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Climate of the Past Discussions

Moving beyond the age-depth model paradigm in deep sea palaeoclimate archives: dual radiocarbon and stable isotope analysis on single foraminifera.

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Abstract. Late-glacial palaeoclimate reconstructions from deep-sea sediment archives provide valuable insight into past rapid changes in ocean chemistry, but only a small proportion of the ocean floor is suitable for such reconstructions using the existing state-of-the-art using the age-depth approach. We employ ultra-small radiocarbon (^{14}C) dating on single microscopic foraminifera to demonstrate that the longstanding age-depth method conceals large age uncertainty caused by post-depositional sediment mixing, meaning that existing studies may underestimate total geochronological error. To overcome these problems, we use dual ^{14}C and stable isotope ($\delta^{18}O$ and $\delta^{13}C$) analysis on single microscopic foraminifera to produce a palaeoclimate time series independent of the age-depth paradigm. This new and novel method will address large geographical gaps in late-glacial benthic palaeoceanographic reconstructions by opening up vast areas of previously disregarded deep-sea archives, leading to improved understanding of the global interaction between oceans and climate.

1 Introduction

The past seven decades in palaeoceanography research have produced a wealth of valuable palaeoclimate data from the calcareous, foraminiferal ooze contained in deep sea sediment archives, greatly improving our understanding of past ocean chemistry and palaeoclimate (Bond et al., 1993; Emiliani, 1955; Shackleton, 1967). The longstanding geochronological state-of-the-art that has been applied to these sediment archives since the inception of palaeoceanography as a field of study, the *age-depth model* method, relies on the geological law of superposition. This law states that sediment age increases progressively with sediment core depth. The method involves first slicing deep sea sediment cores into discrete core depth intervals of 1 cm thickness or greater. Sufficient numbers of suitable foraminifera tests are subsequently picked from select intervals and analysed using mass spectrometry with ages being inferred using ^{14}C dating and/or orbital tuning (Martinson et al., 1987; Pisias et al., 1984) of $\delta^{18}O$ values. Finally, statistical methods (Blaauw and Christen, 2011; Bronk Ramsey, 2008) are used to interpolate ages for all discrete depth intervals of the sediment core.

Post-depositional sediment mixing (PDSM) of deep sea archives (due to, e.g., bioturbation) can cause the relationship between sediment core age and sediment core depth to become more complex. This complexity can be masked from researchers because, up until now, successful stable isotope ratio mass spectrometry (IRMS) or ^{14}C accelerated mass spectrometry (AMS) analysis has required the analysis multi-specimen samples containing tens (Metcalfe et al., 2015; Waelbroeck et al., 2005) and hundreds (Hughen et al., 2006) of single foraminifera tests, respectively. IRMS and AMS analyses only report a mean sample value and a machine measurement error, meaning that no information is provided about the true age uncertainty of a discrete depth interval, which is a function of both sediment accumulation rate (SAR) and PDSM. Subsequently, high resolution sampling of core depth does not necessarily translate into high resolution sampling of time. Researchers are aware that the concealment of intra-sample age heterogeneity can pose problems for the age-depth model method (Bard, 2001; Keigwin and Gagnon, 2015; Löwemark and Grootes, 2004; Löwemark and Werner, 2001; Pisias, 1983; Ruddiman and Glover, 1972), which can potentially lead to incorrect interpretation of temporal climate offsets, or apparent ^{14}C age offsets between different species and/or sizes of foraminifera that are, in fact, an artefact of PDSM (Löwemark et al., 2008; Löwemark and Grootes, 2004). With these problems in mind, researchers seeking to reconstruct rapid (i.e. sub-millennial and centennial) climate processes have concentrated on sediment archives with a SAR greater than 10 cm/ka (Hodell et al., 2015; Shackleton et al., 2000; Vautravers and Shackleton, 2006), with the assumption that high SAR minimises the effects of PDSM upon age-depth models. However, the inability to quantify intra-sample age heterogeneity means that this assumption has yet to be rigorously tested. Moreover, the vast majority of the ocean floor exhibits a SAR of less than 10 cm/ka (Fig. 1), meaning that many potentially useful study sites above the calcite compensation depth are essentially rendered unusable by the longstanding geochronological state-of-the-art. Concentrating only on these select parts of the ocean floor with high SAR introduces a geographical bias into our understanding of global ocean processes.

In this study, we utilise the latest developments in ultra-small (<100 μg $CaCO_3$) sample ^{14}C dating (Synal et al., 2007; Wacker et al., 2013a, 2013b, 2013c) to reduce sample size to a single benthic foraminifer specimen (*Cibicidoides wuellerstorfi*), thereby allowing us to directly quantify intra-sample age heterogeneity and statistically analyse PDSM in the case of the low SAR (~2 cm/ka) sediment core T86-10P from the Azores region of the North Atlantic (Fig. 1). We discuss the consequences of our results for existing studies and provide a framework for adding realistic geochronological errors to existing deep sea palaeoclimate records that have applied the longstanding age-depth model method. Furthermore, we analyse both ^{14}C and stable isotopes on select single foraminifer tests of sufficient mass, demonstrating the possibility to construct palaeoclimate time series that are independent of the age-depth paradigm and its associated problems, thereby opening up vast, low SAR regions of the ocean to late-glacial palaeoceanography research, which will lead to a more integrated global picture of ocean ventilation and water mass reorganisation processes during the last deglaciation, a period of rapid climate change.

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2 Method

2.1 Sediment core retrieval and subsampling

Sediment core T86-10P (Fig. 1) was retrieved from the North Atlantic (37° 8.13' N, 29° 59.15' W, 2610 mbsl) by the vessel R/V *Tyro* as part of the APNAP-I project. We chose core T86-10P for this study because preliminary oxygen isotope measurements on planktonic foraminifera indicated the possible presence of significant PDSM. 185 single specimen benthic foraminifera tests (*Cibicidoides wuellerstorfi*) ranging between 25 and 500 μg in mass were retrieved from the >250 μm fraction of 1 cm slices of the sediment core material. Care was taken to pick whole tests that had not been subjected to dissolution. Of these 185 tests, 100 were measured for stable isotopes only ($\delta^{18}O$ and $\delta^{13}C$) and 49 measured for ^{14}C only, while 36 tests of sufficient mass were successfully analysed for both ^{14}C and stable isotopes. These 36 tests were cut using a scalpel (future work may use more efficient gaseous splitting) according to an approximate 80/20 ratio, with the larger fraction being reserved for ^{14}C AMS analysis and the smaller fraction being reserved for stable isotope IRMS analysis. All data are available in spreadsheet format in Table S1.

2.2 ^{14}C analysis

AMS analysis was carried out at the Laboratory for Ion Beam Physics at ETH Zürich using a permanent magnet equipped *Mini Carbon Dating System* (MICADAS) AMS (Synal et al., 2007) with Helium stripping system coupled to an *Ionplus* carbonate handling system (Wacker et al., 2013a). The MICADAS setup allows for direct ^{14}C measurement, using a gas ion source (Wacker et al., 2013b), of gaseous CO_2 liberated from $CaCO_3$ samples by acidification with phosphoric acid – i.e. no graphitisation step is necessary. The exclusion of the graphitisation step allows for the required sample mass to be reduced down to 100 μg of $CaCO_3$ (12 μg C) and less (Lougheed et al., 2012; Wacker et al., 2013c), enabling sample size to be reduced to one specimen in the case of a suitable foraminifera species and specimen. Procedural single specimen foraminifera blank samples (assumed Eemian age) from core T86-10P indicated an average blank value of 0.0115 $F^{14}C$ (n=10). Procedural IAEA-C1 standard blank material of similar mass as the single foraminifera tests yielded an average blank value of 0.0100 $F^{14}C$ (n=10). Reported ^{14}C ages (Table S1) are rounded following standard conventions (Stuiver and Polach, 1977). Our small single specimen tests are slightly more susceptible to the influence of secondary carbonate phases, because pre-treatment was often not possible on such small samples. To control for this effect, select single specimens (n=5) of sufficient size were ^{14}C analysed for both an initial phosphoric acid leach fraction and the residual foraminifer fraction. Of these five specimens, three specimens yielded leach and residual ^{14}C ages that were not significantly different within 1σ, a fourth specimen was not significantly different within 2σ (the fifth was specimen not significantly different within 2.1σ)

Benthic *C. wuellerstorfi* ^{14}C ages were calibrated using *MatCal 2.2* (Lougheed and Obrochta, 2016), employing the *Marine13* (Reimer and et al., 2013) ^{14}C calibration curve and an appropriate marine reservoir age (ΔR=35±290 ^{14}C yr), the latter of which was calculated as follows: Previous studies in this region using planktonic foraminifera have employed the standard marine calibration curve (i.e. ΔR=0), but the possibility of spatiotemporally dynamic ΔR for the Azores region has

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been alluded to previously (Schwab et al., 2012; Waelbroeck et al., 2001). We are aware of the potential uncertainties associated with ΔR, so we employ a planktonic ΔR with a large uncertainty: 0±200 ^{14}C yr. Seeing as we carried out our investigation upon benthic foraminifera, we must additionally take into account the possibility that benthic ΔR may be different from that of the surface mixed layer. Using available data from a nearby sediment core archive from the Azores region (MD08-3180) (Sarnthein et al., 2015), we analyse ^{14}C determinations from a late-glacial sequence of co-occurring benthic and planktonic foraminifera (S1 and Fig. S1). We find that the long-term (7 ka) average ^{14}C age difference between the planktonic and benthic foraminifera is 35±210 ^{14}C yr, suggesting that there is only a small absolute difference between benthic and planktonic ^{14}C ages in this region, but with considerable variation. We arrive at our final benthic ΔR by correcting our planktonic ΔR (0±200 ^{14}C yr) for the benthic offset (35±210 ^{14}C yr) with error propagation, resulting in a final ΔR of 35±290 ^{14}C yr.

2.3 Stable isotope analysis

IRMS analysis on the smaller foraminifera test fractions from the cut tests (as well as some whole tests) was carried out at the stable isotope laboratory of the Department of Earth Science, University of Bergen, using a *Kiel IV* carbonate device coupled to a *Thermo MAT-253* dual inlet IRMS. The use of a dual-inlet IMRS, as opposed to a continuous flow mass spectrometer, leads to a reduced size difference between sample and standard gas, combined with a continuous switching between standard and sample gas, which enables a higher analytical precision. Procedural standard samples (Carrara marble powder) of representative mass indicated an external precision (1σ) better than 0.10 ‰ and 0.05 ‰ for δ^{18}O and δ^{13}C, respectively. Additional whole tests were analysed using a *GasBench II* preparation device coupled to a continuous flow *Thermo Delta+* mass spectrometer at the Department of Earth Sciences, Vrije Universiteit Amsterdam. For these measurements, the external precision (1σ) of international standards was better than 0.12 ‰ for both δ^{18}O and δ^{13}C (Feldmeijer et al., 2015; Metcalfe et al., 2015). All IRMS measurements are reported in per mil (‰) against the Vienna Peedee Belemnite (V-PDB) scale.

3 Results and Discussion

3.1 Age uncertainties concealed by the current state-of-the-art

^{14}C analysis carried out on 85 single specimen foraminifera tests for core T86-10P (Fig. 2A, Table S1) indicate the presence of significant PDSM, with the average standard deviation for all discrete 1 cm core depth intervals containing three or more ^{14}C dates being 4670 ^{14}C yr. We show that such significant PDSM can be concealed by the current geochronological state-of-the-art, by imitating the longstanding age-depth model approach involving multi-specimen samples. To achieve this, we average all uncalibrated single specimen ^{14}C data from discrete depths with three or more measured single specimens into pseudo multi-specimen ^{14}C dates with an uncertainty of 60 ^{14}C yr (a typical AMS machine error for larger samples). We subsequently calibrate these pseudo multi-specimen dates and produce a Bayesian age-depth model for core T86-10P (Fig.

2B) using the *Bacon* software (Blaauw and Christen, 2011). Considering the large intra-sample heterogeneity present in core T86-10P, our pseudo multi-specimen Bayesian age-depth model exhibits unrealistically well-constrained confidence intervals, thus concealing the true age-depth variation present within core T86-10P. Additionally, the Bayesian age-depth modelling routine excludes a number of pseudo multi-specimen dates as outliers. Rather than being regarded as outliers, we propose that downcore multi-specimen ^{14}C dates in non-sequential temporal order may actually serve as useful indicators for the presence of significant PDSM throughout an entire sediment sequence.

While core T86-10P may not be representative of all sediment cores, the fact that very large intra-sample age heterogeneity can be concealed by the longstanding geochronological state-of-the-art has significant implications for existing studies relying on the age-depth model method. We note that our pseudo multi-specimen ^{14}C dates were assembled using data from an average of four foraminifera tests each. Typically, multi-specimen samples containing many tens to hundreds of foraminifera tests are used for ^{14}C dating. Were such large sample sizes to be applied to T86-10P, it is possible that no age-depth outliers would be present and that all information about intra-sample heterogeneity would be lost, thus concealing the full temporal uncertainty from the researcher. Such an affect was seen in one of the earliest studies using ultra-small ^{14}C dating of foraminifera samples (Lougheed et al., 2012), whereby downcore age-depth reversals were found for a sequence of multi-specimen samples with <500 µg mass, whereas a sequence of multi-specimen samples with a greater mass did not exhibit such a behaviour.

We investigate the influence of ^{14}C sample size upon the concealment of age-depth outliers by using multiple simulated synthetic sediment core scenarios whereby foraminifera PDSM is generated using Gaussian noise (S2 and Fig. S2). These simulations suggest that when sample size is five to ten specimens or more, no age-depth outliers are present in a simulated sediment core with intense PDSM. Considering that the longstanding state-of-the-art in ^{14}C analysis requires up to hundreds of foraminifera specimens (e.g., Hughen et al., 2006), it is possible that the full extent of PDSM has been hidden by existing methods at certain study locations.

3.2 Quantifying intra-core post-depositional movement of single foraminifera

We can construct an ideal superposition ranking of the single foraminifera from core T86-10P by ranking them by median calibrated ^{14}C age. We can also rank the foraminifera by sediment core depth, i.e. by the 1 cm depth interval they were retrieved from. By comparing the two rankings we can visualise the post-depositional upcore and downcore movement of the single foraminifer tests (Fig. 3A). Analysis of the post-depositional ranking change for all foraminifera indicates that the ranking change appears normally distributed, but just fails a Kolmogorov-Smirnov (K-S) test for normal distribution (Fig. 3B). However, the youngest and oldest foraminifera within our population are biased to show minimal ranking change, as they are at the temporal edge of our population and we do not have the ability to sample into infinity. To overcome this ‘edge effect, we subsequently exclude the 20 youngest and 20 oldest foraminifera, after which the ranking change for the middle of our population can be described as normally distributed using the K-S test procedure (Fig. 3C). No correlation was found between foraminifera size and ranking change (S3 and Fig. S3). The ranking change and K-S test procedure was

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repeated 10^6 times (each time analysing the computed middle of the population) using probability weighted random sampling of the calibrated age PDF of each foraminifera, and the ranking change was found to be normally distributed for 99.98% of the 10^6 runs.

The indication that the effect of PDSM upon single foraminifera age-depth distribution in sediment core T86-10P can be approximated using a normal distribution allows us to use Gaussian noise to explore theorised intra-sample age heterogeneity for multiple synthetic sediment core scenarios. We simulate the age heterogeneity (i.e. the 1σ age value) of 10^5 synthetic foraminifera within a 1 cm sediment core slice in the case of 10^4 sediment core scenarios involving 10^2 SAR scenarios and 10^2 PDSM intensity scenarios (Fig. 4). Using an estimated SAR for T86-10P of 2.2 ±0.9 cm/ka (Fig. 2B), and knowing that the average intra-sample age heterogeneity (1σ age value) for discrete 1 cm depths in core T86-10P is 4670 ^{14}C yr, we can plot the approximate interval of core T86-10P in Fig. 4. The resulting interval suggests that the post-depositional movement of single foraminifera is at least 6 cm (1σ).

3.3 Consequences for the longstanding geochronological state-of-the-art

The fact that significant PDSM can essentially be concealed by the current state-of-the-art has significant consequences for recent studies that use age-depth reconstructions from deep sea sediment archives to reconstruct rapid changes in palaeoclimate. Many such studies (Barker et al., 2015; Caley et al., 2012; Simon et al., 2016) use tuning to the LR04 (Lisiecki and Raymo, 2005) benthic stack to produce an age-depth chronology. Were the LR04 stack to display similar PDSM uncertainty as T86-10P, one could expect an intra-sample heterogeneity (1σ age value for a 1 cm slice) of between 1500-2000 years (Fig. 4), in addition to any uncertainties related to the tuning process itself, which may be in the order of multiple millennia (Blaauw, 2012; Martinson et al., 1987; Pisias et al., 1984).

For some continental margin sites, such as those from the Iberian Margin, SAR is very high (20-30 cm/ka) and such study sites have been used for centennial resolution age-depth climate reconstructions (i.e. ±50 years precision), with the assumption that high SAR essentially minimises the effect of bioturbation upon age-depth reconstructions (Hodell et al., 2015; Shackleton et al., 2000; Vautravers and Shackleton, 2006). Other studies suggest that such high SAR can be best used for millennial resolution (i.e. not centennial) (Bard, 2001). Our analysis suggests that for such sites (e.g., U1385, one of the "Shackleton sites" (Hodell et al., 2015)), it is only possible to detect centennial resolution from 1 cm sediment core slices when PDSM intensity is almost negligible, i.e. when the 1σ value for foraminifera redeposition depth is less than 1 cm (Fig. 4), assuming that one does not use sediment slices thicker than 1 cm. Were PDSM at Iberian margin sites to be as intense as T86-10P, then 1cm intra-sample heterogeneity could be between 400 and 800 years (1σ).

It must be stressed that core T86-10P represents a single sediment archive location and may not be wholly representative for all locations. However, the intra-sample age heterogeneity at other locations is essentially unknown because it can be concealed by the longstanding state-of-the-art. Furthermore, the intra-sample age heterogeneity for less consolidated sediment within actively bioturbated younger sediment sequences may differ from the intra-sample age heterogeneity for older, more consolidated sediment. We propose, therefore, that the ultra-small sample ^{14}C methods and statistical analysis we outline in this study can be used to definitively quantify intra-sample age heterogeneity for various sediment sequences at other study locations (including those in the LR04 benthic stack), thus allowing for the application of a suitable downcore geochronological uncertainty. Such an approach will ultimately lead to a better integration of deep sea sediment archives within the global palaeoclimate record.

3.4 Bypassing the age-depth model paradigm?

A traditional, discrete depth average (multi-specimen) downcore stable isotope stratigraphy for core T86-10P (Figs. 5A and 5B) shows many spurious, large excursions in $\delta^{18}O$ and $\delta^{13}C$, indicating that it would not be possible to use the longstanding state-of-the-art (i.e. the age-depth model method) to retrieve temporally useful information about palaeoclimate or benthic ocean ventilation from the low SAR core T86-10P. The underlying cause for these large excursions is revealed by single specimen foraminifer $\delta^{18}O$ and $\delta^{13}C$ data (Figs. 5A and 5B), which show a large spread in values, an artefact of PDSM of the core material due to, e.g., bioturbation. This spread in values is significantly larger than the machine error associated with IRMS analysis (typically 0.1‰), meaning that it would be masked by multi-specimen analysis.

Dual measurements of both ^{14}C and stable isotopes ($\delta^{18}O$ and $\delta^{13}C$) on the same single specimen foraminifer in core T86-10P can contribute palaeoclimate information that is independent of the geological law of superposition, thereby decoupling an individual foraminifer from the sediment archive to provide a floating, temporal snapshot of ocean chemistry. Multiple such snapshots can facilitate a time history of ocean chemistry that is wholly insensitive to sediment core PDSM and associated issues involving multi-specimen samples within the age-depth paradigm, such as spurious age artefacts between foraminifera with different species/morphologies/preservation conditions (Löwemark et al., 2008; Löwemark and Grootes, 2004).

Due to the combined measurement size requirements of both AMS and IRMS, our dual ^{14}C and stable isotope measurements on single *C. wuellerstorfi* specimens were limited to those of sufficient mass (>100 µg $CaCO_3$), which are generally less abundant during the coldest stadial conditions, such as the last glacial maximum (LGM); a problem that also affects studies using traditional, multi-specimen reconstructions (e.g., Shackleton et al., 2000). Nevertheless, we were able to produce successful dual ^{14}C and stable isotope measurements for a sufficient number of foraminifera, revealing a *C. wuellerstorfi* benthic deglaciation signal for core T86-10P. This benthic deglaciation signal is in good agreement with existing *C. wuellerstorfi* data from a previous study using a nearby (140 km proximity) high SAR (~20 cm/ka) record (Repschläger et al., 2015) (Figs. 5C and 5D). Specifically, we find good temporal agreement with the absolute values for $\delta^{18}O$, indicating a valid benthic deglaciation signal. We also find good temporal agreement with a sharp peak in $\delta^{13}C$ values that has previously been interpreted as a local increase in Eastern North Atlantic Deep Water (ENADW) linked to the onset of the Holocene (Repschläger et al., 2015). These results demonstrate that it is possible to use our dual ^{14}C and stable isotope method on single foraminifera to extract temporally accurate late-glacial benthic palaeoceanographic data from a low SAR site, with comparable success when compared to data extracted from a high SAR site using the existing state-of-the-art.

4 Conclusion

Analysis of ^{14}C on single foraminifera opens up new possibilities for quantifying the total geochronological error in existing studies due to PDSM, which may have been previously underestimated due to inherent limitations associated with the longstanding geochronological state-of-the-art using multi-specimen species within an age-depth paradigm. Using the methods outlined in this study, it is possible to quantify the age-depth geochronological uncertainty for existing late-glacial palaeoceanographic records, thus placing them within an accurate geochronological framework. Subsequent improved evaluation of perceived regional leads and lags in climate processes will lead to an improved understanding of rapid climate change.

We also demonstrate that dual ^{14}C and stable isotope ($\delta^{18}O$ and $\delta^{13}C$) measurement on single foraminifera can produce temporally accurate benthic ocean chemistry data that is independent of the age-depth paradigm. This development opens up many new avenues in late-glacial palaeoceanographic research, specifically for the vast low SAR areas of the ocean (<10 cm/ka; Fig. 1) that are inaccessible for research using existing methods, thus filling in large spatial gaps in the global, late-glacial climate record.

Author contributions: BCL and BM designed the study. BM picked and cut suitable foraminifera tests. LW and BCL carried out ^{14}C dating. BM, USN and BCL carried out stable isotope analysis. BCL analysed the data and wrote the manuscript with input from the co-authors.

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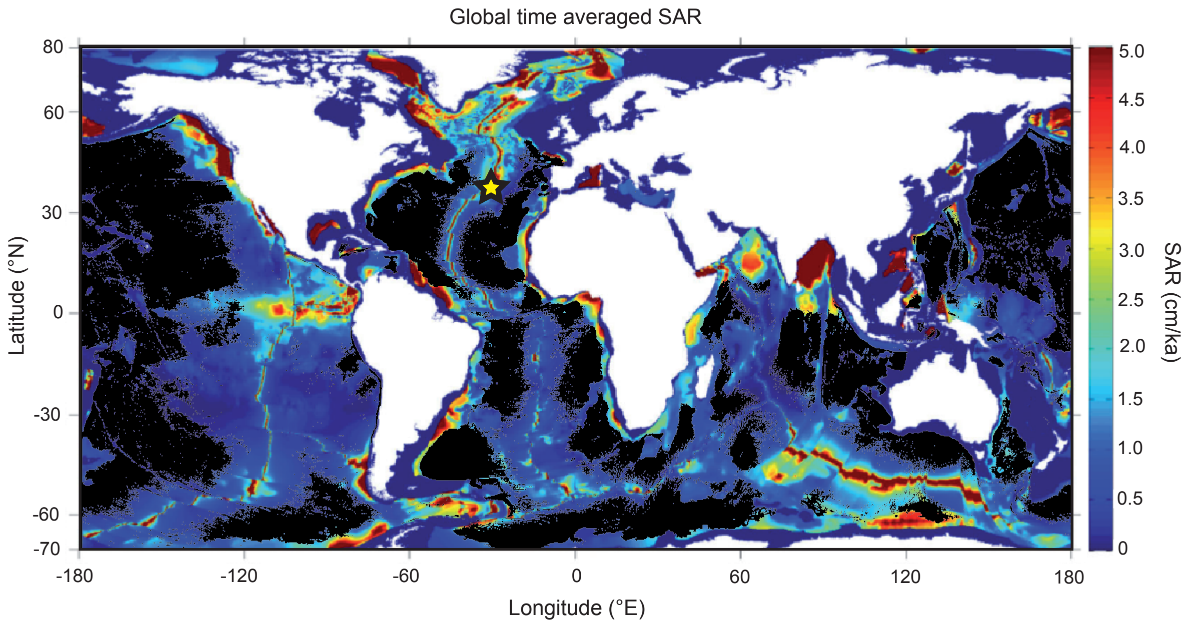

Fig. 1. Map of time averaged deep sea sediment accumulation rates (SAR) adapted from Olson et al. (2016). Note that continental margins are not included in the SAR estimate. Superimposed on this map in black is an approximate indication of seafloor areas under the calcite compensation depth, estimated using a global water depth of 4500 m derived from global bathymetry (General Bathymetric Chart of the Oceans, 2015). The location of core T86-10P (37° 8.13’ N, 29° 59.15’ W, 2610 mbsl) is indicated by a yellow star.

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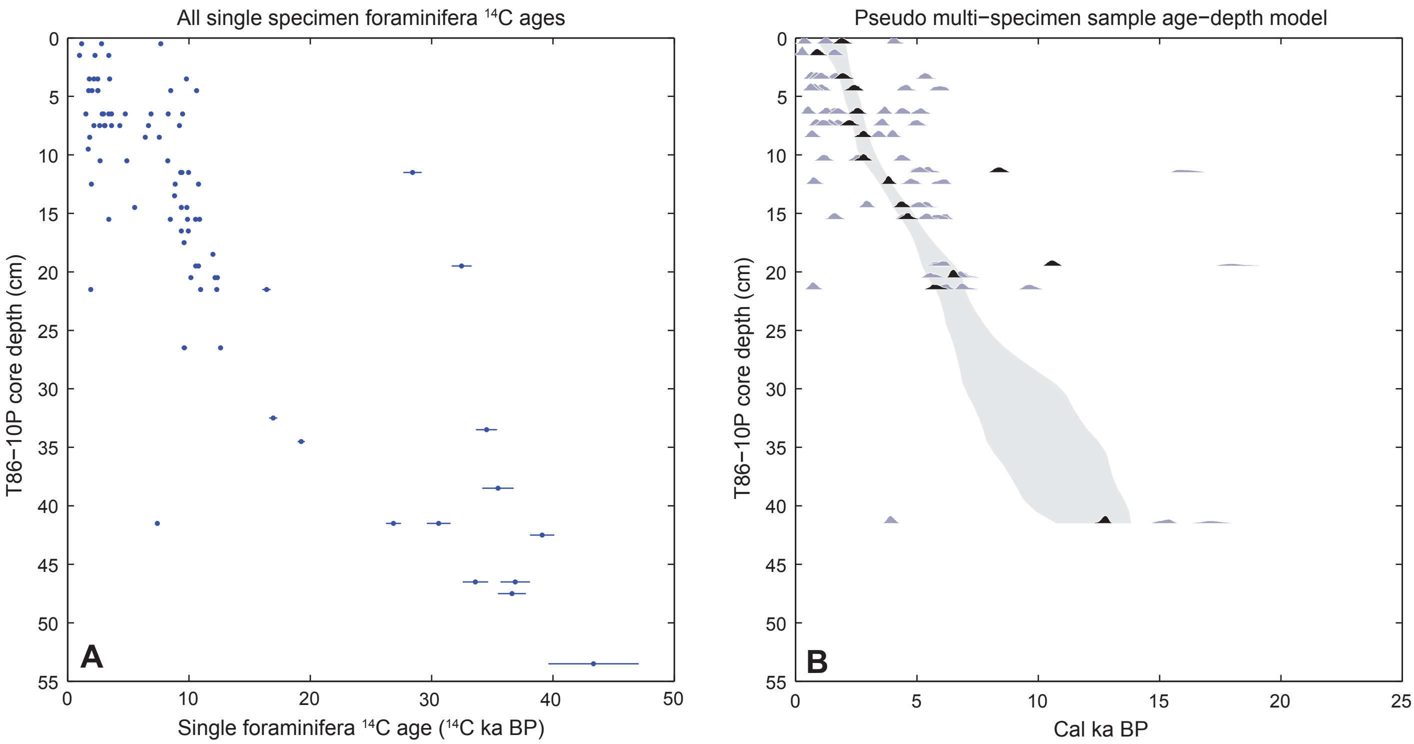

Fig 2. Results of single foraminifera *C. wuellerstorfi* ^{14}C dating in core T86-10P. **(A)** ^{14}C determinations (uncalibrated) on single *C. wuellerstorfi* foraminifera from core T86-10P, with 1σ measurement uncertainty shown. **(B)** A demonstration of the concealment of large intra-sample heterogeneity by the current geochronological state-of-the-art. Calibrated single specimen benthic foraminifera ^{14}C ages (light blue probability density functions [PDFs]; see Method for ^{14}C calibration process) for all discrete 1cm core depths with three or more subsampled foraminifera. To demonstrate the potential concealment of PDSM by the longstanding geochronological state-of-the-art involving dating of multi-specimen foraminifera samples, we also show the 95% confidence interval (light grey) of a *Bacon* (Blaauw and Christen, 2011) age-deph model created using calibrated pseudo multi-specimen foraminifera ^{14}C ages (black PDFs – see text 3.1). The *Bacon* age model displays an average SAR of 2.2 ±0.9 cm/ka.

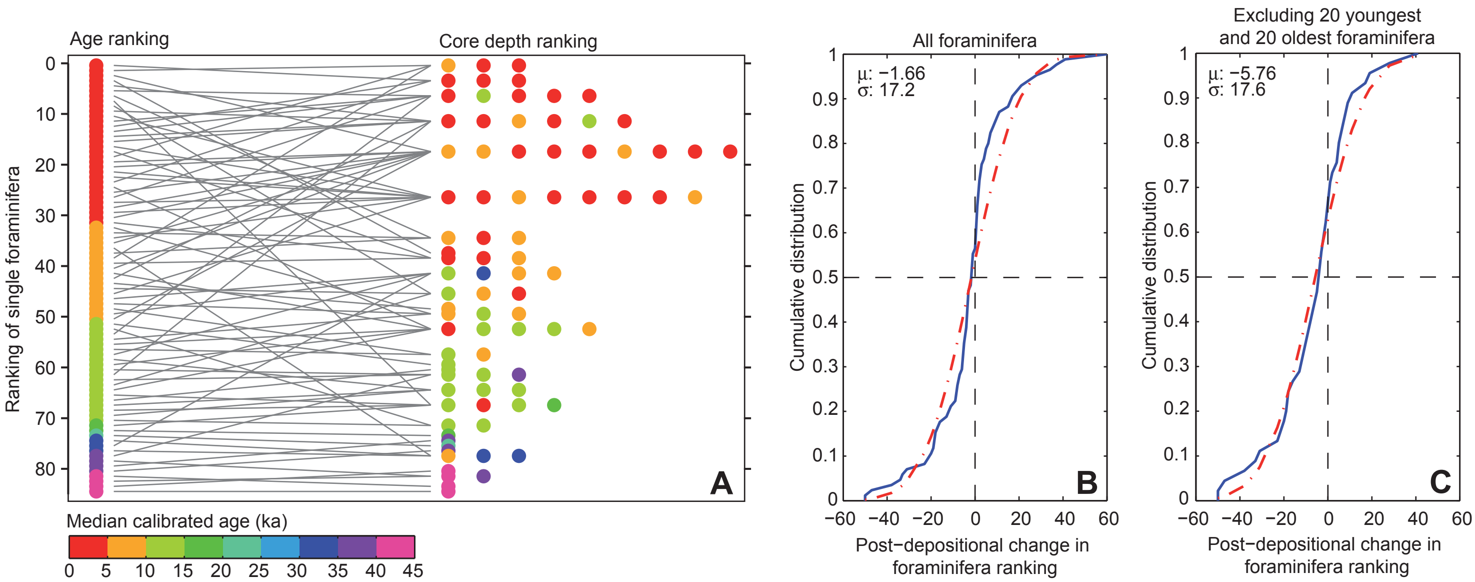

Fig 3. (A) Visualization of PDSM in core T86-10P. Single *C. wuellerstorfi* benthic foraminifera (represented by colored dots coded by median age) from core T86-10P are ranked by median calibrated age (left) and by core depth (right). Single foraminifera recovered from the same core depth interval are given the same core depth ranking. Grey lines visualize the reconstructed post-depositional change in ranking. **(B), (C)** Cumulative distribution plots of ranking change (as ascertained from Fig. 4) for single *C. wuellerstorfi* benthic foraminifera. The blue line represents an empirical cumulative distribution of the ranking change data. The broken red line represents a fitted normal cumulative distribution function (CDF) based on the mean and standard deviation of the ranking change data. Kolmogorov–Smirnov (K-S) testing is used to test a null hypothesis of the fitted normal distribution being similar to the empirical data. Hence, a P value *greater* than 0.05 (i.e. *not* less than or equal to) indicates normal distribution of the data at the $\alpha=0.05$ significance level. Panel B is based on all foraminifera (P=0.047; not greater than 0.05). Panel C excludes the top 20 and bottom 20 age ranked foraminifera (P=0.54; greater than 0.05).

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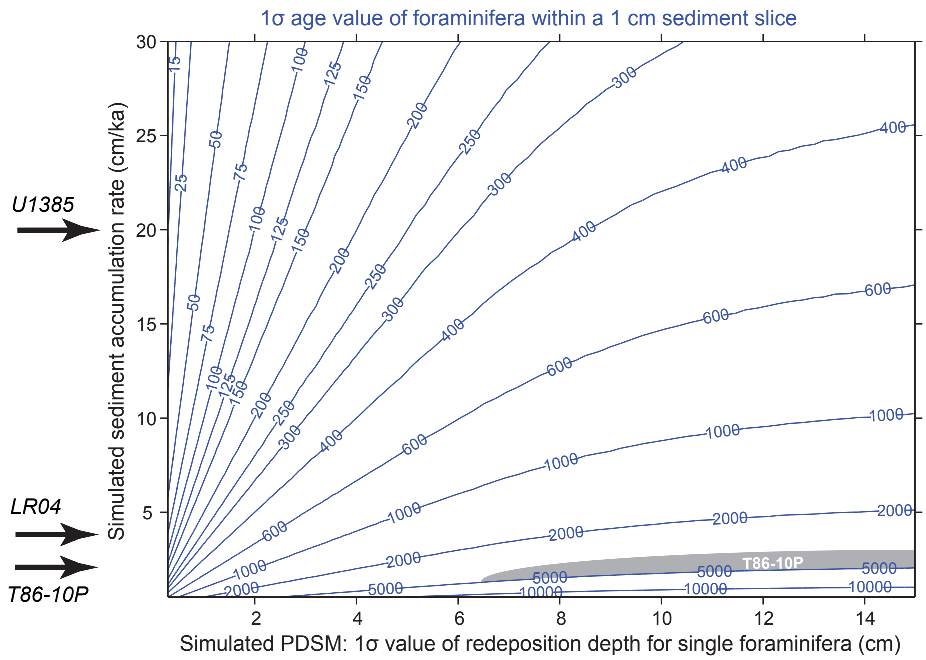

Fig 4. Contour plot showing the simulated 1σ value in foraminifera age for a 1 cm discrete depth interval in the case of various sediment accumulation rates (SAR) and PDSM scenarios. Based on simulations using 10^2 linear SAR scenarios and 10^2 PDSM intensities, resulting in a total of 10^4 sediment core scenarios. PDSM is generated by applying Gaussian noise to the linear SAR scenarios to simulate vertical mixing within the sediment core. Each sediment core scenario contains 10^5 synthetic foraminifera per 1 cm core depth interval, and a 1σ age value is calculated from these 10^5 synthetic foraminifera. A 100 by 100 matrix containing 10^4 1σ age values is subsequently used to create the contour plot in the figure. The approximate SAR values for T86-10P (this study), the LR04 benthic stack (Lisiecki and Raymo, 2005) and Iberian Margin site U1385 (Hodell et al., 2015) are indicated by black arrows.

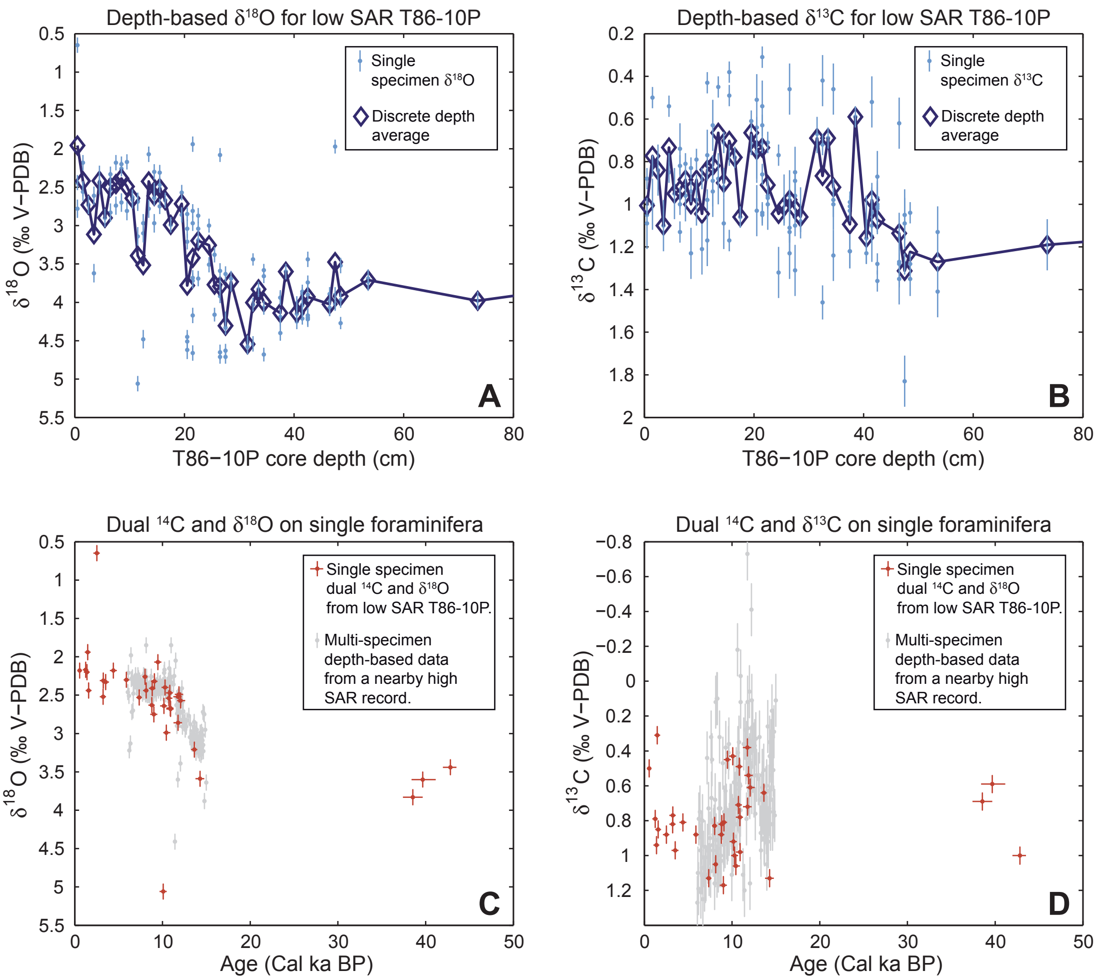

Fig. 5. Demonstration of successful use of dual ^{14}C and stable isotope analysis on single foraminifera to retrieve useful paleoclimate information from the low SAR core T86-10P. **(A)** To visualise the inability to retrieve useful paleoclimate data from the low SAR core T86-10P using the longstanding geochronological state-of-the-art, we show single specimen *C. wuellerstorfi* $\delta^{18}O$ data against core depth (with 1σ measurement error). Also shown is the average $\delta^{18}O$ value of the single specimens for each discrete sediment core depth analysed (i.e. representative of the current state-of-the-art using multi-specimen samples). **(B)** Same as for panel A, but with $\delta^{13}C$ instead of $\delta^{18}O$. **(C)** Successful dual ^{14}C and $\delta^{18}O$ measurements on single foraminifera from core T86-10P. Vertical error bars denote 1σ error measurement. Horizontal error bars denote the 68.27% highest posterior density interval of the calibrated ^{14}C age (see method for ^{14}C calibration process). Also shown are previously published multi-specimen $\delta^{18}O$ data from a nearby high SAR (20 cm/ka) record (Repschläger et al., 2015). Vertical error bars represent 1σ measurement error. **(D)** Same as for panel C, but with $\delta^{13}C$ instead of $\delta^{18}O$.