

We appreciate the time the reviewer took to review the manuscript and thank the reviewer for their constructive comments. We have tried to address them all and feel that they have improved the manuscript.

The reviewer's comments are in black italics, followed by our responses in blue. A revised manuscript with tracked changes is also included.

*Anonymous Referee 1*

*The paper presents new geochronological data in the form of amino acid racemisation of N. pachyderma and C. wuellerstorfi from a range of cores in the Arctic Ocean. New age estimates are derived for these cores and the discrepancies between different dating techniques in this area are addressed in detail. This work also demonstrates the utility of C. wuellerstorfi for AAR, a species which has not been previously investigated in detail using modern separation methods. I therefore recommend this paper for publication with minor revisions, detailed below.*

*Specific comments:*

*Line 159: It should be stated that during hydrolysis, Asn and Gln irreversibly hydrolyse to Asp and Glu, so the 'Asp' and 'Glu' reported in this study also includes any Asn and Gln present in the biomineral (see Hill 1965 [https://doi.org/10.1016/S0065-3233\(08\)60388-5](https://doi.org/10.1016/S0065-3233(08)60388-5)).*

**We altered to text to include that 'Asp' and 'Glu' reported in this study also include any Asn and Gln present in the biomineral.**

*Table 3: Table 3 gives a count of subsamples destroyed during analysis, but this is not mentioned in the text.*

**We have omitted any mention of destroyed subsamples as these do not influence the data.**

*Figures 4 and 5: The authors mention the reduced confidence in the power function for C. wuellerstorfi from the Alpha Ridge due to the small number of C. wuellerstorfi samples analysed at this site; as only 4-5 samples of N. pachyderma were analysed from the Alpha Ridge and of C. wuellerstorfi from the Iceland Sea, this uncertainty should also be discussed for these sites/species.*

**The power model for central Arctic Ocean cores was used in combination with sample depth rather than proposed sample age due to the reduced confidence in the ages. We do not specifically mention reduced confidence in the power function for C. wuellerstorfi due to small number of samples analysed from this area.**

*Lines 293-300: Equations for a simple power model applied to the data are given here. These should be given when the models are first introduced (in Section 3c). I would also suggest briefly summarising the precedent of using simple power functions to model racemisation (e.g. Clarke and Murray-Wallace 2006 <https://doi.org/10.1016/j.quageo.2006.12.002>), justifying why the authors used this model and how the exponent for each model was derived.*

**In Section 3c we show that the trends at individual areas conform to simple power functions, characteristic of racemization under isothermal conditions (e.g. Kaufman, 2006; Clarke and Murray-Wallace, 2006). We have added these references to the text. The power model used in the Discussion (equations 1 and 2) combines samples from the Greenland and Iceland seas, and only applies to samples up to 400 ka old. Hence, we prefer to keep these in the Discussion. Exponents were obtained using regression, as stated in the text.**

**Line 391-409:** *The authors suggest that differences in microbial environments during diagenesis may account for some of the discrepancy between racemisation and other dating methods. As this should only affect open-system inter-crystalline material, it would be worth addressing recent work on isolating the intra-crystalline fraction in foraminifera (see Penkman et al. 2008 <https://doi.org/10.1016/j.quageo.2007.07.001> for ICPD overview and Wheeler et al. 2021 <https://doi.org/10.1016/j.quageo.2020.101131> for ICPD of *N. pachyderma*), as the intra-crystalline approach may minimise or eliminate environment-specific effects on racemisation rates.*

**We extended the Discussion to include that isolation of the intra-crystalline fraction, which behaves as a closed system during diagenesis (Penkman et al., 2008; Wheeler et al., 2021), by means of bleaching could minimise the influence of bacterial activity on racemization rates. However, recent work (Millman et al., 2022) showed that bleaching does not necessarily improve the quality of the results, thus the current study used the standard weak oxidative pre-treatment.**

**Technical corrections:**

**All figures:** *increase the line thickness of error bars – they are very difficult to see, especially for green/yellow data. As figure 8 presents data from only one species (thus placing Asp on the lefthand plot and Glu on the righthand plot), I would recommend switching the layout of the other plots that the amino acid is faceted horizontally and the species vertically, so that all figures are consistent in this respect.*

**We have increased the line thickness of the error bars on all figures, and rearranged the figures as suggested by the reviewer.**

**Line 19:** *‘large geographical area, from the Greenland’.*

**Corrected.**

**Lines 23, 241, 244, 403:** *‘foraminifer species/taxa/tests’ or ‘species/taxa/tests of foraminifera’ - the singular ‘foraminifer’ should be used in the adjectival form.*

**We prefer to use the form ‘foraminifera’ for consistency. We refer to Lipps et al. (2011 DOI:10.2113/gsjfr.41.4.309).**

**Line 41-42:** *‘the protein amino acid isoleucine over time in samples of the planktic foraminifer Neoglobobulimina pachyderma and the benthic species Cibicides wuellerstorfi’.*

**Corrected.**

**Line 69:** *Consider removing the dashes around ‘undetermined’ to improve the readability of this sentence.*

**Removed.**

**Line 110-111:** *Consider listing the Nordic Sea cores here explicitly, e.g. ‘Cores from the Nordic Seas (ODP151/907A and PS17/1906-2) primarily relied on oxygen isotope stratigraphy’.*

**Changed.**

*Line 122, and in general:* Consider putting references at the end of a sentence/clause to improve readability.

**Changed.**

*Line 149, and in general:* L should be capitalised in mL and  $\mu$ L.

**Changed.**

*Line 155-159:* Consider breaking the sentence starting ‘The peak-area ratio...’ into two sentences at ‘extent of racemisation, but this study’.

**Changed.**

*Table 3:* Full stop at end of table caption.

**Corrected.**

*Line 200:* Consider giving the name of the stratigraphically reversed sample removed from the species comparison.

**Changed.**

*Figures 4, 5 and 9:* Increase line thickness on open circles/diamonds – these are challenging to see, especially for the pale data points.

**Corrected.**

*Figure 6:* Define black/green/red lines in each figure. Also consider changing line style of the blue line (e.g. to dashed or dotted) to make it clear that it is an age model derived from other data, especially as the colour of this line is to denote data from this paper in other figures.

**We included in the figure caption that the green, black and red lines mark power function fits for the various areas.**

*Line 264:* In abstract, a standard deviation is given for the difference between racemisation rates of the two species; this should be quoted here rather than ‘approximately 16 %’.

**The SD is already stated in the Results and here we are simplifying for purposes of the Discussion.**

*Line 280:* Consider changing ‘since we established that AAR is faster’ to ‘as racemisation proceeds more quickly’.

**Changed to ‘racemization proceeds faster in this taxon than...’**

*Figures 7 and 8:* Consider adjusting palette – blue and purple are very similar, and yellow and green challenging to separate under red-green colourblind conditions. I would also recommend not reusing blue for the LMROG12-PC03 data and the Kaufman 2013 model, as this implies a connection between them.

**We changed the colour palette to a colour-blind-friendly one.**

**Line 315:** *'what are interpreted as'*

**We altered the sentence to refer to *'intervals interpreted as substages in MIS 5'*.**

**Line 325:** *Make sure that 'marine isotope stage' is defined in its first instance and that the acronym is used thereafter.*

**Defined in Line 66.**

**Table 4:** *Left-align text on row 2, as justified text is difficult to read in narrow columns.*

**Changed.**

**Line 384:** *Consider changing 'seems untenable' to 'is unlikely' or 'is highly unlikely' – more scientific language.*

**Changed to *"highly unlikely"*.**