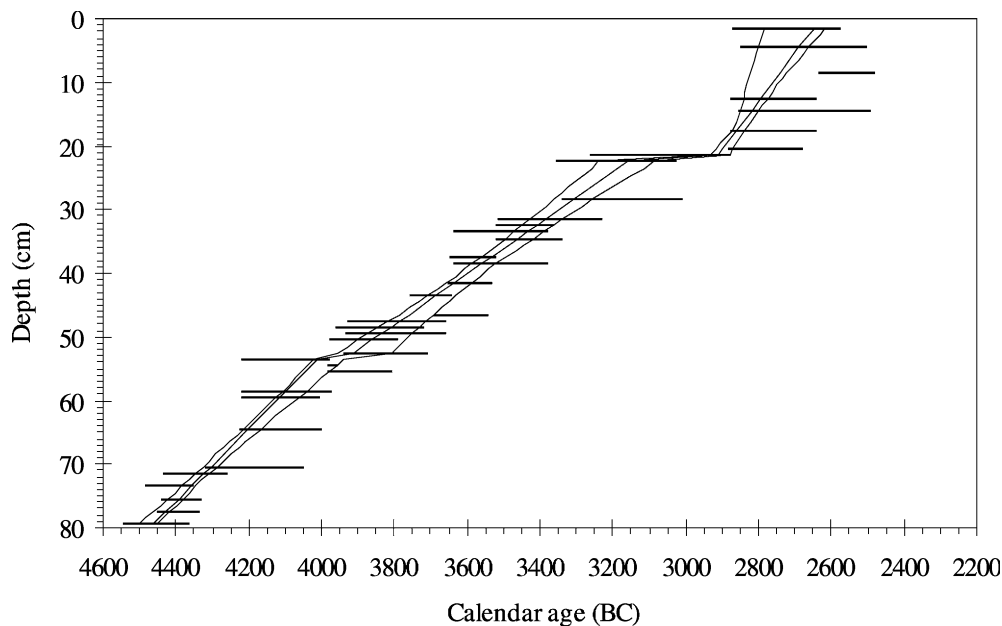


Fig. 9. Comparison between calibration of individual ^{14}C dates (thick horizontal lines, 1σ confidence intervals) and WLS (weighted least squares; thin connected lines: middle shows proposed MLH [maximum likelihood] chronology, outer lines show 1σ confidence intervals WLS) of core MSB-2K.

subset becomes low when the *Pinus* pollen increase as found at 40 cm depth is placed against the historically known event of planting of pine within the region around AD 1740–1760. Only at 2σ level of WLS does a statistically allowable wiggle-match occur during the Maunder Minimum.

The wet-shifts, indicative of climatic deteriorations, occurred coeval in both cores and during major decreases of solar activity (increases in atmospheric ^{14}C concentration; Mauquoy et al., 2002a). Best estimates and confidence intervals for these wet-shifts obtained by WMD are listed in Table 3.

4. Discussion

Using the ^{14}C wiggle-match results of cores Eng-XV, MSB-2K, LVM and WLM-19 as case studies, the assumptions, advantages and limitations of ^{14}C wiggle-match dating of peat cores are discussed.

4.1. Chronology assumptions

According to Belyea and Clymo (2001), long-term rates of peat accumulation are surprisingly steady, despite great variability in the short-term rates of peat accumulation. Assuming linear accumulation over time (Kilian et al., 2000), and using information from the lithology for division into subsets to account for hiatuses or sudden changes in accumulation rate, we arrived at satisfactory wiggle-matches (almost all ^{14}C

dates of our peat sequences overlapped the ^{14}C calibration curve at 1σ error bars).

Higher polynomial curves could be employed to describe the relationship between depth and calendar age. Every added parameter could indeed result in a better wiggle-match of a sequence. However, with every added parameter to estimate a calendar age, the amount of necessary calculation time increases exponentially, and the number of degrees of freedom decreases, making the statistics less robust. Moreover, a higher-order polynomial could still not cope with hiatuses or sudden accumulation rate changes in sequences. Occam's razor theorem ('the simplest theory that fits the facts of a problem is the one that should be selected') directs us to use the lowest possible number of parameters that satisfactorily describes our data. As the model of linear accumulation, with division into subsets when necessary, already gives a satisfactory wiggle-match result, the use of higher polynomial models therefore is not favoured.

Ideally, at levels where ^{14}C dates of a sequence start to deviate from the calibration curve, one would find obvious indications of hiatuses or changes in accumulation rate. The sequence would then need division into subsets at these levels. Moreover, in the ideal case, lithological data (e.g., local vegetation composition, charcoal occurrence, major changes in arboreal pollen concentration) would suggest that the subsets thus arisen would appear to have accumulated at a more or less constant rate. As can be seen from core Eng-XV however, division of a sequence into subsets that have accumulated at a constant rate as suggested by the

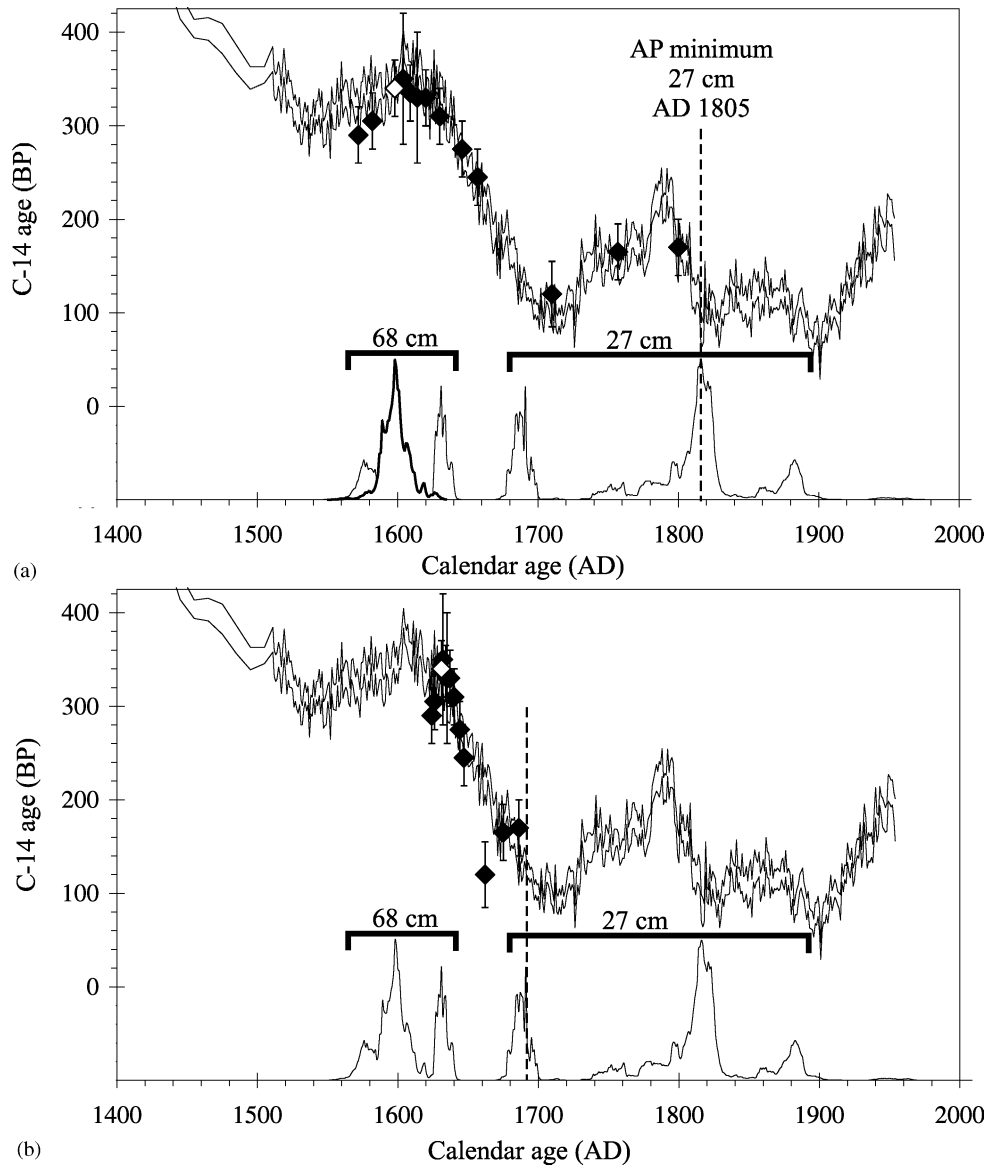


Fig. 10. ^{14}C Wiggle-match dating of the upper subset from core LVM (Mauquoy et al., 2002a, b). At 26.5 cm depth arboreal pollen reached a minimum which was ascribed to the historically documented minimum in regional forest cover at AD 1805. Wiggle-match of (a) places the depth of 26.5 cm at a correct calendar age. (b) A wiggle-match solution as suggested by another local optimum of MLH (maximum likelihood). This wiggle-match is considered unrealistic as the 26.5 cm level is placed at a far too old calendar age (ca AD 1690). Therefore, the local optimum that results in the wiggle-match of (b) is rejected. Using this knowledge, the MLH confidence levels of another dated level (68 cm depth, a wet shift) can be narrowed down to the thick curve of (a).

match of ^{14}C dates to the calibration curve, does not always correspond entirely with the division into subsets with constant accumulation as suggested by the lithology. With cores MSB-2K, LVM and WLM-19 there was no disagreement between ^{14}C dates and lithology about where to divide the sequence into subsets. Still, mostly while deciding which subsets to take, some subjectivity had to be involved.

Indications about accumulation rate changes can be obtained by investigating arboreal pollen (AP) concentration. When constant influx of AP is assumed (Middeldorp, 1982; Kilian et al., 2000; Speranza et al., 2000), decreased AP concentration indicates increased

accumulation rate, and vice versa. However, there are several drawbacks to using AP concentration for reconstructing accumulation changes:

- During preparation of samples, volume is often estimated in an approximate way (precision 1 decimal, e.g., 0.8 cm^3). This figure has a major impact on the resulting estimate of pollen concentration. Moreover, the amount of added marker grains, used to calculate pollen concentration, is only known by approximation (e.g., Young et al., 1999).
- The assumption of constant AP production is probably invalid when, e.g., bogs are expanding at

Table 3

Best estimates and confidence intervals for major wet-shifts during the Spörer and Maunder Solar minima in cores LVM and WLM-19

	Spörer minimum		Maunder minimum	
	WLS	MLH	WLS	MLH
<i>Core: LVM (Denmark)</i>				
Best estimate calendar age	1455 (1450–1459)	1451 (1448–1455)	1600 (1597–1603)	1598 (1595–1601)
Confidence intervals	1446–1474 (1442–1479)	ca 1435–1490 (ca 1432–1496)	ca 1580–1620 (ca 1577–1623)	ca 1580–1620 (ca 1577–1622)
<i>Core: WLM-19 (England)</i>				
Best estimate calendar age	1444 (1441–1449)	1446 (1442–1450)	1580 (1570–1591)	1583 (1572–1594)
Confidence intervals	1433–1457 (1431–1461)	ca 1420–1475 (ca 1418–1482)	ca 1569–1603 (ca 1556–1613)	ca 1560–1620 (ca 1549–1631)

As the wet-shifts were recorded in 1 cm peat slices, these levels have been deposited during a certain period. Dates with deposition periods included are given in brackets. All dates are in AD. Wet-shifts during Maunder minimum: confidence intervals are narrowed down by historical pollen evidence (see text). WLS: weighted least squares, MLH: maximum likelihood. WLS confidence levels are at 1σ level except for WLM-19 at the Maunder minimum, where the 2σ level is given.

the cost of surrounding forest, or when humans cut down forests.

- Local bog composition could influence the amount of pollen rain being trapped. Precipitation could wash away pollen from hummocks and accumulate pollen at hollows. Some plants could be an efficient pollen ‘trap’ (Kilian et al., 2000), whereas other taxa could dilute pollen concentration secondarily, e.g., by in-growth of roots. ‘Pollen dates’ could be inaccurate as well: pollen could be transported downwards into a sequence.

Using AP influx instead of depth did not result in a better wiggle-match of core Eng-XV (Fig. 5). This was not surprising, as the core showed several major changes in vegetation composition, and as it accumulated during a period with bog extension and human impact on the regional forest.

4.2. AMS ^{14}C measurements

For ^{14}C dating of the cores discussed in this study, above-ground remains of macrofossils were used only, and all visible contamination was thoroughly removed. We did not find a systematic difference in ^{14}C age between remains of different species dated at similar depths. Pairs of ^{14}C dates of various above-ground macrofossils dated by Kilian et al. (2000) and Nilsson et al. (2001) neither showed any systematic age offset. Although in this study no systematic offset was identified, no pair of ^{14}C dates had exactly similar ^{14}C ages. Every ^{14}C date is a measurement/estimate of the true ^{14}C age only. A ^{14}C age of, e.g., 1410 ± 50 ^{14}C BP should be read as: ‘there is a 68% probability that the real ^{14}C age lies between 1360 and 1460 ^{14}C BP’.

4.3. Numerical approach

WLS and MLH show approximately the same local optima on the calendar year scale, although heights of local optima sometimes differ. They also show comparable widths and placements of confidence intervals (Figs. 3,4 and 8). The depth of a WLS optimum indicates how well a sequence of ^{14}C dates matches with the calibration curve; the closer an optimum is to zero, the better the goodness-of-fit (a perfect match of the dates with the calibration curve, without any scatter, would give a WLS of 0). Confidence intervals of WLS and MLH are comparable: calendar ages where WLS values start to fall outside 1σ limits are placed at approximately the same calendar age as where MLH values approach 0. MLH was designed to identify the best and alternative wiggle-matches.

The WMD as proposed by the highest optima of MLH and WLS of individual subsets is not necessarily the most realistic one. When the chronology as suggested by the optima of WLS of subsets 1 and 2 of core Eng-XV would have been used, overlaps in calendar age would have occurred. Such overlaps between neighbouring subsets are considered unrealistic, as this would imply a jump backward in time in a chronology. When the highest optimum of MLH was used, subset 1 did not overlap anymore with subset 2 of core Eng-XV. In core WLM-19 the wiggle-matches as proposed by WLS and MLH were considered unrealistic; pollen evidence related to historically known vegetation changes placed levels at calendar ages quite long after those proposed by the optima of WLS and MLH.

During some periods, even high-resolution ^{14}C sequences such as those of cores LVM and WLM-19

cannot provide unambiguous wiggle-matches. Several wiggle-match solutions are possible in which the ^{14}C dates match those of the calibration curve from ca AD 1700 to AD 1950, because during this period the calibration curve shows large wiggles with re-occurring ^{14}C ages. In such cases, only with a sequence dated at even higher resolution would it be possible to reconstruct the complex shape of the ^{14}C calibration curve, instead of merely having the sequence ‘touch’ the calibration curve at some occasions (Fig. 10).

A limitation to our approach of ^{14}C wiggle-match dating is that optima and confidence intervals are obtained with the assumption of linear accumulation. The assumption of linear accumulation should only be made if supported by the lithology and ^{14}C data. When linear accumulation is incorrectly assumed, the shape of a ^{14}C sequence differs from the shape of the calibration curve. In such cases it is difficult to match both shapes; only a very narrow range of accumulation rates and horizontal shifts results in a possible wiggle-match, and therefore the confidence intervals become very narrow (illusionary precision). A comparable case occurs when there is a large vertical scatter of ^{14}C dates around the calibration curve. Also in this occasion there is a very small range of possible wiggle-matches (resulting in very narrow confidence intervals), as with even small changes in the parameters α and/or β , the ^{14}C dates would fail to match the calibration curve. This problem is discussed by Bronk Ramsey et al. (2001).

Because the ^{14}C calibration curve uses ^{14}C ages rounded to years (and not decades), for comparison purposes the ^{14}C dates of cores MSB-2K and Eng-XV were also rounded to years. For accuracy-of-measurement reasons however, reported ^{14}C ages are often rounded to decades (e.g., cores LVM and WLM-19). Moreover, the ^{14}C calibration curve on average has a decadal resolution on the calendar axis (in this paper ^{14}C ages for calendar years were obtained by linear interpolation), and the resolution of a ^{14}C sequence that is to be wiggle-matched often is significantly lower than that of the calibration curve. Because these phenomena are not taken into account in the method described in this paper, given confidence intervals are possibly slightly underestimated (we cannot quantify this additional ‘noise’).

4.4. Wiggle-matching vs. calibration of ^{14}C dates

With the studied cores WMD always resulted in narrower confidence intervals than when individual ^{14}C dates were calibrated (Table 1, Figs. 6 and 9). The success of WMD depends on the shape of the calibration curve. During periods where the calibration curve does not show pronounced excursions, the approach of WMD does not appear to provide a much better chronology than in case of calibration of

individual dates. This is true for subsets 1 and 2 of core Eng-XV (confidence intervals have approximately similar widths). However, WMD does provide a substantially more precise chronology during periods with pronounced excursions in the ^{14}C calibration curve. Examples of this are subset 3 of core Eng-XV (confidence intervals are ca 6 times narrower) and all subsets of core MSB-2K (confidence intervals are ca 2–3 times narrower).

With calibration of individual ^{14}C dates, often there appear several local optima of the probability distribution on the calendar scale. Often there are no indications about which of those local optima is the most probable. Therefore, regularly the minimum and maximum of the 1σ confidence intervals on the calendar age scale are looked up to give the 1σ calendar age range, and the midpoint of the range is considered to be the most probable calendar age. This midpoint does not always coincide with one of the local optima (in other words, this point is not necessarily a probable calendar age). With WMD, local optima on the calendar scale are taken into account.

5. Conclusions

The numerical approach to ^{14}C wiggle-match dating described in this paper provides suggestions for several wiggle-match solutions, and can assess the statistical aspects of calendar age precision.

When supported by lithology, the assumption of linear accumulation over time (with subdivision into subsets where appropriate) resulted in satisfactory ^{14}C wiggle-matches for the studied sequences. More ‘sophisticated’ growth models (such as higher polynomial curves, or models based on constant arboreal pollen influx), would make use of more assumptions and are not considered to be of added value.

At times of major wiggles in the ^{14}C calibration curve, the approach of wiggle-match dating of high-resolution ^{14}C dated sequences provides a far more precise chronology than the approach of calibration of individual dates (on special occasions, precision can be ca 6 times higher). During periods with less pronounced excursions in the calibration curve, WMD is less successful. In these cases, confidence levels as obtained by WMD are only slightly narrower (but still narrower) than those obtained by calibration of individual ^{14}C dates.

With WMD, a sophisticated choice between local optima on the calendar time scale is made, whereas with calibration there is no indication of the most probable calendar age (in case of several local optima of the probability distribution on the calendar scale).

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