Uppsala, Sweden
March 5, 2020

Dear Dr. Irka Hajdas,

Thank you for considering to allow us to submit a revised version of our manuscript and thanks to the referees for their input which has helped to improve the manuscript. Please find attached our updated manuscript, where we have completed the minor revisions that have been requested.

Overview of changes:

Figure 5 now shows four dynamic sediment scenarios with independent changes for the following dynamic parameters: **(1)** sediment accumulation rate (SAR), **(2)** bioturbation depth (BD), **(3)** species abundance; **(4)** reservoir age. These particular dynamic sediment scenarios use constant $\Delta^{14}C$ (instead of Marine13), so that the reader can independently judge the effect of the dynamic input parameters.

The introduction has been rewritten to incorporate "Background and Rationale" and "Experimental Design" subsections which help lay out the rationale behind the study and the unique strength in using 'best-case' scenarios for the goal of our study. This should help the readers to better understand the value of our modelling study.

After further feedback, legends have been added to the calibration plots in Fig 1, Fig 3 and Fig 5.

When evaluating the manuscript, you stated that the analytical blank (46806 ^{14}C yr) seemed too low when compared to laboratory blanks. While it is possible to apply a much lower blank (e.g. 50,000 or 55,000) within the model, the model we use explicitly simulates foraminifera in the time domain, and thus requires a realistic ^{14}C activity to be assigned to all single foraminifera that are generated for all time periods. Since we don't know what the ^{14}C activity is beyond the end of *Marine13,* it is in practice not possible to use an analytical blank beyond the limit of *Marine13* without guessing/inferring what the Earth's ^{14}C activities were for periods beyond the limit of the calibration curve. Since we prefer not to do that, we use an analytical blank that is equivalent to the lowest activity in *Marine13.* This reasoning was absent from the original manuscript, so it has now been fully explained in the method section of the new manuscript, which will greatly assist the reader. The analytical blank is only relevant when interpreting Fig. 4, so we have provided additional information in the text when discussing Fig. 4 about how it can be interpreted in the case of a laboratory blank of e.g. 50,000 or 55,000 (the same principles apply).

We have also carried out other, minor changes requested by the referees, such as re-running the simulations with a measurement error of 500 ^{14}C yr (instead of 200) for old samples close to the analytical blank.

A "track changes" version of the manuscript is also appended for your convenience. As this track changes file was auto-generated by the computer by comparing two docx files, it might overstate the level of changes somewhat. Apologies for that.

Thank you again for your interest in our manuscript.

Kind regards,

Bryan Lougheed

Re-evaluating ^{14}C dating accuracy in deep-sea sediment archives.

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Abstract

The current geochronological state-of-the-art for applying the radiocarbon (^{14}C) method to deep-sea sediment archives lacks key information on sediment bioturbation. Here, we apply a sediment accumulation model that simulates the sedimentation and bioturbation of millions of foraminifera, whereby realistic ^{14}C activities (i.e. from a ^{14}C calibration curve) are assigned to each single foraminifera based on its simulation timestep. We find that the normal distribution of ^{14}C age typically used to represent discrete-depth sediment intervals (based on the reported laboratory ^{14}C age and measurement error) is unlikely to be a faithful reflection of the actual ^{14}C age distribution for a specific depth interval. We also find that this deviation from the actual ^{14}C age distribution is greatly amplified during the calibration process. Specifically, we ~~We~~ find a systematic underestimation of total geochronological error in many cases (by up to thousands of years), as well as the generation of age-depth artefacts in downcore calibrated median age. Even ~~Specifically, we find that even~~ in the case of "perfect" simulated sediment archive scenarios, whereby sediment accumulation rate (SAR), bioturbation depth, reservoir age and species abundance are all kept constant, the ^{14}C dating and calibration process generates temporally dynamic median age-depth artefacts, on the order of hundreds of years – whereby ~~even in the case of~~ high SAR scenarios (~~of~~ 40 cm kyr~~ka~~$^{-1}$ and 60 cm kyr^{-1}) are not immune~~ka^{-1}~~. Such age-depth artefacts can be especially pronounced during periods corresponding to dynamic changes in the Earth's Δ^{14}C, when~~where~~ single foraminifera of varying ^{14}C activity can be incorporated into single discrete-depth sediment intervals. For certain lower ~~In certain~~ SAR scenarios, we find that downcore discrete-depth true median age can systematically fall outside ~~the 95.45%~~ calibrated age range predicted by the ^{14}C dating and calibration process, thus leading to systematically inaccurate age estimations. In short, our ~~. Our~~ findings suggest the possibility of ^{14}C-derived age-depth artefacts in the literature. Furthermore, since such ~~; since~~ age-depth artefacts are likely to coincide with large-scale changes in global Δ^{14}C, which themselves can coincide with large-

scale changes in global climate (such as the last deglaciation), ^{14}C-derived age-depth artefacts may have been previously incorrectly attributed ~~(partially) misinterpreted as due~~ to changes in SAR coinciding with global climate. Our study highlights the need for the development of improved deep-sea sediment ^{14}C calibration techniques that include an *a priori* representation of bioturbation for multi-specimen samples.

1.0 Introduction

1.1 Background and rationale

For over half a century, radiocarbon (^{14}C) dating has been applied to deep sea sediment archives. The material that is typically analysed from these archives consists of the calcareous tests of foraminifera. The minimum amount of material required for viable ^{14}C analysis has meant that researchers have had to pick tens to hundreds of individual foraminifera specimens (depending on specimen size) from a single discrete-depth core interval (typically 1 cm of core depth) and combine these into a single sample~~subsample~~ for analysis. Such multi-specimen samples are likely to be heterogeneous in ^{14}C activity~~age~~ (i.e. combine individual specimens of varying true age). The ^{14}C laboratory measurement (and reported machine error) applied to such an amalgamated multi-specimen sample will simply represent the mean ^{14}C activity of the total carbon of all individual specimens. Consequently, the true intra-sample ^{14}C age heterogeneity of a sample is concealed from the researcher. Failure to consider the actual ^{14}C age heterogeneity of multi-specimen samples can lead to downcore ^{14}C age artefacts when post-depositional processes mix foraminifera with differing ^{14}C activities, especially during periods coinciding with periods of dynamic Δ^{14}C history of the Earth. Furthermore, one must also take into consideration that younger specimens within a sample~~subsample~~ contribute exponentially more to the sample~~subsample~~'s mean ^{14}C activity than older specimens do, a process referred to as the isotope mass balance effect (Erlenkeuser, 1980; Keigwin and Guilderson, 2009), due to ^{14}C being a radioactive isotope (specimen ^{14}C activity decreases exponentially with the passing of time).

Systematic bioturbation has long been recognised as an inherent feature of deep-sea sediment archives (Bramlette and Bradley, 1942; Arrhenius, 1961; Olausson, 1961). Long-established mathematical models of bioturbation in deep-sea sediment archives consider the uppermost ~10 cm of a sediment archive to be uniformly mixed due to active bioturbation - the bioturbation depth (BD) (Berger and Heath, 1968; Berger and Johnson, 1978; Berger and Killingley, 1982). The presence of such a BD has been supported by the detection of a uniform mean age in the uppermost intervals of sediment archives (Peng et al., 1979; Trauth et al., 1997; Boudreau, 1998; Teal et al., 2008) and by the ^{14}C analysis of single foraminifera (Lougheed et al., 2018). The total range of single specimen ages mixed within the BD is dependent upon two main factors: the depth of the BD itself, and the sediment accumulation rate (SAR), both of which can exhibit spatiotemporal variation due to environmental and biological factors (Müller and Suess, 1979; Trauth et al., 1997). The presence of uniform mixing within the BD throughout the sedimentation history of a deep-sea sediment archive ultimately results, in the case of temporally constant SAR and BD, in the single specimen population of discrete sediment intervals being characterised by an exponential probability density function (PDF) for true age, with a maximum probability for younger ages and a long tail towards older ages. The existence of such a distribution has been supported by the post-depositional mixing of tephra layers (Bramlette and Bradley, 1942; Nayudu, 1964; Ruddiman and Glover, 1972; Abbott et al., 2018) and the smoothing out of the downcore mean signal (Guinasso and Schink, 1975; Pisias, 1983; Schiffelbein, 1984; Bard et al., 1987; Löwemark et al., 2008; Trauth, 2013), the smoothing of which can change downcore in tandem with foraminiferal abundance changes (Ruddiman et al., 1980; Peng and Broecker, 1984; Paull et al., 1991; Löwemark et al., 2008). If SAR, BD and the Δ^{14}C history of the planet~~Earth~~ were all to be temporally constant, then the idealised ^{14}C activity PDF of each discrete depth (expressed as, e.g., the ^{14}C/^{12}C ratio or normalised as fraction modern [F^{14}C]) would, therefore, exhibit the combination of two exponential functions (the exponential PDF of true age plus the exponential PDF of ^{14}C activity vs time predicted by the half-life of ^{14}C). However, the distribution of the ^{14}C activity PDF is made complicated by the fact that ^{14}C activity vs time is not always the exact exponential function that would be predicted by the radioactive half-life of ^{14}C, seeing as the Earth's carbon reservoir ~~-~~exhibits a dynamic Δ^{14}C history, as demonstrated by ~~-with~~ temporal changes in atmospheric ^{14}C activity (Suess, 1955, 1965; de Vries, 1958; Reimer et al., 2013). These changes are brought about by changes in ^{14}C production in the atmosphere in combination with climatic and oceanic influence upon the carbon cycle (Craig, 1957; Damon et al., 1978; Siegenthaler et al., 1980). Furthermore, non-uniform mixing of the oceans can contribute to temporal changes in local water ^{14}C activity at a given coring site, further affecting the idealised PDF shape.

When applying the ^{14}C method to sediment core material, researchers represent the ^{14}C activity of a discrete-depth interval using a normal (Gaussian) distribution, based on the conventional mean ^{14}C age (a reporting convention for ^{14}C activity) and measurement error reported by the ^{14}C laboratory (Stuiver and Polach, 1977). In some cases, this ^{14}C age normal distribution is widened by researchers to also incorporate a reservoir age uncertainty, but it remains a normal distribution. This normal distribution of ^{14}C age is subsequently calibrated using a suitable reference record of past Δ^{14}C (e.g. those produced by the *IntCal* group), allowing researchers to arrive at an estimation of the discrete depth interval's true (i.e. calendar) age. Such an approach inherently excludes the effects of bioturbation, because one would not expect a normal ^{14}C age distribution to be representative of a discrete depth interval, for the reasons described in the previous paragraph. Currently, systematic investigation is lacking into whether neglecting to include the effects of bioturbation has significant impact upon the interpretative accuracy of ^{14}C dating as it is currently applied in palaeoceanography, i.e. if it may ultimately lead to spurious geochronological interpretations.

1.2 Experimental design

Here, we we take advantage of computer modelling to construct an ideal experimental design whereby we can evaluate how the current ^{14}C state-of-the-art within palaeoceanography would work in the case of best-case sediment conditions. Such best-case conditions do not exist in in the field, meaning that a computer modelling environment can uniquely be used to create such a best-case scenario, which is ideal for testing the current state-of-the-art. We use the ~~When applying the ^{14}C method to sediment core material, researchers represent the ^{14}C age of a discrete-depth interval using a normal (Gaussian) distribution, based on the conventional mean ^{14}C age and measurement error reported by the ^{14}C laboratory (Stuiver and Polach, 1977). In some cases, this ^{14}C age normal distribution is widened by researchers to incorporate a reservoir age uncertainty, but it remains a normal distribution. This normal distribution of ^{14}C age is subsequently calibrated using a suitable reference record of past Δ^{14}C (e.g. those produced by the *IntCal* group), allowing researchers to arrive at an estimation of the discrete depth interval's true (i.e. calendar) age. Such an approach inherently excludes the effects of bioturbation, because one would not expect a normal ^{14}C age distribution to be representative of a discrete depth interval, for the reasons described in the previous paragraph. Currently, systematic investigation is lacking into whether neglecting to include the effects of bioturbation has significant impact upon the interpretative accuracy of ^{14}C dating as it is currently applied in palaeoceanography, i.e. if it may ultimately lead to spurious downcore geochronological interpretations or not. To investigate for the presence of such artefacts, we employed the~~ Δ^{14}C-enabled, single-specimen SEdiment AccuMUlation Simulator (SEAMUS) (Lougheed, 2020~~2019~~). This model uses the long-established~~a similar~~ understanding of bioturbation as included in existing bioturbation models (Trauth, 2013; Dolman and Laepple, 2018), but differs in that it explicitly simulates the accumulation and bioturbation of single foraminifera, each with individually assigned ^{14}C activities, to create a synthetic sediment archive history. Subsequently, current palaeoceanographic subsampling and ^{14}C dating practices are virtually applied to the 1 cm discrete-depth sediment intervals ~~depths~~ of the model's outputted synthetic archive, resulting in discrete-depth ^{14}C ages and calibrated ages that are representative of the existing palaeoceanographic state-of-the-art. These results are subsequently compared to the actual discrete-depth ~~^{14}C-calibrated age and~~ true age distributions within ~~predicted by~~ the model, allowing us to quantitatively evaluate contemporary palaeoceanographic ^{14}C dating and calibration techniques. By keeping multiple model input parameters constant, we can construct an experimental environment whereby we have full control over the degrees of freedom. This modelling approach allows us to test, at a most fundamental level, the accuracy of the current ^{14}C dating state-of-the-art as applied to deep-sea sediments.

2.0 Method

2.1 The synthetic core simulation

The SEAMUS model (Lougheed, 2020) synthesises *n* number of single foraminifera raining down from the water column per simulation timestep, whereby *n* is the capacity of the synthetic sediment archive being simulated (analogous to sediment core radius) scaled to the SAR of the timestep as predicted by an inputted age-depth relationship (Lougheed, 2020). To provide good statistics, all simulations use a timestep of 5 years and 10^4 synthetic foraminifera per cm core depth. An abundance of 10^4 specimens per cm is also similar to a best-case scenario value for a particular sample in the field (Broecker et al., 1992).

In each timestep, all newly created single foraminifera are assigned an age (corresponding to the timestep), a sediment depth (according to the age-depth input), as well as a ^{14}C age (in ^{14}C yr BP) and normalised ^{14}C activity (in F^{14}C) based on *Marine13* (Reimer et al., 2013) after the application of a prescribed reservoir age for the timestep. For older sections of the *Marine13* calibration curve, where only 10 year timesteps are available, linear interpolation is used to provide a 5 year ^{14}C activity timestep resolution. Within SEAMUS, all single foraminifera older than the oldest available age within the chosen calibration curve (in this case *Marine13*) are assigned the same ^{14}C activity: that of the analytical blank, which must be set in the simulation. In this way, the model incorporates the principles of ^{14}C dating, whereby individual very old foraminifera contained within a sample will contribute a ^{14}C signal equivalent to the analytical blank. Here, we choose to set the the simulation's analytical blank value to 46806 ^{14}C yr BP (more precisely the F^{14}C equivalent thereof), which corresponds to the lowest activity level in the *Marine13* calibration curve. The analytical blank activity in most laboratories is somewhat lower (e.g., >50000 ^{14}C yr BP), but we have no way of accurately applying an activity to single foraminifera older than the oldest value contained within *Marine13*. Rather than infer a Δ^{14}C history beyond the limit of *Marine13*, we simply set the analytical blank in our simulation to 46806 ^{14}C yr BP. In some scenarios we wish to investigate parameters within an experimental construct with temporally constant Δ^{14}C, and in such scenarios we assign ^{14}C activity (as F^{14}C) as follows: $F^{14}C(t) = e^{([t+R(t)] / -8267)}$, where t is the single foraminifera age in years before 1950 CE, and $R(t)$ is the reservoir age for age t.

~~The SEAMUS model (Lougheed, 2019) synthesises *n* number of single foraminifera raining down from the water column per simulation timestep, whereby *n* is the capacity of the synthetic sediment archive being simulated (analogous to core radius) scaled to the SAR of the timestep as predicted by an inputted age-depth relationship (Lougheed, 2019). To provide good statistics, all simulations use a timestep of 5 years and 10^4 synthetic foraminifera per cm core depth. An abundance of 10^4 specimens per cm is also similar to a best-case scenario value for a particular subsample in the field (Broecker et al., 1992). In each timestep, all newly created single foraminifera are assigned an age (corresponding to the timestep), a sediment depth (according to the age-depth input), as well as a ^{14}C age (in ^{14}C yr BP) and normalised ^{14}C activity (in F^{14}C) based on *Marine13* (Reimer et al., 2013) after the application of a prescribed reservoir age for the timestep. For older sections of the *Marine13*~~

~~calibration curve, where only 10 year timesteps are available, linear interpolation is used to provide a 5 year ^{14}C activity timestep resolution. The simulation uses a synthetic ^{14}C blank value corresponding to the lowest activity value in *Marine13* (46806 ^{14}C yr BP), i.e. any single foraminifera that are too old to be assigned a ^{14}C activity using *Marine13* are simply assigned a ^{14}C activity (in F^{14}C) corresponding to 46806 ^{14}C yr BP. As we are simulating a core with synthetic foraminifera and synthetic ^{14}C dates, we can essentially choose any blank value we desire, and the oldest value within *Marine13* is therefore appropriate. It is also a useful blank value because, in practice, it is not possible to correctly calibrate samples containing single specimens with ^{14}C ages older than those contained within the calibration curve.~~ After the creation of all new single foraminifera within the synthetic core for a specific timestep, bioturbation is simulated. Specifically, for each timestep the depth values corresponding to all simulated foraminifera within the contemporaneous BD are each assigned a new depth by way of uniform random sampling of the BD interval. In this way, uniform mixing of foraminifera within the BD is simulated following established understanding of bioturbation (Berger and Heath, 1968; Trauth, 2013). All of the aforementioned processes are repeated for every simulation timestep until such point that the end of the age-depth input (i.e. the final core top) is reached. All simulations are initiated at 70 ka (in true age) in order to confidently exclude the influence of model spin-up effects upon our period of interest (0 – 45 ka), given the possibility of a given cm of sediment to have a long-tail ~~(up to 20 ka, dependent on the scenario)~~ of older foraminifera specimens. While SEAMUS can in principle be run on a local machine, to save time multiple simulations were run in parallel on a computing cluster provided by the Swedish National Infrastructure for Computing (SNIC) at the Uppsala Multidisciplinary Centre for Advanced Computational Science (UPPMAX).

2.2 Virtual discrete-depth analysis

After the completion of the synthetic core simulation, synthetic foraminifera (and corresponding values for true age, F^{14}C, and ^{14}C age) are picked from each discrete 1 cm interval of the sediment core. In this study, we assume best-case scenarios where it is possible to pick all whole foraminifera contained within the sediment intervals. Subsequently, each of these picked 1 cm samples also undergoes a synthetic ^{14}C determination analogous to a perfect accelerator mass spectrometry (AMS) measurement, whereby it is assumed that the AMS determination perfectly reproduces the mean ^{14}C activity (in F^{14}C) of the sample. Within the discrete-depth subsampling simulation, this mean ^{14}C activity is calculated by taking the mean of all F^{14}C values of all the single foraminifera contained within the picked sample. As mentioned in Section 2.1, the analytical blank is already included when assigning ^{14}C to single foraminifera, meaning that the influence of the analytical blank upon sample AMS measurements is incorporated.

~~After the completion of the synthetic core simulation, synthetic foraminifera (and corresponding values for true age, F^{14}C, and ^{14}C age) are picked from each discrete 1 cm interval of the sediment~~

~~core. Subsequently, each of these picked 1 cm subsamples also undergoes a synthetic ^{14}C determination analogous to a perfect accelerator mass spectrometry (AMS) measurement, whereby the mean ^{14}C activity (in F^{14}C) for the entire subsample is calculated by taking the mean of all F^{14}C values of all the single foraminifera within the picked subsample. Using the Libby half-life, this mean F^{14}C value is also reported as a conventional ^{14}C age determination (in ^{14}C yr). All such synthetic determinations are assigned a synthetic 1σ measurement error analogous to a typical laboratory-reported counting error for a large sample. The prescribed synthetic measurement error ranges from 30 ^{14}C yr in the case of near-modern samples to 200 ^{14}C yr in the case of samples nearing the blank value, and is linearly scaled to F^{14}C, such that the error increases exponentially with ^{14}C age. Synthetic laboratory ^{14}C determinations and associated synthetic measurement uncertainties for each 1 cm slice are subsequently converted to calibrated years within SEAMUS using the embedded MatCal (v 2.5) ^{14}C calibration software (Lougheed and Obrochta, 2016), the Marine13 calibration curve (Reimer et al., 2013) and a prescribed reservoir age (according to the scenario – see following sections), to produce a calibrated age probability density function (PDF) for every cm core depth, i.e. analogous to what would be typically produced using contemporary palaeoceanography methods in the case of every discrete cm of core depth being ^{14}C dated.~~

Using the Libby half-life, a sample's mean F^{14}C value is also reported as a conventional ^{14}C age determination (in ^{14}C yr). All such synthetic determinations are assigned a synthetic 1σ measurement error analogous to a best-case scenario laboratory counting error for a large sample. The prescribed synthetic measurement error ranges from 30 ^{14}C yr in the case of near-modern samples to 500 ^{14}C yr in the case of samples nearing the blank value. Specifically, when assigning measurement errors to synthetic AMS determinations, a ^{14}C determination of 1.0 F^{14}C is assumed to have a measurement error of 30 ^{14}C yr, and a determination with the F^{14}C value $e^{(\mathrm{blankvalue}-1)/-8033}$ (i.e. one ^{14}C yr younger than the blank value) is assumed to have a measurement error of 500 ^{14}C yr. Errors (in ^{14}C yr) for intermediate dates are linearly interpolated to F^{14}C.

The synthetic laboratory ^{14}C determinations and associated measurement uncertainties for each 1 cm discrete-depth sample are subsequently converted to calibrated years within SEAMUS using the embedded MatCal (v 2.6) ^{14}C calibration software (Lougheed and Obrochta, 2016), the *Marine13* calibration curve (Reimer et al., 2013) and a prescribed reservoir age (according to the scenario – see following sections), to produce a calibrated age probability density function (PDF) and 95.4% highest posterior density (HPD) credible interval(s) for every cm core depth, i.e. analogous to what would be typically produced using contemporary palaeoceanography methods in the case of every discrete cm of core depth being exhaustively ^{14}C dated. The MatCal software calibrates ages in F^{14}C space, resulting in an accurate calibration, especially in the case of older samples or samples with large uncertainty.

3.0 Best-~~ ~~case scenario simulations

In order to investigate the baseline accuracy when applying ^{14}C dating to deep-sea sediment cores, the first simulations in this study consider a number of best-case scenarios~~‘best case scenarios’ under perfect conditions~~. Essentially, we seek to test how well the current application of ^{14}C within palaeoceanography would function in the case of such a best-case scenario, thus testing the current state-of-the-art at a most fundamental level~~a theoretical perfect sediment core at a location with perfect water conditions~~. In such ~~these ‘perfect’~~ simulations, we ~~therefore~~ assume that *Marine13* constitutes a perfect reconstruction of past surface-water ^{14}C activity at the synthetic core site, and we therefore employ a temporally constant reservoir age (ΔR = 0 ^{14}C yr). Furthermore, we assume a scenario involving synthetic sediment cores with temporally constant SAR and BD, and we also assume that the synthetic core is made up of a single planktonic foraminiferal species with a temporally constant abundance (10^{4} cm^{-1}) and specimen size. A total of five best case scenarios are carried out, with five different SAR scenarios (5, 10, 20, 40 and 60 cm kyr~~ka~~$^{-1}$). The BD is set to 10 cm in all cases, following established understanding of global BD (Trauth et al., 1997; Boudreau, 1998). In this scenario, we also assume perfection in sub-sampling, i.e. the possibility ~~in that it that it is possible~~ to exhaustively sample~~subsample~~ all foraminifera material from each 1 cm discrete-depth interval when picking for multi-specimen samples, thus excluding noise due to small sample sizes. The results of these five scenarios are visualised in Fig. 1 and Fig. S1-S5.

A second set of best-case scenarios takes into account that relatively older foraminifera contained within a given discrete depth of core sediment will have accumulated a longer residence time in the active bioturbation depth. Due to their longer residence time in the active bioturbation depth, these ~~These~~ foraminifera are more likely to be broken and/or partially dissolved (Rubin and Suess, 1955; Ericson et al., 1956; Emiliani and Milliman, 1966; Barker et al., 2007), and are thus less likely to be picked by palaeoceanographers who preferentially pick whole/unbroken foraminifera specimens for analysis. In this way, palaeoceanographers ~~palaeoceanographers may~~ exclude the oldest, least-well preserved fraction of the sediment. An indication of the BD residence time of single specimens for a given 1 cm discrete depth is shown in Fig. 2 for all five simulated SAR scenarios, along with the median and 90th percentile residence time. The percentage of broken specimens within the sediment archive is chiefly governed by the aforementioned BD residence time, bottom water chemistry (Bramlette, 1961; Berger, 1970; Parker and Berger, 1971), and the susceptibility of a particular foraminifera species to dissolution/breakage (Ruddiman and Heezen, 1967; Boltovskoy, 1991; Boltovskoy and Totah, 1992). Previous studies have indicated that the percentage of foraminifera exhibiting ~~foraminifera~~ test breakage for typically analysed species at locations above the lysocline can hover around 10% (Le and Shackleton, 1992). In the second set of best-case scenarios we, therefore, exclude from the picking process for each 1 cm discrete depth all foraminifera with a number of bioturbation cycles greater than the 90th percentile for that particular discrete depth. This broken foraminifera percentage of 10% is applied to all five SAR scenarios (5, 10, 20, 40, 60 cm kyr~~ka~~$^{-1}$) in a second set of best case scenarios, shown in Fig. 3 and Fig. S6-S10. One should be aware, however, that BD residence time likely varies with~~is likely directly related to~~ SAR itself: when sediment accumulation is slower, single specimens remain in the BD for relatively longer than in the case of faster SAR (Bramlette, 1961).

3.1 ^{14}C age artefacts

Radiocarbon analysis focuses on determining the mean ^{14}C activity of a particular sample, which is reported together with an associated analytical error. This mean activity of samples is often considered in the literature~~reported by the laboratory~~ as conventional ^{14}C age in ^{14}C yr BP. Conventional ^{14}C age, a unit of convenience, ~~^{14}C age~~ is linear vs time, whereas ^{14}C activity is actually exponential vs time, due to ^{14}C being a radioactive isotope. Therefore, with increasing age heterogeneity of a sample, we can expect increased ~~that the~~ offset between the ~~laboratory reported~~ AMS conventional ^{14}C age of a sample (the mean measured activity of the homogenised sample reported as conventional age) and the ~~to diverge from the~~ idealised mean of the conventional ^{14}C ages~~^{14}C age~~ of all single foraminifera~~specimens~~ within the sample. In Fig. 1, we compare the simulated AMS mean conventional ^{14}C age calculated for each discrete depth to the idealised mean ^{14}C age (based on the mean value of all single foraminifera conventional ^{14}C ages contained within a sample~~subsample~~). The resulting offset can help shed light upon how the measurement of age-heteregenous material is inherently biased towards younger (higher ^{14}C activity) specimens contained within the sample. We find that the AMS mean ^{14}C age is generally younger than the idealised mean ^{14}C age in all cases. This effect can be attributed to the fact that younger foraminifera within a heterogeneous sample~~subsample~~ contribute exponentially more to a sample~~subsample~~'s mean ^{14}C activity (what the measurement process is actually analysing) than older foraminifera do. This bias towards younger foraminifera is ~~much~~ most apparent in cases with large intra-sample heterogeneity, such as in scenarios with lower SAR (Fig. 1a), and is also reduced somewhat in the case of more broken foraminifera (Fig. 3a), due to~~resulting in~~ lesser older foraminifera being picked, thus reducing the age heterogeneity. In the case of the highest SAR scenarios (> 40 cm kyr~~ka~~$^{-1}$) the aforementioned bias is insignificant in a practical sense, in that it falls within the typical ^{14}C measurement error. For all scenarios, superimposed upon the general bias are artefacts of the Earth's dynamic Δ^{14}C history, caused by foraminifera from times of markedly differing Δ^{14}C to be mixed together into a single sample~~subsample~~, thus altering a sample~~subsample~~'s ^{14}C activity distribution and causing downcore dynamic offsets between AMS mean ^{14}C age and idealised mean ~~idealisedmean~~ ^{14}C age. The most pronounced example of these artefacts can be seen during known periods of dynamic Δ^{14}C, such as during the Laschamps geomagnetic event (ca. 40~41 ka) (Guillou et al., 2004; Laj et al., 2014), when a large spike in atmospheric ^{14}C production occurred (Muscheler et al., 2014). We note that our simulations assign single foraminifera ^{14}C activity using the *Marine13* calibration curve, while newer records of Δ^{14}C (Cheng et al., 2018) suggest that the Laschamps Δ^{14}C excursion may have been of greater magnitude than was previously thought. A larger excursion would generate even more pronounced ^{14}C artefacts in the downcore, multi-specimen, discrete-depth record. Furthermore, there may exist~~ of~~ as yet undiscovered, past short-lived excursions in Δ^{14}C (Miyake et al., 2012, 2017; Mekhaldi et al., 2015).

We can also visualise how well a sample's ^{14}C activity probability distribution function (PDF) is represented by a ~~^{14}C age normal~~ distribution based on its mean AMS-measured ^{14}C activity~~AMS mean ^{14}C age~~ and 1σ measurement error. This visualisation is shown on the vertical axes of Fig. 1d-i and Fig. 2d-i for a number of simulated discrete depths for the different SAR scenarios with a BD of 10 cm. It can be clearly seen that that the normal distribution derived from a sample~~subsample~~'s AMS mean measurement and associated~~^{14}C age and measurement~~ uncertainty is a poor representation of a sample~~subsample~~'s actual ^{14}C activity~~age distribution. In no cases, neither for high nor low SAR, does it correctly represent the true shape of the ^{14}C age~~ distribution.

3.2 Calibration amplifies ^{14}C age distribution mischaracterisation

When estimating a true age distribution for a particular sample, researchers calibrate a normal distribution of ^{14}C age using suitable calibration curve (in this case *Marine13*). As discussed in the previous section, the aforementioned normal distribution of ^{14}C activity derived from the measurement mean and machine error is not a faithful representation of the actual ^{14}C activity~~age~~ distribution for a particular discrete depth. Such a misrepresentation has the potential to be further amplified during the calibration process itself, potentially resulting in a poor estimation of a discrete depth's 95.4~~45~~% age range and/or median age, the latter of which is often used to calculate e.g. sedimentation rates, or represents the region of highest probability which will steer age-depth modelling routines. In Fig. 1b (0% broken foraminifera) and Fig. 3b (10% broken foraminifera), we show the offset between each discrete depth's true median age, and the corresponding median age derived from ^{14}C calibration process. We find large offsets for all constant SAR scenarios, ranging from ~200 years in the case of the the 60 cm kyr~~ka~~$^{-1}$ scenario, to up to ~700 years in the case of the 5 cm kyr~~ka~~$^{-1}$ scenario. In certain low SAR scenarios that coincide intervals of the calibration curve that are highly resolved (e.g. the late Holocene)~~scenarios~~, the discrete-depth true median age can consistently fall outside the 68.2~~95.45~~% age range predicted by the ^{14}C dating and calibration process. A 68.2~~~95~~% certainty suggests that, statistically, the true median will fall outside of the 68.2% calibrated age range in only 31.8~~~5~~% of cases, but in the case of the 5 cm kyr~~ka~~$^{-1}$ scenario (Fig. S1), the true median falls outside of the 68.2~~95.45~~% calibrated age range for 84~~43~~% of the discrete depths spanning the 5 to 0~~0 — 40~~ cal ka period. In the case of 10% broken foraminifera, this effect is reduced.~~the offsets are reduced slightly in the case of the lower SAR scenarios.~~

All offsets for all scenarios vary dynamically downcore, meaning that they can potentially cause spurious interpretations of changes in SAR. Furthermore, as these offsets occur during periods of dynamic Δ^{14}C, which can be caused by large-scale changes in the carbon cycle caused by climate shifts (such as during the last deglaciation), it is possible that some apparent changes in SAR in the palaeoceangraphic literature may have been erroneously attributed to climate processes, when they may be (partially) an artefact of the current application of ^{14}C dating and calibration within palaeoceanography.

Using the simulation output, it is also possible to quantitatively estimate how well the current ^{14}C dating and calibration state-of-the-art applied within palaeoceanography estimates the true age range contained within discrete-depth sediment intervals. The offset between the calibrated 95.4~~45~~% age range and the true 95.4~~45~~% age range for each discrete depth for all SAR scenarios is shown in Fig. 1c (0% broken foraminifera) and Fig. 3c (10% broken foraminifera) and is further visualised for all scenarios in Fig. S1-S10. For the lower SAR scenarios, the current application of ^{14}C dating within palaeoceanography significantly underestimates the total age range contained within each discrete-depth, by many thousands of years. The underestimation is less in the case of the scenario with 10% broken foraminifera. In the case of higher SAR scenarios, the discrete-depth 95.4~~45~~% age range predicted by the ^{14}C calibration process is similar to that of the discrete depth 95.4~~45~~% age range of the sediment itself. In some cases with very high SAR, the ^{14}C calibration process actually overestimates the 95.4~~45~~% age range (e.g. Fig. 1e, Fig. 3e, Fig. S5 and Fig. S10).

3.3 The influence of the analytical blank~~^{14}C-dead foraminifera~~

A general consequence of bioturbation and the subsequent mixing of single foraminifera specimens is that older foraminifera become systematically mixed upwards throughout the sedimentation history of a sediment archive. This general mixing can have a particular consequence near the analytical limit of the ^{14}C method, in that foraminifera with a ^{14}C activity~~age~~ that is lower than a laboratory's ~~beyond the~~ analytical sensitivity can become mixed into samples. ^{14}C determinations with a ^{14}C age that is older than the established ^{14}C blank value (i.e. they fall below the detection limit ~~the sensitivity~~ of the analytical process) are commonly referred to as "^{14}C-dead". Within older intervals of heterogeneous deep-sea sediment archives, it is possible that a ~~multi-specimen~~ sample with an apparent measured ^{14}C age ~~that is~~ younger than the ^{14}C blank value can already contain a significant proportion of ^{14}C-dead foraminifera. The presence of these ^{14}C-dead specimens within a sample will bias the sample's apparent measured ^{14}C age towards a too young value, because they will contribute a ^{14}C activity to the sample that is equivalent to the laboratory's analytical blank. Such artefactually young ^{14}C ages could ultimately erroneously be interpreted as age-depth features. In Table 1, the very first downcore occurrence of at least one simulated ^{14}C-dead foraminifer is detailed for each of the aforementioned constant SAR scenarios introduced in Section 3.0. In the case of low SAR scenarios with 0% broken foraminifera, ^{14}C-dead foraminifera are already present in discrete-depth samples with apparent AMS ages that would normally be considered well above the ^{14}C blank value, e.g. an apparent AMS age of 22647 ^{14}C yr BP in the case of 5 cm kyr~~ka~~$^{-1}$, and 33747 ^{14}C yr BP in the case of 10 cm kyr~~ka~~$^{-1}$. However, the contribution of ^{14}C-dead foraminifera at these levels may still be insignificant. The exact percentage contribution of ^{14}C-dead foraminifera to discrete depth AMS determinations is, therefore, detailed in Fig. 4a, 4c, 4e, 4g and 4i. From this analysis, it transpires that the first occurrence~~occurrence4~~ of at least 1% contribution of ^{14}C-dead foraminifera to discrete-depth AMS determinations occurs in the case of AMS ages of 39158 ^{14}C yr BP and 43601 ^{14}C yr BP, respectively for the 5 cm kyr~~ka~~$^{-1}$ and 10 cm kyr~~ka~~$^{-1}$ scenarios. The percentage increases quickly further downcore. In the case of scenarios involving 10% broken foraminifera, older foraminifera within discrete-depth sediment intervals are no longer whole, and therefore not picked for samples by a palaeoceanographer preferring whole specimens. The consequence of this effect is that the first occurrence of picked ^{14}C-dead whole foraminifera occurs much further downcore (Table 1, Fig. 4b, 4d, 4f, 4h and 4j). This finding further underlines the importance of understanding foraminifera preservation conditions for particular species and/or water chemistry, and the associated consequences for ^{14}C dating.

As motivated~~In the case of scenarios involving 10% broken foraminifera, older foraminifera within discrete-depth sediment intervals are no longer whole, and therefore not picked for subsamples by a palaeoceanographer preferring whole specimens. The consequence of this effect is the first occurrence of picked ^{14}C-dead whole foraminifera occurs much further downcore (Table 2, Fig. 4b, 4d, 4f, 4h and 4j). This finding further underlines the importance of understanding foraminifera preservation conditions for particular species and/or water chemistry, and the associated consequences for ^{14}C dating. As detailed~~ in the method section, for practical reasons we have set the ^{14}C analytical blank value at 46806 ^{14}C yr BP within our model simulations~~the model simulation~~. The laboratory blank value in most laboratories is around ~50000 ^{14}C yr BP, or even greater~~older~~, depending on sample size, preparation conditions and measurement capability~~ and preparation conditions~~. For such greater blank values~~a blank value~~, essentially the same curves~~functions~~ as shown in Fig. 4 would apply (i.e. assuming there are no as of yet undiscovered, large Δ^{14}C excursions around the period of the blank age), but shifted further to the right on the x-axis. In other words, researchers interested in interpreting Fig. 4 in the case of an analytical blank of 50000 ^{14}C yr BP should simply shift the curves to the right ~~(~~such that the 100% ^{14}C-dead contribution exactly coincides with 50000 ^{14}C yr BP on the x-axis~~)~~.

4.0 Dynamic sediment core scenarios~~scenario~~

The multiple sediment archive scenarios carried out in Section 3.0 all involved best-case input parameters with constant SAR. In Fig. 5, we carry out four scenarios to investigate the influence of stepwise changes in the following four input parameters: (1) SAR; (2) BD; (3) species abundance and; (4) reservoir age (ΔR). In each of the four scenarios, one of the aforementioned input parameters is varied at a certain time while the other three are kept constant (Figs. 5a-d). In this way, the influence of one of the dynamic input parameters can be independently judged. To further ensure the ability to independently judge the dynamic sediment input parameters, in these scenarios we do not employ a dynamic Δ^{14}C history using *Marine13*, but instead assign ^{14}C activities to foraminifera using a constant Δ^{14}C history (with an added constant 400 yr reservoir age). This constant Δ^{14}C history is assigned as detailed in the method (Section 2.1). For the calibration process, we also constructed a calibration curve with same aforementioned constant Δ^{14}C (also with an added constant 400 yr reservoir age), whereby the confidence interval sizes of *Marine13* are copied for incorporating a realistic calibration uncertainty. The scenario with dynamic ΔR (Fig. 5d) is simulated upon the foraminifera by additionally subtracting (ΔR = -100) or subtracting (ΔR = +100) to/from the ^{14}C age of simulated foraminifera respectively younger or older than 20 ka. During the simulated picking and calibration processes, it is assumed that the researcher is aware of the change in ΔR and applies a ΔR of -100 to all discrete depths shallower than 200 cm, and a ΔR of +100 to all discrete depths deeper than 200 cm.

The simulations using dynamic parameter inputs demonstrate that temporal changes in any of the four main input parameters (SAR, BD, species abundance, ΔR) can result in the generation of ^{14}C-induced age-depth artefacts in the discrete-depth domain, due to the median calibrated age dynamically deviating from the true median age downcore (Fig. 5f). We also note that the changes in the input parameters can cause the ^{14}C dating and calibration process to generate artefacts in the over- or underestimation of the true 95.4% age range of the sample by the calibration process, artefacts which are superimposed upon a long-term change in the underestimation of the true age range of the sample caused by a long term change in the confidence intervals in the calibration curve (Fig 5g). Specifically regarding ΔR, the current method for correcting for reservoir age during calibration, which we apply in this simulation, involves subtracting the ΔR from the the AMS date just prior to calibration. This method poses a particular challenge for periods near temporal changes in ΔR, where multi-specimen samples will incorporate single foraminifera with varying individual ΔR values. The blanket application of a single ΔR correction to the entire sample fails to adequately represent the ΔR heterogeneity of the foraminifera population.

The influence of the various dynamic parameters upon the ^{14}C dating and calibration process, as outlined in Fig. 5, represent further sources of age-depth bias in addition to the large biases caused by dynamic Δ^{14}C history previously outlined in Section 3.0. Furthermore, as has been detailed in previous studies, changes in abundance and bioturbation depth can in themselves also cause additional general age-depth artefacts, no matter what geochronological method is being used (independent of the ^{14}C method), (Bard, 2001; Löwemark and Grootes, 2004; Löwemark et al., 2008; Lougheed, 2020). Such effects can be seen in age-depth artefacts also visible in the true median age for the dynamic BD scenario (Fig. S12) and the dynamic abundance scenario (Fig. S13). Such artefacts occur in addition to the artefacts related to the ^{14}C dating and calibration process outlined in this study.

Researchers should be aware that periods of long-term climate change can cause many input parameters to change in concert. For example, the last deglaciation in the North Atlantic is known to be characterised by highly dynamic Δ^{14}C (Stuiver et al., 1986; Reimer et al., 2013), dynamic reservoir age (Austin et al., 1995; Waelbroeck et al., 2001; Butzin et al., 2020) and dynamic foraminiferal abundance (Ruddiman and McIntyre, 1981). It is possible that all of these parameters can combine at once to produce very large age-depth artefacts, which could lead to spurious interpretations regarding the relationship between, e.g., the last deglaciation and the perceived magnitude of associated SAR change.

~~The multiple sediment archive scenarios carried out in Section 3.0 all involved "perfect" input conditions with constant SAR. In Fig. 5, a scenario with dynamic inputs (Fig. 5a-d) for SAR and species abundance is considered. In this scenario, a sudden reduction in SAR (from 10 cm ka^{-1} to 5 cm ka^{-1}) and species abundance (from 50% abundance to 25% abundance) is inserted into the simulation at 11 ka. Reservoir age (ΔR) and BD are both kept constant, and a constant percentage of broken foraminifera of 10% is applied. The main consequence of such dynamic input is that, unlike the scenarios with constant input, the distribution for true age is no longer always a perfect exponential function (e.g. Fig. 5i and 5j). Specifically, changes in abundance and SAR can cause multi-modal true age population distributions for particular downcore discrete depths, which are not well captured by the calibrated age distribution resulting from the ^{14}C dating and calibration process (Fig. 5j). Furthermore, dynamic offsets between the true median age and calibrated median age occur around or near the change in SAR and abundance at 11 ka (Fig. 5f), meaning that the resulting ^{14}C-derived calibrated age-depth relationship doesn't correctly track the true age-depth relationship of the sediment archive simulation (Fig. S11). Finally, as is expected for a relatively low SAR scenario, the current palaeoceanographic geochronological state-of-the-art systematically underestimates the true age range of the sediment archive, with the underestimation being greater during the 5 cm ka^{-1} section of sediment archive than the 10 cm ka^{-1} section (Fig. 5f and S11).~~

5.0 Conclusion

This study demonstrates the possibility for the current ^{14}C dating and calibration method, as it is applied to multi-specimen samples within palaeoceanography, to produce age-depth artefacts, even in the case of best-case ~~theoretically perfect~~ sediment archives where SAR, BD, species abundance and reservoir age are all constant. We also find that high SAR sediment archives (40 cm kyr~~/ka~~$^{-1}$ and 60 cm kyr~~/ka~~$^{-1}$) are not immune to the generation of age-depth artefacts during the ^{14}C dating and calibration process. Additional age-depth artefacts can be generated in the case of real-world sediment archives where the aforementioned SAR, BD, species abundance and reservoir age processes are inherently dynamic. Researchers should be aware, therefore, of the possible existence of such artefacts when interpreting deep-sea sediment geochronologies developed using ^{14}C methods applied to multi-specimen samples. Key to understanding the possible existence of such artefacts is a good quantification of the possible magnitude of temporal change in both foraminiferal abundance and preservation conditions, as well as awareness of the possibility of changes in local ^{14}C activity due to the influcence of dynamic Δ^{14}C and reservoir age. It may also be necessary to revisit existing studies and re-evaluate the magnitude of changes in deep-sea sediment SAR inferred from ^{14}C-based geochronologies, especially close to periods of dynamic Δ^{14}C and/or dynamic foraminiferal abundance. These ^{14}C-specific artefacts should be considered in addition to previously highlighted general age-depth artefacts that can occur in sedimentary records~~We note that even δ^{18}O-based geochronologies (e.g., those developed using orbital tuning) are affected by temporal changes in foraminiferal abundance~~ (Bard, 2001; Löwemark and Grootes, 2004; Löwemark et al., 2008; Lougheed, 2020). One should also consider that paired analysis of mulispecimen samples for both ^{14}C and another proxy could lead to a signal offset between the two proxies due to the ^{14}C method, as currently applied within palaeoceanography, being prone to the generation of age artefacts as outlined in this study~~)~~.

6.0 Outlook and future research

We demonstrate that the failure to take into account the effect of bioturbation upon the (^{14}C) age distribution of foraminifera in multi-specimen samples sourced from deep-sea archives can lead to spurious age interpretations, especially during the ^{14}C calibration process. We propose, therefore, ~~propose~~ that the ^{14}C calibration process for deep-sea sediment archives could be improved in future studies through the development of a new ^{14}C calibration method including ~~to include~~ bioturbation *a priori*, seeing that no information regarding bioturbation is included in the current palaeoceanographic state-of-the-art~~ with regards to ^{14}C dating~~. This new approach would involve constructing a representative distribution for ^{14}C age that includes *a priori* information regarding the approximate SAR and BD of the sediment archive, while also taking into account some basic information regarding possible temporal changes in species abundance and ΔR. Such a future development ~~process~~ would go some way to providing more realistic uncertainties (i.e. 95.4~~45~~% age range) to ^{14}C-derived age-depth geochronologies in deep-sea sediment archives.

Finally, we note that increased automation and cost-effectiveness in ^{14}C analysis of ultra-small carbonate samples (Ruff et al., 2010; Lougheed et al., 2012; Wacker et al., 2013b, 2013a) can allow for the parallel measurement of δ^{18}O, δ^{13}O and ^{14}C on a single foraminifer of suitable size (Lougheed et al., 2018), thereby allowing for the extraction of both age and palaeoclimate data from single foraminifera~~foraminifer~~ in a manner that is independent of the sediment depth and bioturbation aspects~~depth aspect~~ of deep-sea sediment archives.

Author contributions

BCL carried out the model runs, with scenarios conceived with input from BM. BCL wrote the manuscript with input from the co-authors.

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First downcore occurrence of "^{14}C-dead" foraminifera

	0 % broken foraminifera scenario				*10% broken foraminifera scenario*			
	Discrete depth (cm)	*Median true age (yr)*	*AMS ^{14}C age (^{14}C yr BP)*	*Median ^{14}C calibrated age (cal yr BP)*	*Discrete depth (cm)*	*Median true age (yr)*	*AMS ^{14}C age (^{14}C yr BP)*	*Median ^{14}C calibrated age (cal yr BP)*
SAR 5 cm kyr^{-1} *BD 10 cm*	133-134	26110	22647	26493	237-238	46690	44096	46833
SAR 10 cm kyr^{-1} *BD 10 cm*	375-376	37250	33747	37654	486-487	48260	45422	48396
SAR 20 cm kyr^{-1} *BD 10 cm*	900-901	44855	41973	45002	986-987	49125	46090	49186
SAR 40 cm kyr^{-1} *BD 10 cm*	1894-1895	47285	44582	47383	1987-1988	49585	46455	49544
SAR 60 cm kyr^{-1} *BD 10 cm*	2866-2867	47725	44912	47775	2986-2987	49710	46556	49621

~~**First downcore occurrence of ^{14}C-dead foraminifera**~~

	~~*0 % broken foraminifera scenario*~~				~~*10% broken foraminifera scenario*~~			
	~~*Discrete depth (cm)*~~	~~*Median true age (yr)*~~	~~*AMS ^{14}C age (^{14}C yr BP)*~~	~~*Median ^{14}C calibrated age (cal yr BP)*~~	~~*Discrete depth (cm)*~~	~~*Median true age (yr)*~~	~~*AMS ^{14}C age (^{14}C yr BP)*~~	~~*Median ^{14}C calibrated age (cal yr BP)*~~
~~*SAR 5 cm ka^{-1}*~~ ~~*BD 10 cm*~~	~~133-134~~	~~26110~~	~~22647~~	~~26493~~	~~237-238~~	~~46690~~	~~44096~~	~~46833~~
~~*SAR 10 cm ka^{-1}*~~ ~~*BD 10 cm*~~	~~375-376~~	~~37250~~	~~33747~~	~~37654~~	~~486-487~~	~~48260~~	~~45422~~	~~48396~~
~~*SAR 20 cm ka^{-1}*~~ ~~*BD 10 cm*~~	~~900-901~~	~~44855~~	~~41973~~	~~45002~~	~~986-987~~	~~49125~~	~~46090~~	~~49186~~
~~*SAR 40 cm ka^{-1}*~~ ~~*BD 10 cm*~~	~~1894-1895~~	~~47285~~	~~44582~~	~~47383~~	~~1987-1988~~	~~49585~~	~~46455~~	~~49544~~
~~*SAR 60 cm ka^{-1}*~~	~~2866-2867~~	~~47725~~	~~44912~~	~~47775~~	~~2986-2987~~	~~49710~~	~~46556~~	~~49621~~

~~*BD 10 cm*~~								

Table 1. The first downcore discrete-depth where “^{14}C-dead whole” foraminifera occur (i.e. $n_{dead} \geq 1$) for the various constant SAR and broken foraminifera scenarios discussed in Section 3 of ~~simulated in~~ this study. Also shown are the simulated median true ages, AMS ^{14}C ages and median ^{14}C calibrated ages corresponding to the discrete depth. The simulation analytical blank value is set at 46806 ^{14}C yr BP (see Section 2.1), thus any single foraminifera with a ^{14}C age older than that blank value are assumed “^{14}C-dead”~~^{14}C-dead~~.