[RADIOCARBON, VOL 29, NO. 2, 1987, P 169–175]

THE IMPACT OF BIOTURBATION ON AMS ^{14}C DATES ON HANDPICKED FORAMINIFERA: A STATISTICAL MODEL

MICHAEL ANDREE

Physics Institute, University of Berne, Switzerland

ABSTRACT. When single species of foraminifera picked from marine sediments are ^{14}C dated with Accelerator Mass Spectrometry (AMS), bioturbation puts limits on the minimal sample size to be used, as uncertainty is added to the result by statistics of the picking process. The model presented here simulates the additional statistical uncertainty introduced into the measurement by the coupling of bioturbation and small sample amounts. As there is no general solution for this problem, we present two simple cases only. The model can also be used to simulate more complicated situations occurring in sediments.

INTRODUCTION

With the advent of AMS it became possible to date much smaller amounts of sample material than with conventional decay-counting methods. In oceanography it became possible to ^{14}C date single species of foraminifera (Andrée *et al,* 1984). Applications are described by Broecker *et al* (1984) and Duplessy *et al* (1986). A problem with dating marine sediments originates from bioturbation, the mixing of the top few centimeters of the sediment by bottom dwelling organisms (Peng, Broecker & Berger, 1979; Berger & Killingley, 1982). The problem of statistic limitations to sampling of foraminifera has been demonstrated for chemical and stable isotope data by Boyle (1984). In this paper, the scatter introduced in radiocarbon dates by the combination of bioturbation with small sample amount is investigated.

THE PROBLEM OF SMALL SAMPLES

For AMS measurements, ca 10mg of carbonate (*ie,* a few hundred shells of a single foraminifera species) are needed. Depending on the weight of a shell, this amount of carbonate corresponds to 150 (eg, *P obliquiloculata*) to 700 (eg, *G ruber*) individual shells. If we assume homogeneous, infinitely rapid mixing of the sediment in the bioturbated layer, shells of all ages between 0 and ∞ years are, in principal, present in this layer. The number of particles of a given age will decrease exponentially with increasing age. The "decay" constant for this decrease is given by the ratio of accumulation rate to thickness of bioturbated layer. Figure 1 shows, for example, the distributions of simulated ages of single foraminifera shells for three different accumulation rates and a bioturbated layer thickness of 8cm each for constant abundance with time (Fig 1A) and for an abrupt abundance increase by a factor of five 10,000 years BP (Fig 1B). From this entity, a fraction is taken to determine the age. The question is how well the age of the fraction represents the age of the entity. With the model described below, a multiple sampling of a layer with a given age distribution can be simulated and the error of a single measurement can be estimated.

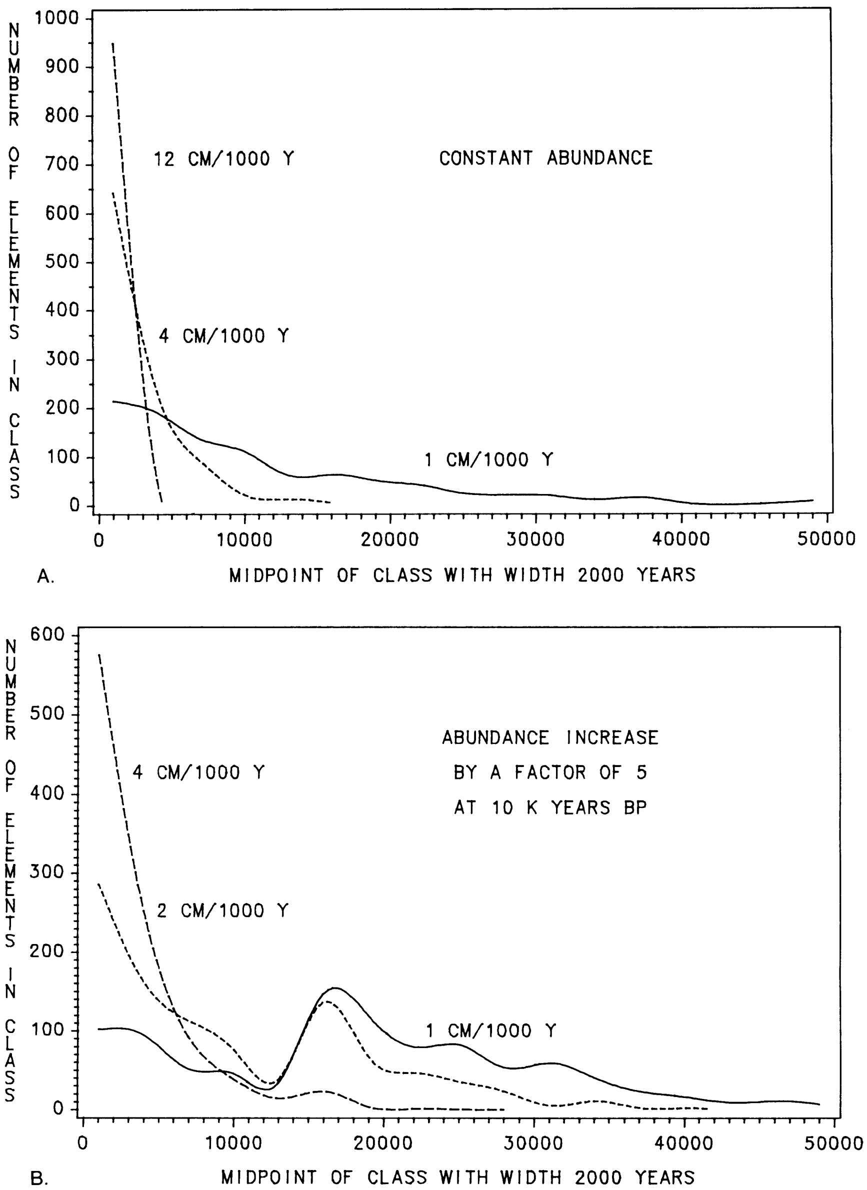

Fig 1. Distribution of simulated ages for three different accumulation rates: A. For constant abundance with time. B. For an abrupt change increasing the abundance by a factor of five before 10 ky BP.

THE STATISTICAL MODEL

The basic idea of the model is that the picking of a given number of shells from a given age distribution is simulated by random number generation.

The basic age distribution is exponential (Fig 1A) as required by the assumption of infinitely fast mixing in a reservoir with a given mean residence time of the particles, in this case, of the shells in the bioturbated layer. Slightly modified, the same model can also be applied to other tracers in sediments, eg, $\delta^{18}O$. This basic age distribution corresponds to constant abundance of a given species for all times. Then the mean age of the bioturbated layer can be calculated (Broecker & Peng, 1982):

$$t = -8033 \ln (1 + h/8.033A)$$

h is the thickness of the bioturbated layer in cm (in our case 8cm), A the accumulation rate in cm/ky and 8033 the e-folding time of radiocarbon.

The model can also be used when the abundance changes with time. In this case, changes can be defined by a discrete probability density function according to which FORTRAN library routines (IBM Numerical Algorithms Group MK10, 1983, routines G05EXF and G05EYF) select at random points from the basic exponential age distribution. An example of resulting age distributions is shown in Figure 1B.

The procedure followed by the program can be described by the following steps:

1a) Generation of random numbers according to a given probability density function.
1b) Summation of the first k_i of these random numbers according to the amount of shells needed for a given species. In this program, i allows for three different numbers per run.
1c) Calculation of the age and standard deviation defined by the sum of k_i random numbers.
2) Repetition of steps 1a to 1c 100 times and calculation of mean age and standard deviation of a single measurement from the 100 samples simulated for each species.

The printout lists all 100 individual mean ages with the asymmetric errors for all three species and the mean of the 100 measurements with the standard deviation of a single measurement.

RESULTS OF SIMULATIONS

For all simulation runs, a thickness of 8cm for the bioturbated layer was assumed. All model tests were done for two extremes of accumulation rate (1cm/ky and 12cm/ky) and all model runs additionally for the accumulation rates of 1.25, 1.6, 2.0, 2.5, 4, and 8cm/ky. These assumptions lead to mean residence times of particles in the bioturbated layer, *ie,* ratios of thickness of bioturbated layer to accumulation rate, between 8000 yr (accumulation rate 1cm/ky) and 667 yr (12cm/ky). Generalized, the results hold for all situations leading to the same mean residence times, eg, 8000 yr mean residence time is equivalent to a thickness of the bioturbated layer of

TABLE 1

Comparison of simulated bioturbated layer ages with analytically calculated ages for constant abundance

Mean residence time (yr)*	^{14}C age of bioturbated layer (yr): Calculated**	^{14}C age of bioturbated layer (yr): Modeled mean of repeated model runs	No. of model runs†
667	640	643 ± 4	18
1000	943	941 ± 4	3
2000	1786	1780 ± 9	3
3200	2694	2711 ± 6	3
4000	3246	3253 ± 12	18
5000	3887	3912 ± 6	3
6400	4707	4692 ± 14	3
8000	5552	5562 ± 21	21

* Ratio of thickness of bioturbated layer to accumulation rate
** Calculated with formula given in the text
† Each model run simulates the ages of $7 \cdot 10^5$ shells

TABLE 2

Reproducibility of simulated ages and errors for constant abundance

Run	150 shells mean age/error*		300 shells mean age/error*		700 shells mean age/error*	
Accumulation rate 1 cm/ky						
1	5547	354	5549	214	5532	173
2	5544	390	5566	274	5572	173
3	5566	343	5560	246	5564	172
4	5583	374	5579	269	5552	179
5	5571	371	5616	283	5596	188
6	5572	417	5547	275	5544	177
7	5531	359	5544	251	5562	193
Mean	5559	373	5566	259	5560	179
Error	19	25	25	24	21	8
Rel %	0.3	6.7	0.4	9.3	0.4	4.5
Accumulation rate 12 cm/ky						
Run	150 shells mean age/error*		300 shells mean age/error*		700 shells mean age/error*	
1	645	57	643	34	644	25
2	643	49	644	34	646	23
3	638	50	641	30	643	21
4	653	59	649	41	647	24
5	636	50	641	38	641	25
6	637	46	642	34	642	24
Mean	642	52	643	35	644	24
Error	7	5	3	4	2	2
Rel %	1.1	9.6	0.5	11.4	0.3	8.3

* Mean age of 100 simulations of the age of the bioturbated layer with standard deviation from the mean

10cm and an accumulation rate of 1.25cm/ky as well as the situation presented here for 8cm and 1.0cm/ky.

Test of the Model

First the validity and performance of the model had to be checked. For this, the case of constant abundance through time was chosen, as then the

TABLE 3
Simulated uncertainties in years for different numbers of shells and accumulation rates*

Number of shells	Accumulation rate in cm/ky							
	1.0	1.25	1.6	2.0	2.5	4.0	8.0	12.0
A. For constant abundance with time								
5							400	280
10							300	170
20							210	120
50	660	580	460	420	350	200	130	100
100	540	400	370	290	260	140	90	70
150	370	320	250	210	200	130	70	50
200	360	280	240	210	170	110	60	40
300	260	240	190	160	130	90	50	40
400	230	170	180	160	110	80	40	30
500	200	150	150	150	100	60	40	30
600	180	140	140	120	90	60	40	20
700	180	170	110	100	90	50	30	20
800	150	150	120	110	80	60	40	20
900	140	130	110	100	70	60	30	20
1000	140	130	110	90	60	50	30	20
B. For an abrupt increase in abundance by a factor of five before 10 ky BP								
5							560	480
10							420	330
20					510	370	320	230
30					440	320		
40					380	270		
50					450	270	200	100
100					350	230	140	90
150					270	170	120	70
200	500	430	350	320	170	100	70	50
300	460	350	340	250	110	90	40	40
400	370	310	240	210	120	70	40	30
500	330	260	240	190	110	60	40	30
600	330	270	210	200	80	60	30	30
700	270	240	210	160	90	50	40	20
800	260	220	200	150	80	50	30	20
900	270	220	170	160	70	50	30	20
1000	230	200	170	130	70	50	30	20
1240				120				
1500	170		130					
1600				110				
1900		130	120	100				
2000	150							
2300		110	110					
2500	130							
2700		110						

* The values are rounded. One has to keep in mind that the uncertainty of the simulation is ca 10% of the values given here.

mean age of the bioturbated layer for a given accumulation rate can be calculated using the formula given above. As can be seen in Table 1, the model reproduces the expected mean ages of the bioturbated layer. No trend that the modeled ages would be systematically older or younger than the calculated ones is observed. Multiple runs were performed to determine the reproducibility of the results given by the model. As shown in Table 2, the standard deviation of an age determination is reproduced within ca 10% accuracy.

Simulated Situations

For eight accumulation rates and shell numbers, between 5 and 2700 (Table 3), the additional statistical uncertainty introduced into the measurement was simulated for constant abundance with time (Table 3A) as well as for an abrupt change increasing the abundance by a factor of five before 10 kyr BP (Table 3B). It was assumed that all shells have the same weight, *ie,* contribute with the same weight to the mean. It would be easy to include uneven weights into this model.

The results in Table 3 show a wide range of uncertainty which can be up to one order of magnitude larger than the measurement error of the ^{14}C date itself in unfavorable cases. Comparing Tables 3A and 3B, the difference between the two cases becomes the more pronounced, the less shells are used for a date, and the smaller the accumulation rate becomes. This is easy to understand qualitatively; as Figure 1 shows, the occurrence of old

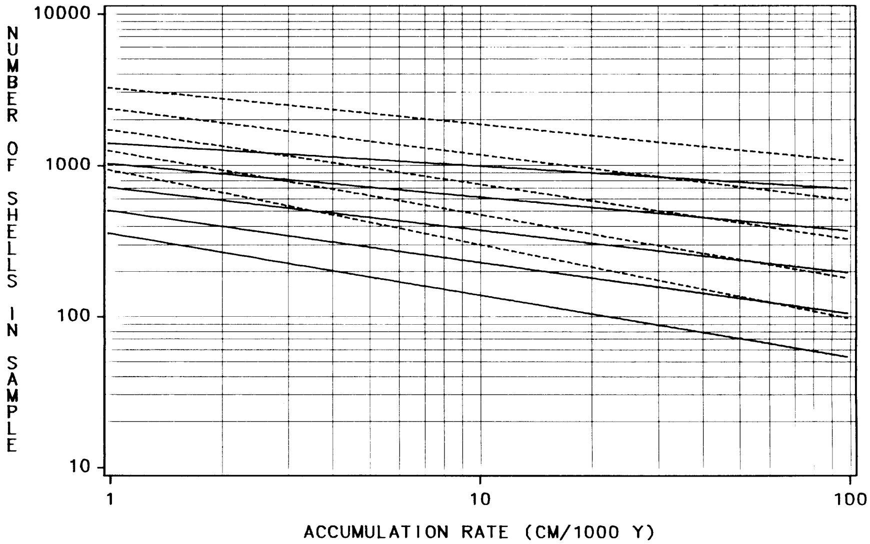

Fig 2. Plot of two sets of iso-standard deviation lines on a plot of the number of foraminifera shells per sample *vs* accumulation rate. Each set of lines indicates (from top to bottom) standard deviations of 50, 100, 150, 200, and 250 yr, respectively. A thickness of the bioturbated layer of 8cm is assumed (for generalization see text).
—— based on constant abundance with time.
----- based on an abrupt change increasing the abundance by a factor of five before 10 ky BP.

ages drops off very quickly for high accumulation rates; hence, an event in the old age tail of the age distribution is recorded only very weakly (*cf* the case of 4cm/ky accumulation, Figure 1A and 1B). On the other hand, this weak representation of the event is strong enough to show up as increased scatter when sampling only a few foraminifera shells. More detailed modeling shows that the influence on the age of the bioturbated layer becomes largest if the event occurs at the bottom of it, while the influence on the scatter in age determinations is largest if the event is placed at a depth of 1.6 times the bioturbated layer thickness.

In Figure 2 we try to summarize these results by plotting interpolated iso-uncertainty lines in a number of shells *vs* accumulation rate plot. If the accumulation rate is known and the allowable uncertainty chosen, the minimal number of shells needed can be determined.

CONCLUSION

As this work demonstrates, the interpretation of measurements on single foraminifera species is strongly affected by the sample picking strategy. For this reason, it is important to keep track of the numbers of foraminifera used for a measurement. As is evident, high accumulation rate cores are more favorable for such studies. Depending on the accumulation rate, the minimal number of shells to be picked per sample has to be estimated by modeling the deconvolved abundance trend (A C Mix, unpub model) in order to get this picking effect on the data under control. Thus, the planning of a study must include a reasonable compromise between the amount of material and work time available and the uncertainty in the results tolerable for the specific question.

ACKNOWLEDGMENTS

This work was supported by a NASA postdoctoral fellowship and the Swiss National Science Foundation. I would like to thank T Wenk and P Kalt for their help with computer problems and W S Broecker for his suggestions and comments on the manuscript.

REFERENCES

Andrée, M, Beer, J, Oeschger, H, Broecker, W S, Mix, A C, Ragano, N, O'Hara, P, Bonani, G, Hofmann, H J, Morenzoni, E, Nessi, M, Suter, M and Wölfli, W, 1984, ^{14}C measurements on foraminifera of deep sea core V28-238 and their preliminary interpretation: Nuclear Instruments & Methods, v 233, no. B5, p 340–345.

Berger, W H and Killingley, J S, 1982, Box cores from the equatorial Pacific: ^{14}C sedimentation rates and benthic mixing: Marine Geol, v 45, p 93–125.

Boyle, E A, 1984, Sampling statistic limitations on benthic foraminifera chemical and isotopic data: Marine Geol, v 58, p 213–224.

Broecker, W S, Mix, A C, Andrée, M and Oeschger, H, 1984, Radiocarbon measurements on coexisting benthic and planktic foraminifera shells: potential for reconstructing ocean ventilation times over the past 20,000 years: Nuclear Instruments & Methods, v 233, no. B5, p 331–339.

Broecker, W S and Peng, T H, 1982, Tracers in the sea: New York, Eldigio Press, p 489.

Duplessy, J C, Arnold, M, Maurice, P, Bard, E, Duprat, J and Moyes, J, 1986, Direct dating of the oxygen-isotope record of the last deglaciation by ^{14}C accelerator mass spectrometry: Nature, v 320, p 350–352.

Peng, T H, Broecker, W S and Berger, W H, 1979, Rates of benthic mixing in deep-sea sediment as determined by radioactive tracers: Quaternary Research, v 11, p 141–149.