[RADIOCARBON, VOL 31, NO. 3, 1989, P 846–864]

A COMPARISON OF METHODS USED FOR THE CALIBRATION OF RADIOCARBON DATES

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ABSTRACT. Current calibration methods for single and replicate ^{14}C dates are compared. Various forms of tabular and graphic output are discussed. Results from all the methods show reasonable agreement but further methodological development and improvements in computer output are required. Comparison of existing techniques for a series of non-contemporaneous dates showed less agreement amongst participants on this issue. We recommend that calibrated dates should be presented as a combination of graphs and ranges, in preference to mean and standard deviation.

INTRODUCTION

Three automatic calibration methods for ^{14}C dates were presented at the 2nd international symposium, Archaeology and ^{14}C, held in Groningen, 1987 (van der Plicht, Mook & Hasper; Michczynska, Pazdur & Walanus; Warner, in press). Two automatic methods for calibration had already been suggested (Otlet, pers commun; Robinson, 1986) during the 12th international ^{14}C conference in Trondheim in 1985. There is now the widely distributed program, CALIB, for ^{14}C age calibration (Stuiver & Reimer, 1986). Finally, Aitchison, Ottaway and Scott (in press) suggested an extension of the quartile interval method, dealing with groups of ^{14}C dates and their subsequent calibration. It is important that these various methods should be compared and contrasted.

THE DATA

It was suggested at Groningen to bring together these methods and compare them on the same data. The resultant sets sent out by B S Ottaway (Table 1, Questionnaire Qn 2) consisted of:

Data Set A: Six single dates, A1–A6, from different laboratories with different errors, dating separate events and spanning the period, 8th to 2nd millennia BP;

Data Set B: Four groups of ^{14}C dates (B1–B4) from different archaeological cultures. This suite is assumed to date the most active period of each culture, thus providing information on the duration of culture.

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Data Set C: One set of replicate estimates (C1) *ie,* the same material dated by different laboratories and two sets of results from homogenized replicate samples (C2.1 & C2.2), from one laboratory, *ie*, counting replicates.

The eight groups participating in this study (Aitchison, Ottaway & Scott; Leese; Otlet; Pazdur; van der Plicht, Mook & Hasper; Robinson; Stuiver & Reimer; Weninger) subjected the data sets to various calibration routines and completed a questionnaire, on practical details of the methods used.

TABLE 1

The three data groups for the calibration comparison

Data Set A: Single ^{14}C Dates

Sample no.	Date (BP)	±	Site	Context	Ref
IRPA-520	7030	80	Drie Grachten 7	Peat	R, 1986,28(1):71
Gif-2749	5900	140	Port Leucate P.2	Charcoal	R,1986,28(1):20
GrN-6483	4790	40	Niederwil	Carbonized grain	Lanting & Mook, 1977:63
H-2123/1538	3745	60	Dornburg		R,1970,12(2):400
GrN-7457	2480	35	Texel-Den Burg	Mollusks	Lanting & Mook, 1977:151
BM-372	1598	70	Moerzeke-Marie Kerke	Carved wood	Lanting & Mook, 1977:196

Data Set B: Groups of ^{14}C Dates

Group B1
Michelsberg II culture
Material from several sites

Group B2
Michelsberg III culture
Material from 1 site

(Lanting & Mook 1977, p 60–61)

Sample no.	Date (BP)	±	Sample no.	Date (BP)	±
KN I-663	5440	85	KN I-306	5260	40
KN I-664	5490	95	KN I-311	5210	40
KN I-418	5270	40	Bln-54	5140	80
KN I-419	5080	50	Bln-70	5240	100
KN I-773	5280	85	Bln-71	5200	100
KN I-574	5480	105	H-61/149	5140	130
KN I-720	5400	60	H-125/107	5200	200
KN I-722	5250	60	KN I-304	5190	60
KN I-724	5050	85	KN I-305	5160	60
GrN-6345	4965	40			

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Table 1 (continued)

Group B3 – Pfyn culture
Material from 3 sites
(Lanting & Mook, 1977: 62–63)

Sample no.	Date (BP)	±
GrN-241	4735	135
LJ-1279	4938	40
LJ-1265	4982	40
B-45	4780	130
GrN-5957	5020	40
GrN-5958	4965	40
GrN-4202	4750	60
GrN-4203	4990	60
GrN-4204	4750	60
GrN-6482	4915	40
GrN-6483	4790	40
GrN-6484	4765	40
GrN-6485	4800	40
GrN-6486	4755	40
GrN-7179	4875	50
GrN-7090	4980	70
B-44	4690	180

Group C1 – Results on identical sample each from a different laboratory (ISG, 1982)

Date (BP)	±
5110	50
4930	50
5012	48
5106	31
5115	65
5110	60
5000	60
5138	19
5112	12
5050	90
5175	60
5027	36
5160	70
5130	90
4907	37
5223	51
4940	80
5030	90

Group B4 – Cham culture
Material from 3 sites
(Ottaway, (ms) 1986)

Sample no.	Date (BP)	±
GrN-5732	4220	55
GrN-6425	4340	40
GrN-7159	3885	40
GrN-7556	4430	45
GrN-8689	4305	35
H-7415/7442	4350	40
H-7415/7443	4170	70
UB-2551	4285	85
GrN-12561	4255	40
GrN-12562	4290	45
GrN-12563	4150	60
GrN-12564	4210	60
GrN-12699	4510	30
GrN-12700	4225	30
GrN-12701	4280	35
GrN-12702	4385	35
GrN-14426	4420	35
GrN-14427	4245	50
GrN-14428	4500	80
GrN-14429	4310	60

Group C2 – Results from homogenized replicate samples (counting replicates) (Scott *et al*, 1983)

Date (BP)	±	
5057	40	
5167	40	
5152	41	C2 Batch 1
5085	50	
5242	71	
5003	56	
5169	57	
5170	60	C2 Batch 2
4970	68	
5314	64	

TABLE 2

Summary of questionnaire responses

Question No.	Aitchison Ottaway & Scott	Leese	Otlet & Walker	Pazdur & Michczyn-ska	van der Plicht Mook & Hasper	Robinson	Stuiver & Reimer	Weninger
1. Calibration Curve Used								
Stuiver & Pearson, 1986	×	×	×	×	×	×	×	×
Pearson & Stuiver, 1986	×	×	×	×	×	×	×	×
Pearson *et al*, 1986	×	×	×	×	×	×	×	×
Kromer *et al*, 1986			×		×		×	×
Linick *et al*, 1986			×		×		×	×
Stuiver & Becker, 1986			×		×		×	×
Vogel *et al*, 1986			×		×		×	×
de Jong *et al*, 1986			×		×		×	×
Stuiver *et al*, 1986 (Marine samples)			×		×		×	×
2a. Curve Fitting								
Piecewise linear fitting		×	×	×		×	×	×
Spline Function					×			
Direct Curve Fitting	×							
2b. Estimation of Error on Curve								
15 years		×						
20 years		×						×
Variable	×				×			× (possible)
Error reported for closest neighbours/for curve band width			×				×	
Neglected				×		×		
3. Confidence Level								
50%								×
68.3% (1σ)	×	×		×		×	×	×
95.4% (2σ)	×	×	×	×		×	×	×
99.7% (3σ)				×	×	×		
100% (4σ)				×				
Variable 0–100%	×							×

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TABLE 2 (continued)

Question No.	Aitchison Ottaway & Scott	Leese	Otlet & Walker	Pazdur & Michczyn-ska	van der Plicht Mook & Hasper	Robinson	Stuiver & Reimer	Weninger
4. *Final Form of Presentation*								
As confidence ranges: 50%				×				×
68%		×				×	×	×
80%				×		×		
90%				×		×		
95%		×	×	×		×	×	×
Variable	×							
As probability distribution histogram		×		×	×	×	×	×
As point estimates of probability distribution						×		
Mean & SD of transformed distribution			×					
Interquartile range	×							×
Interquantile ranges				×				
Cumulative probability				×	×		×	
Weighted average (centroid)						×		×
6. *Language*	N/A	Fort 77	Fort	GWBas or HBas	T Pasc 4.0	Bas & Turbo	Fort Rev 3.2	Fort 77 & (Plot 79)
7. *Size of Program*		60K		180K	64K	77.4K	255K	30K
8. *Operating System*		RTE-6/VM (H-P)	MS-DOS	DOS 2.10	MS-DOS	MS-DOS 2 or 3	MS-DOS	Univac 1100 Sperry
9. *Graphics*	N/A	(On screen only)	Yes	Yes	Yes	Yes	Yes	Yes
Graphics Card			CGA	HGC	CGA* EGA HGC			
10. *Program Available*	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
14. *Can Results Be Used For Analysis of Series of Dates (eg, of Cultures)?*	Yes	No	Using $\bar{x}$ & SD	Yes	Yes	No	As Average	Yes
15. *Can Arch. Info Be Built into Analysis?*	Yes	No	No	No	No	Yes upper & lower limits can be imposed	Yes by choice of plotting order	Yes by wiggle matching

KEY: Fort = Fortran; T = Turbo; Pasc = Pascal; H-P = Hewlett-Packard; Bas = Basic; HGC = Hercules; CGA = Colour Graphic Adaptor; EGA = Enhanced Graphics Adaptor; * = Recommended.

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TABLE 3
Sample output for a single date from all participants
Values quoted by groups for calibrated ages of date A3:
GrN-6483:4790±40 BP

Leese (*cf* Fig 1)

68% confidence limits (CL) estimated from histogram (bin size 10yr)
(results for 95% CL also provided)

Limits	(cal BC)	Rel freq
5470	3520	
5500	3550	18%
5520	3570	
5530	3580	8%
5560	3610	
5600	3650	41%
Total		67%

Otlet (*cf* Fig 2)

Calibrated date

95% range	Mean and SD
3695–3383 cal BC	3572±73 cal BC

Pazdur (*cf* Fig 3)

Max probability (P) for dates: 5518, 5490, 5576, 5340

Interval of cal age: (5322, 5658) (5695, 5726)

P (T<to)	To cal BP	Ranges:	
0.01	5338	0.50	(5491, 5570)
0.05	5452	0.95	(5345, 5627)
0.10	5471	0.98	(5338, 5636)
0.25	5491		
0.50	5521		
0.75	5570		
0.90	5591		
0.95	5615		
0.99	5636		

van der Plicht, Mook & Hasper

The following is how the users are told, by instructions that come with the program, to analyze the graphs. The results cannot be printed out automatically, since there are no general algorithm which fit all cases. For this reason, the results are presented in graphic form.

Calibrated results in terms of 16/50/84% probability

50% P (median)	:	3567 cal BC
84% P	:	3526 cal BC
16% P	:	3629 cal BC

TABLE 3 (Continued)

Ranges and Probabilities

3375–3410 cal BC	6%
3505–3595 cal BC	57%
3595–3655 cal BC	30%
3655–3695 cal BC	7%

Robinson (cf Fig 4)

Cal-Centroid = –3585±61

68% CL = –3648 to –3542
80% CL = –3657 to –3533
90% CL = –3667 to –3513
95% CL = –3693 to –3404

Stuiver & Reimer (cf Fig 5)

Calibrated age(s) –BC: 3626, 3568, 3540
–BP: 5575, 5517, 5489

cal AD/BC (cal BP) age ranges obtained from intercepts (Method A)
1σ** cal BC 3641–3607 (5590–5556) 3584–3520 (5533–5469)
2σ** cal BC 3694–3503 (5643–5452) 3407–3384 (5356–5333)

Summary of above
Min of cal age ranges (cal ages), max of cal age ranges:
1σ cal BC 3641 (3626, 3568, 3540) 3520
cal BP 5590 (5575, 5517, 5489) 5469
2σ cal BC 3694 (3626, 3568, 3540) 3384
cal BP 5643 (5575, 5517, 5489) 5333

cal AD/BC age ranges (cal ages as above) from probability distribution (Method B)

% area enclosed	cal BC (cal BP) age ranges	relative area under probability distribution
68.3 (1σ)	cal BC 3642–3605 (5591–5554)	.34
	3585–3519 (5534–5468)	.66
95.4 (2σ)	cal BC 3692–3505 (5641–5454)	.96
	3403–3385 (5352–5334)	.04

Aitchison, Ottaway & Scott (cf Fig 6)

Since the Pearson & Stuiver curves are in the form of calibration curve ± one standard error on the curve intersecting such curves with ^{14}C date ± k*, quoted error on the date will give appropriate confidence intervals, eg, k = 0.71 gives ~68% confidence while k = 1.77 gives ~95% confidence.

– 68% confidence interval is 3640–3520 cal BC
– 95% confidence interval is 3700–3505 cal BC
3420–3390 cal BC

Weninger

Non-normalized dates

95% Peak center is 3671 BC – 3385 BC
68% Peak center is 3619 BC – 3505 BC
50% Peak center is 3601 BC – 3525 BC

Normalized dates:

95% Peak center is 3682 BC – 3406 BC
68% Peak center is 3617 BC – 3505 BC
50% Peak center is 3596 BC – 3521 BC

RESULTS

This report does not indicate final results; it is very much a working report and provides an initial interpretation of general findings. Critical comments are quite incomplete.

A summary of the questionnaire can be found in Table 2. The first three questions give technical calibration details.

All groups provide some form of printout of the results (Table 2.4). We illustrate the presentation for date A3 (GrN 6483: 4790±40) in Table 3, which also demonstrates the different approaches. However, the graphic output best illustrates the underlying philosophy. Using date A3, Leese (Fig 1) gives a histogram showing the distribution of the calibrated values. Otlet (Fig 2) reproduces the appropriate part of the calibration curve and presents the results as a probability distribution quoting its mean and standard deviation (SD). He also gives the 95% confidence range but this is obtained directly from the ±2 SD limits of the ^{14}C determination, taking the widest intercepts given by the curve band width at each end of the range. Pazdur (Fig 3) plots the initial probability distribution of the conventional ^{14}C age, together with the appropriate part of the calibration curve and the resulting probability distribution of the calibrated age. He then gives a second graph where the same probability distribution as in Figure 3 is shown together with the cumulative distribution function of the calibrated age. (Note: Pazdur plans to adjust these graphs slightly to improve presentation).

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GrN-6483
Calibration based on Pearson et al (1986),Radiocarbon Vol 28,No 2b,p911-934

Radiocarbon date to be calibrated:     4790 BP    Total error :     47

(Measurement error:   40  Short growth error:   15  Calibration error:   20)


Approximate histogram showing distribution of 4971 calibrated values,BP, consistent with given radiocarbon date and error

Frequency     2  158  122   35    9    0    0    0    0  108  265  455  401  263  549  149  227  565 1177  177   39   36  234
------------------------------------------------------------------------------------------------------------------------------
Each * equals   66 points

      1122                                                                                                *
      1056                                                                                                *
       990                                                                                                *
       924                                                                                                *
       858                                                                                                *
       792                                                                                                *
       726                                                                                                *
       660                                                                                                *
       594                                                                                                *
       528                                                                            *              *    *
       462                                                                            *              *    *
       396                                                             *    *         *              *    *
       330                                                             *    *         *              *    *
       264                                                        *    *    *         *              *    *
       198                                                        *    *    *    *    *         *    *    *                   *
       132         *                                              *    *    *    *    *    *    *    *    *    *              *
        66         *    *                                    *    *    *    *    *    *    *    *    *    *    *              *
------------------------------------------------------------------------------------------------------------------------------
Interval  5318.     5348.     5378.     5408.     5438.     5468.     5498.     5528.     5558.     5588.     5618.     5648.
mid-points     5333.     5363.     5393.     5423.     5453.     5483.     5513.     5543.     5573.     5603.     5633.
(Years BP)
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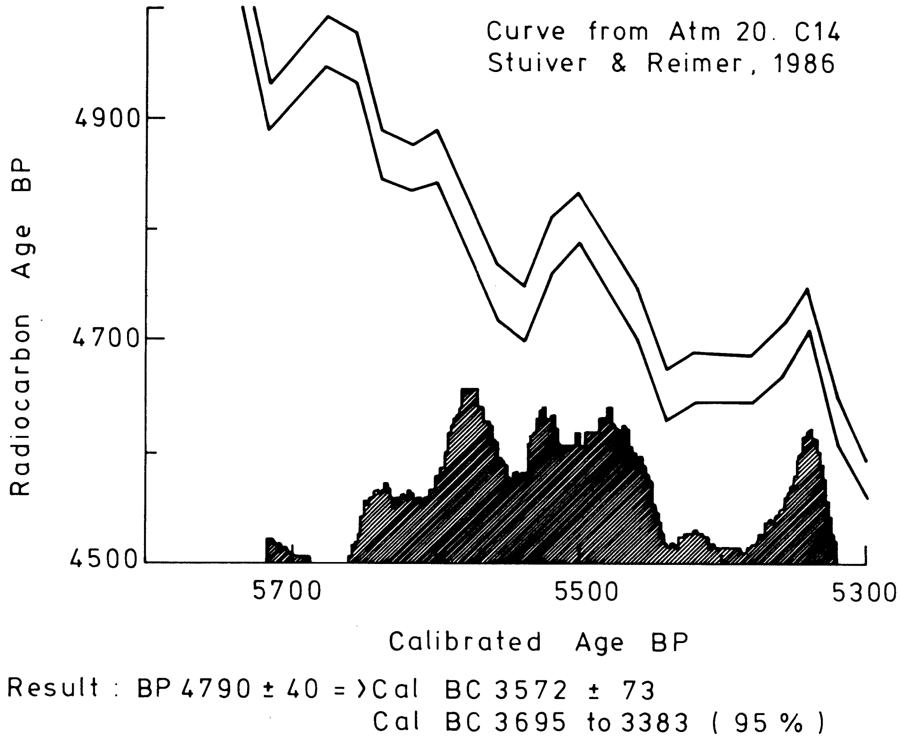

Fig 2. Graphic output for date A3 (Otlet)

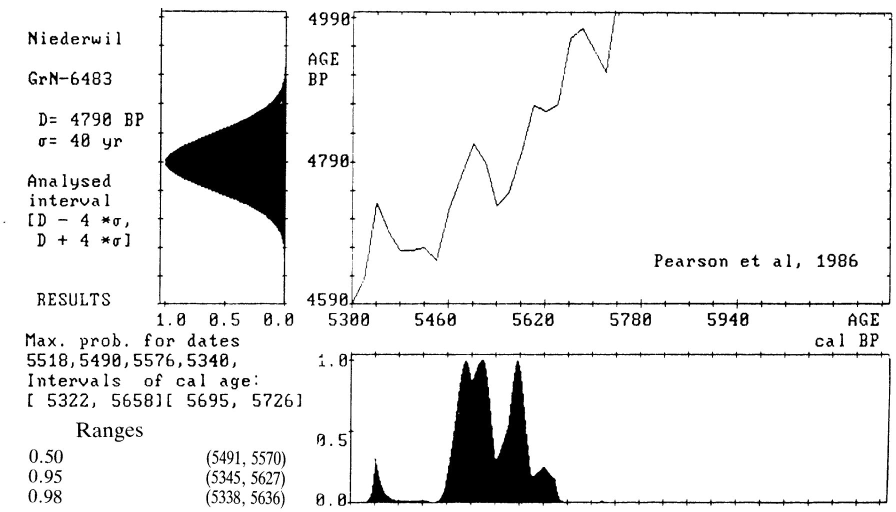

Fig 3. Graphic output for date A3 (Pazdur *et al*)

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Van der Plicht, Mook and Hasper also plot the probability distribution of the ^{14}C age and that of the calibrated age together with the relevant part of the calibration curve all on one graph. The same probability distribution is printed out on a second graph together with the cumulative probability. Thus, the approaches of Pazdur and van der Plicht are almost identical. The Groningen code has now been upgraded to include a third graph with the same calibrated probability distribution, analyzed at 68.3 and 95.4% confidence levels. The corresponding age ranges are printed out. (For more details, see van der Plicht & Mook, this issue).

Robinson's (Fig 4) graphic printout shows the probability distribution, in histogram form, of the calibrated age, with the relevant part of the calibration curve and indicates the point estimate computed as the centroid of the probability distribution. Stuiver and Reimer show the probability distribution indicating multiple ranges with the percent of the area under the curve for each range (Fig 5). Weninger plots the normalized and non-normalized probability distribution of the ^{14}C age and of the resulting calibrated age.

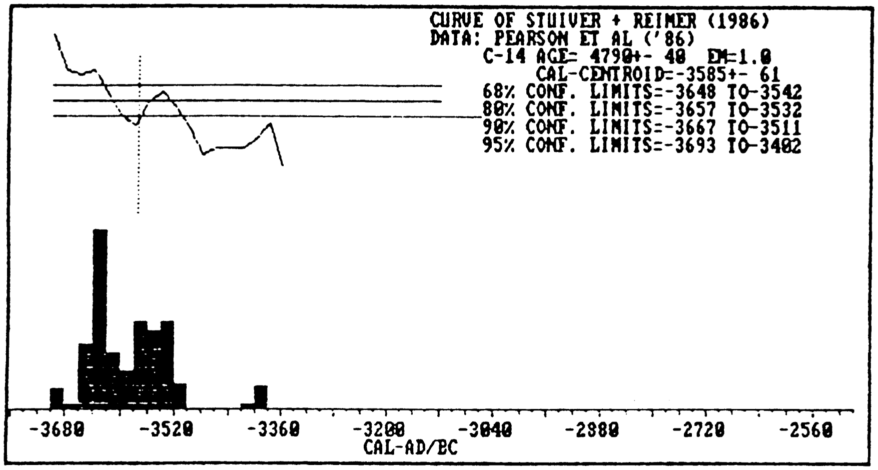

Fig 4. Graphic output for date A3 (Robinson)

Finally, Aitchison, Ottaway and Scott use the graphs from Pearson *et al* (1986) (Fig 6) to provide an appropriate confidence interval for the calibrated age with the width of the interval about the ^{14}C age determining the confidence probability. This method (Aitchison & Scott, 1987) requires no computing and can be carried out directly from the appropriate graph.

The underlying theory behind the calibration methods cannot be discussed in detail here. In summary, the approach of van der Plicht, Mook and Hasper (in press) is very close to that of Michczynska, Pazdur and Walanus (in press). Stuiver and Reimer's (1986) approach is somewhat similar to that of Leese (1988). Robinson (1986) ends up with only one range by excluding a percentage from either end of the calibrated distribution. Aitchison, Ottaway and Scott (in press) follow Ottaway's (1972) earlier simple approach. Otlet (pers commun) and Weninger (1986, 1987) have more individual styles.

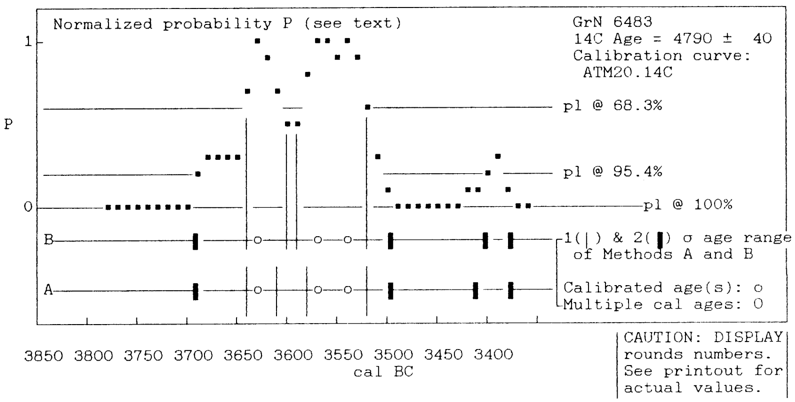

Fig 5. Graphic output for date A3 (Stuiver & Reimer)

There is a basic philosophical question about whether or not the probability associated with a particular ^{14}C activity within the total span should be divided between the several alternative real dates representing that activity. Reimer and Stuiver, Warner and Weninger think it should be divided, whereas van der Plicht and Pazdur do not. R Warner (pers commun) feels that until the underlying philosophy of that question is resolved, only range calibrations should be used. This opinion was not shared by most of the authors.

In an effort to compare directly the results of all the groups,we plotted the 68% confidence intervals of the calibrated ages in data set A as bars (Fig 7) (except Otlet & Walker, where the bar length is the range of $\pm 1\sigma$ of the transformed distribution).

Four of the 8 groups did not calibrate date A1 (7030±80 BP), since it was outside the range of Pearson *et al*'s curve. Results of all four groups (Fig 7.1) showed remarkable agreement; the largest variation is 29yr on the upper part of the scale and 47 on the lower part. Date A2 (Fig 7.2) had a very large error (±140yr). Consequently, the calibrated age intervals span 300–500yr and agreement was poor. Two groups were unable to calibrate this date, since the 99.7% range BP took them outside the limits of the present calibration curve.

Agreement on the calibrated age ranges of data A3 & A4 (Fig 7.3, 7.4) is excellent and does not vary more than a maximal 30yr at either end of the 68% confidence interval bar. Date A5 (2480±35 BP) (Fig 7.5) lies in a part of the calibration curve that is almost horizontal. Any small variation in the treatment of the error will thus be more noticeable, leading to a greater variation in the resulting calibrated age intervals. Consequently, the intervals vary by as much as 60 and 120yr, respectively, at the upper and lower part of the cal BC scale. Date A6 (Fig 7.6) again shows good agreement among the eight groups.

Thus, comparing the 68% confidence intervals for the individual dates in Data Set A, we find an overall agreement of the results. If we were to consider the scientifically more acceptable 95.7% confidence intervals,

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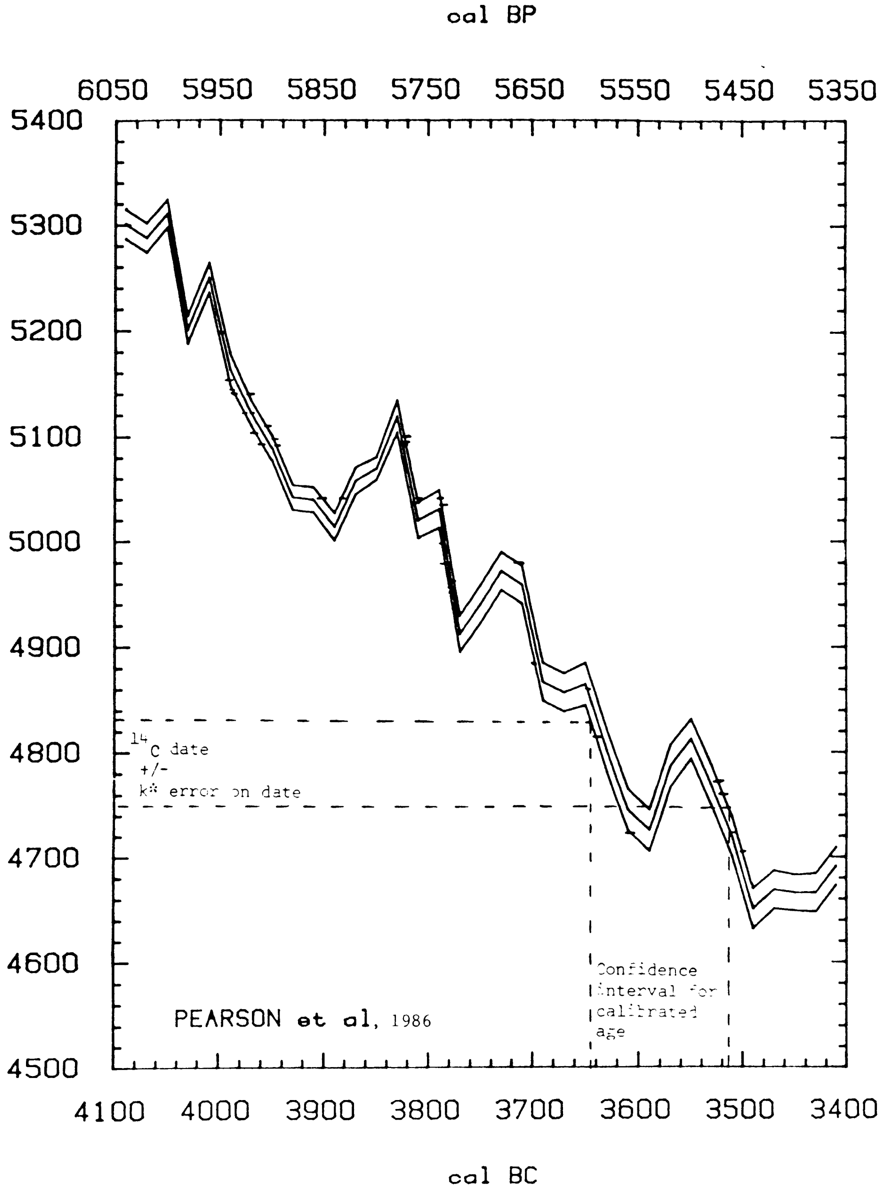

Fig 6. Graphic output for date A3 (Aitchison *et al*)

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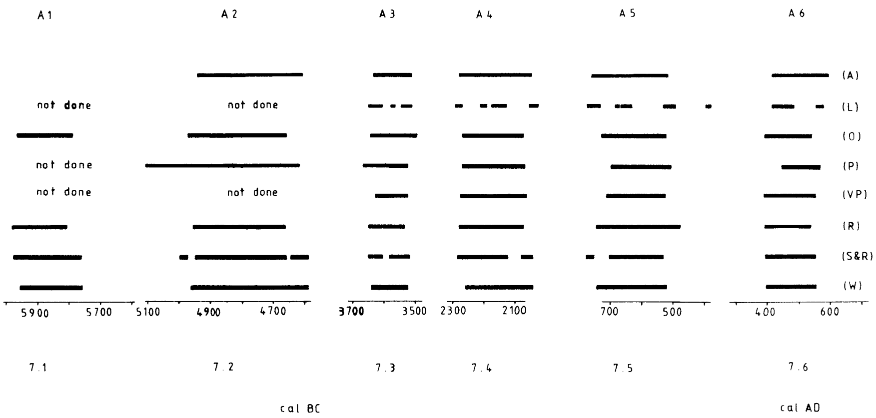

Fig 7. Summary of results for A3 (at 68% confidence): A – Aitchison *et al*; L – Leese; O – Otlet; P – Pazdur; VP – van der Plicht *et al*; R – Robinson; S & R – Stuiver & Reimer; W – Weninger

agreement is even better and the disjoint intervals merge into one continuous line.

Most of the eight groups used different methods of calibrating identical samples dated by different laboratories (Table 1, C1) and of counting replicates of homogenized samples (C2.1, C2.2). Most groups calculated either the weighted mean or the average of all dates in one batch before calibration (Robinson did this, although he did not actually give the results for these two groups of dates), thus achieving a better estimate of the true age. Two groups did not do this; their calibrated age spread over ca 250yr (Fig 8). Thus, when dealing with truly replicate dates, a common approach would be very desirable to ensure comparable results.

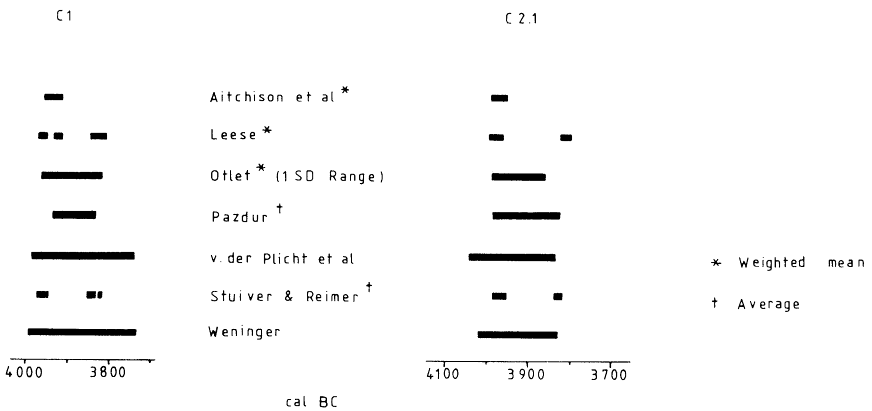

Fig 8. Summary of results for data C1 and C2.1 – homogenized replicates (at 68% confidence)

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Thus, we have agreement on calibrating single dates, *ie,* the intervals are approximately the same width. Stuiver, Reimer and Leese's results gave disjoint intervals. The van der Plicht *et al*, Pazdur and Stuiver and Reimer results have the added advantage of giving probabilities to each of the peaks within the calibrated interval.

There is also agreement on treatment of replicate dates, dating the same artifact, which after calculation of the weighted mean and SD, should be treated as a single value. Calculation of the weighted mean and its accompanying new standard deviation is only advised if the dates are genuine replicates, *ie,* the same object/sample. It is NOT advised for dates of material from one archaeological layer, context or horizon of dates.

Groups B1–B4 (Table 1) were included to deal with the problem of non-contemporaneous dates. These would be used to quantify duration of time and when combined with other data, might answer questions of contemporaneity of cultures.

Pazdur & Michczynska (1989), van der Plicht, (1988), Weninger (1987) and Aitchison, Ottaway and Scott (in press), have developed methods for calibrating such dates. The latter three authors felt that the comparison of the methods should be based on a single archaeologically meaningful quantity. The *floruit* (Ottaway, 1972), the period over which the middle 50% of all the culture's datable artifacts were produced, was chosen. Figure 9 shows the *floruit* and its mathematical definition: the period between the two quar-

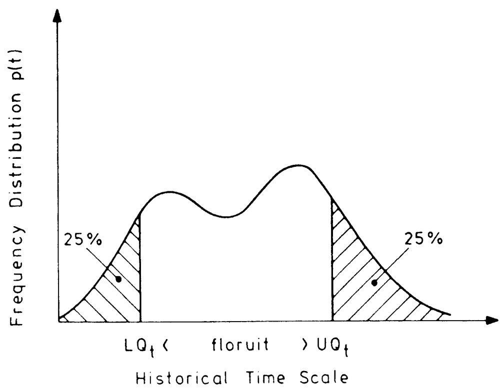

Fig 9. Graphic representation of a *floruit*

tiles of the frequency distribution of the culture's artifacts. A major assumption underlies our use of the sampled dates to estimate the *floruit,* namely, that the artifact sampling process provides us with a representative sample of the entire population of cultural artifacts.

Table 4 shows results of four groups of dates. Some participants did not return estimates of the *floruit* and point estimates had to be derived from the supplied information. In addition, Aitchison *et al* provided interval estimates for the *floruit*. Details of this approach are to appear soon.

TABLE 4

Results submitted for groups of non-contemporaneous ^{14}C dates

A. Point estimates of the *floruit*

		Weninger	Pazdur	Aitchison	van der Plicht
Group	B_1	4325–4009	4318–4056	4320–3925	–
	B_2	4132–3947	4130–3994	4030–3980	4140–3960
	B_3	3743–3529	3757–3520	3770–3560	3760–3550
	B_4	3054–2748	3000–2723	3010–2810	3020–2800

B. Interval estimates of the *floruit* (provided by Aitchison *et al*)

Group	B_1	4400	3780
	B_2	4045	3955
	B_3	3800	3500
	B_4	3075	2760

Resulting estimates are shown in Figure 10. Some differences in the results are apparent, particularly for series B2, which is due, in part, to a very small wiggle at the limit of the calibration limits for this series.

It is clear that further work is necessary in this area of archaeological interest to make available the techniques necessary to construct interval estimates for the *floruit* as well as to clarify and use the cultural frequency distribution.

CONCLUSIONS

In comparing eight methods of calibrating ^{14}C dates, we found reasonably good agreement between the methods in calibrating single dates. Genuine replicate dates gave equally good agreement, after calculation of the weighted mean and standard deviation and subsequent treatment as single dates. Series of ^{14}C dates pertaining to the duration of a period could only be meaningfully handled by four groups.

Further calibration work is needed to ensure a sound methodological base to deal with the remaining procedural and interpretational problems.

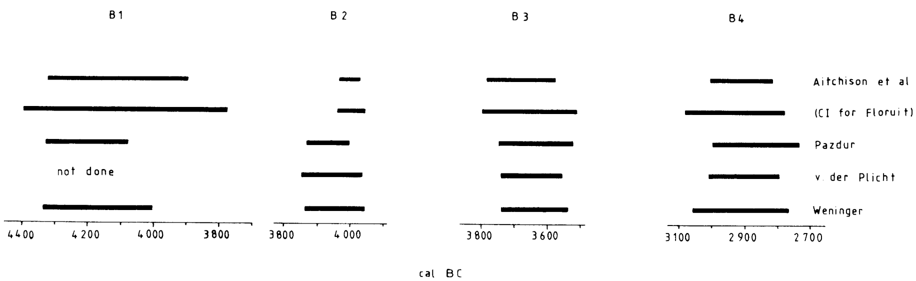

Fig 10. Presentation of results at 68% confidence for data sets B1–B4

https://doi.org/10.1017/S0033822200012479 Published online by Cambridge University Press

Many of the methods described here are being developed further. Stuiver and Reimer's program will be revised to include Aitchison *et al*'s strategy for series of dates and the calculation of weighted mean and standard deviation. Layouts and graphics will also be improved.

The general recommendation for presentation of calibrated dates from the ^{14}C laboratories to the archaeological users is a combination of graphs and ranges. The use of quoting a calibrated age as a mean and SD is recommended only if the graph on the absolute time scale shows an approximately Gaussian distribution.

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IV. APPLICATIONS

A. Hydrology
B. Geochronology and Paleoclimatology
C. Archaeology and Material Culture
D. Radiocarbon Data Base