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**HELMHOLTZ**

## Reply to: Influence of deep-reaching bioturbation on Arctic Ocean radiocarbon chronology

REPLYING TO: L. Löwemark and A. Singh *Communications Earth & Environment* (2024)

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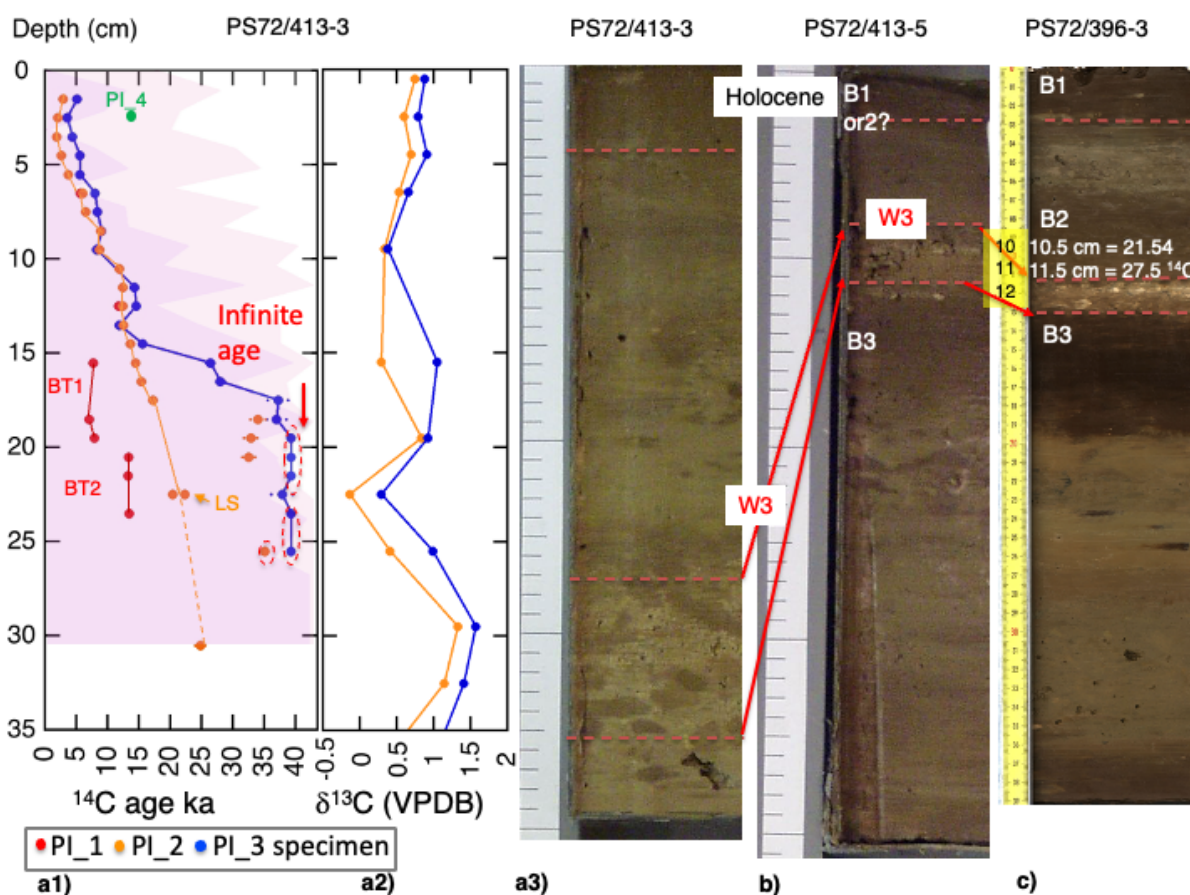
In our original contribution, we demonstrated that in the Arctic Ocean, authigenic carbonate precipitates affect foraminifera shells used for paleoceanographic reconstructions. We proved the presence of such secondary precipitates using a wide range of mineralogical, geochemical, isotopic and optical tools. Such precipitates are not commonly seen to this extent on foraminifera in other ocean basins, however, PI\_3 specimens (containing detectable amounts of overgrowth) are obviously no suitable tools to reconstruct environmental conditions during the growth of the organism. We also showed that previous reconstructions are likely to include effects of such authigenic overgrowth, also affecting radiocarbon values. In our Reply, we concur with Löwemark and Singh that bioturbation may bias Arctic records in specific instances, as outlined in the original publication. However, the specifically Arctic problem of the widespread authigenic overgrowth persists, independent of any possible bioturbation.

In their comment on our paper Löwemark and Singh address the bioturbation, an important process known to occur globally in oxygenated deep-sea sediments<sup>1-4</sup>. They identify *Zoophycos* in kastenlot core (GC) PS2185-6, box core (BC) PS72/413-3, and mostly (Figs. 2-3) in gravity core (GC) PS72/413-5, which is located 1.3 km away from BC PS72/413-3 used in our study. GC PS72/413-5 (Fig. 2a Comment) has a condensed lithology, therefore, the BC does not contain this older high bioturbation unit shown in Figs. 2-3 of the Comment. Partly intense bioturbation in the low-sedimentation records of the central Arctic Ocean have been described already in the earliest studies<sup>5</sup>. Here, bioturbation is usually most intense in the brown layers (B), assigned to interglacial or interstadial conditions<sup>6</sup>. Deep-reaching traces are most obvious in the grey layer below B3<sup>5,6</sup> (Fig. 1 this reply and Figs. 2-3 of the Comment). In our manuscript we did not discriminate between different trace fossils but collectively referred to the dark brown mottles in the grey sediments below B1 as bioturbation. In these sediments, cool-white to off-white PI\_2 specimens of the planktic foraminifera *Neogloboquadrina pachyderma* were regarded as best-preserved autochthonous specimens, whereas pristine translucent PI\_1 specimens were assigned to dark brown trace fossil fillings within this grey unit (Figs. 1-2). The coloration of our *Zoophycos* traces indicate that the filling consists of sediments of the B1 layer assigned to Holocene to GI 1/Bølling age<sup>6</sup> (Fig. 1) which matches the radiocarbon ages of our PI\_1 specimens. The presumption of Löwemark and Singh that PI\_2 specimens of MIS2-3 age originate from these trace fossils, contrasts with the presumed trace fossil age/color and the increased food demand of *Zoophycos* creating organisms indicating a Holocene formation<sup>4</sup>. Furthermore, it contrasts with the synchronous  $\delta^{13}\text{C}$  downcore variations in PI\_2 and PI\_3 specimens (Fig. 5a, e<sup>7</sup>) which we would not expect from bioturbated vs. in situ specimens. Brownish-discolored

specimens PI\_4 were excluded from AMS dating in Wollenburg et al.<sup>7</sup>, but are provided for comparison from the 2.5 cm-sample (Fig. 1). Since overgrowth increases with sediment depth in glacial sediments, the assumption of extremely low sedimentation in MIS2<sup>8,9</sup> cannot be upheld until being proven by radiocarbon analyses on correspondingly diagenetically unchanged shells. We isolated PI\_2 and PI\_3 specimens that matched in coloration and transparency and were closest to the biogenic shell. Within the BC the appearance of PI\_2 specimens changed from translucent in the Holocene to cool-white in the deglaciation and off-white in glacial sediments. As off-white is not the original color of a *N. pachyderma* shell, these glacial PI\_2 shells were diagenetically altered to variable degrees. Consequently, some glacial PI\_2 measurements failed, generating ages comparable to PI\_3 specimens, whereas, at 22.5 cm the preservation improved and even allowed for an additional high precision radiocarbon measurement of a large sample (1000 µgC) which resulted in reasonable radiocarbon ages supporting previous measured on small samples (<100 µgC) (see Mollenhauer et al.<sup>10</sup> for details on uncertainties of both <sup>14</sup>C analyses). Support for the MIS 2/3 radiocarbon ages of the original manuscript comes from PI\_2 *Cibicidoides wuellerstorfi* measurements from nearby BC PS72/396 which revealed a B3/W3 border age of 27.5 C<sup>14</sup> ka (Fig. 2).

In their comment, Löwemark and Singh raise the concern that the observed radiocarbon offset between *Neogloboquadrina pachyderma* shells of different diagenetic overprint in glacial sediments is likely an artifact and that the observed age offsets are rather due to *Zoophycos* bioturbation. In our cores, until becoming infinite (>39.2 ka) the age offset between PI\_2 and PI\_3 increases with depth as does the thickness of overgrowth estimated by SEM images.

**Fig. 1 Radiocarbon ages and lithological units of sediment cores discussed in this reply**

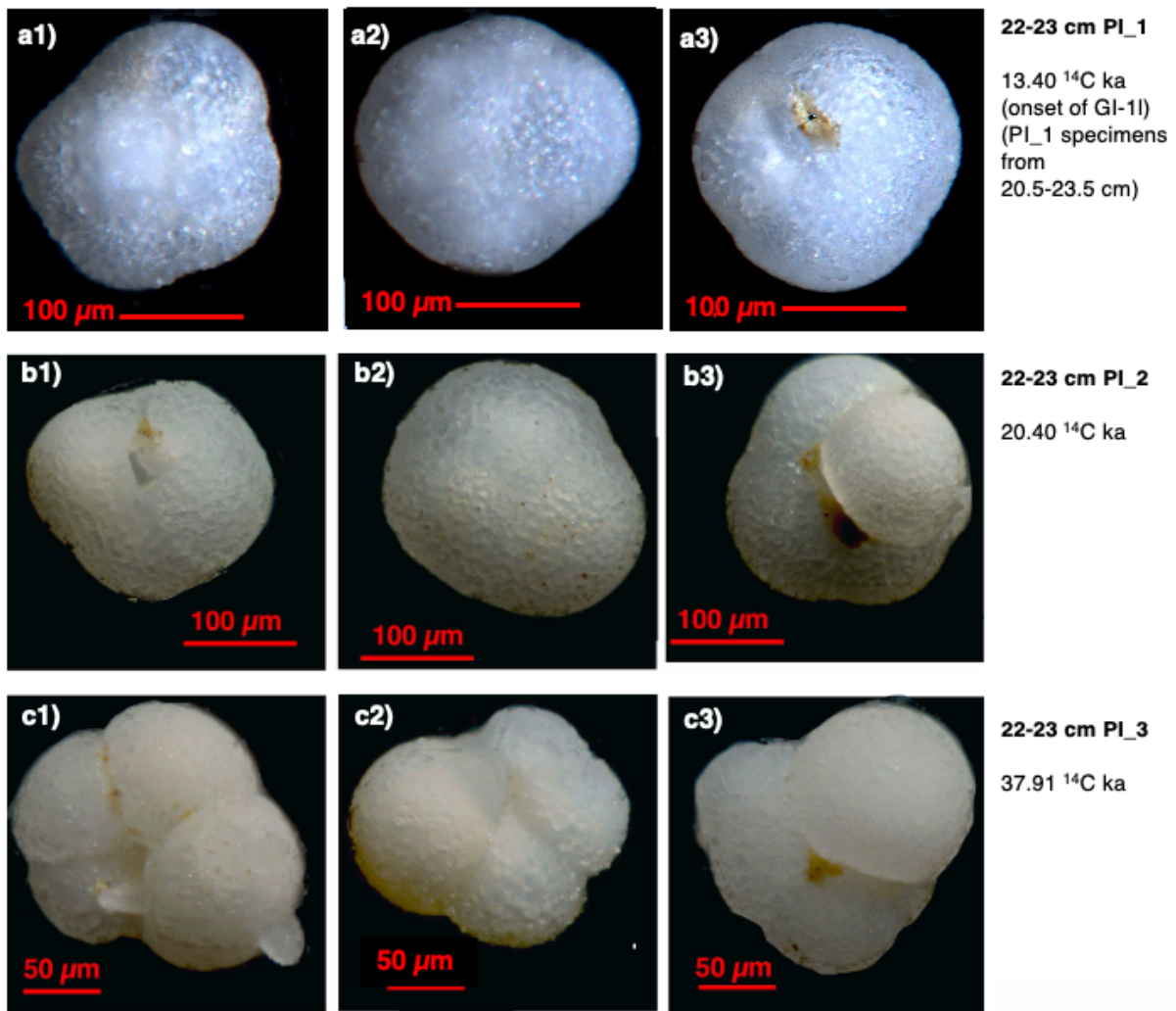


**a)** BC PS72/413-3. **a1)** Downcore distribution of *Neogloboquadrina pachyderma* PI\_1-3<sup>7</sup> and exemplified discolored PI\_4 radiocarbon ages. Green dot exemplified radiocarbon measurement of discolored PI\_4 *N. pachyderma* (14.61 ka <sup>14</sup>C). Dark pink shading = major overgrowth, light pink shade = moderate overgrowth<sup>7</sup>. **a2)** Carbon isotope values. **a3)** Core image of BC PS72/413-3, *Lat.* 80.277900, *Long.* -178.515100, *water depth* 1263.0 m, *Recovery* 0.43 m used in Wollenburg et al., 2023; as the W3 layer is disturbed by bioturbation the position in this figure follows the peak abundances of dolomite and high-magnesium calcite (Fig. 8d<sup>7</sup>). **b)** Core image of GC PS72/413-5, *Lat.* 80.288800, *Long.* -178.483600, *water depth* 1274.0 m, *Recovery* 6.44 m used by Löwemark and Singh; note condensed B-section **c)** Linescan of BC PS72/396-3, *Lat.* 80.586600, *Long.* -162.360700, *water depth* -2731.0 m, *Recovery*: 0.43 m. Dashed red lines indicate the boundary of the W3 layer, a sedimentary event with splendid white-pinkish dolomite and Mg-calcites, most prominent in the Alpha-Mendelev Ridge region and on the Morris Jesup Rise<sup>6</sup>. Moreover, a lower boundary of the presumed B1 layer is indicated by such a dashed line<sup>6</sup>. White values = radiocarbon measurements of *C. wuellerstorfi* in ka <sup>14</sup>C ages.

Löwemark and Singh presume that pristine foraminifera were distributed downcore in *Zoophycos* traces and measured as PI\_2 specimens and that this could have been avoided by working on the slabs used for radiography<sup>11</sup>. As has been shown by e.g. Küssner et al.<sup>12</sup>, this is a good method to elucidate the potential impact of large bioturbation structures on proxy measurements in foraminifera-rich sample<sup>12</sup>. However, in our case this was not possible because the slabs and samples were processed 30 and 10 years before our current analyses

for cores PS2185-6 and PS72/413-3, respectively, and the slabs and PS2185-6 sediments are no longer existent. Therefore, allochthonous foraminifera can not be avoided by sampling visually *Zoophycos*-free sediments. The thickness of x-ray sediment slabs is 1 cm, whereas, the mean thickness of a foraminifera is only 100-150  $\mu\text{m}$ . As radiography integrate the sediment density of the 1-cm thick slab, one still has a high chance to include bioturbated foraminifera when sampling non-laminated and *Zoophycos*-free sediments. Central Arctic Ocean sediment cores are usually retrieved from ridges/seamounts where the sedimentation rate is very low and a lot of shallow to intermediate water depth foraminifera are deposited by drifting sea ice (see fig. 29, Wollenburg<sup>13</sup>) or icebergs<sup>14</sup>. Drifting icebergs further may erode sediments and re-deposit them nearby or elsewhere<sup>15</sup>. In addition to massive diagenetic shell changes, allochthonous and autochthonous shells are distributed relatively evenly, especially in the brown layers. It is therefore of great importance to keep an eye on both the lithology and the state of preservation when isolating foraminifera for radiocarbon dating. Our study shows that bioturbated PI\_1 shells can be clearly distinguished from autochthonous PI\_2 and PI\_3 individuals due to their better preservation (Fig. 2). The similar preservation of PI\_2 and PI\_3 and the MIS2 age of PI\_2 individuals further contrast with the brown Holocene to Greenland Interstadial 1 sediments in the *Zoophycos* traces. Finally, we would like to point out that at present, due to the strong diagenetic imprint on shells, the often intense bioturbation and the many<sup>16</sup> allochthonous components, a reliable age model in these cores must be supported by further independent stratigraphic methods (e.g. seawater derived Be isotopes<sup>16</sup>). We concur with Löwemark and Singh that bioturbation may bias Arctic records in specific instances, and we did our best to address and consider these effects in the original publication. However, our aim was to draw attention to the massive authigenic overgrowths on foraminiferal shells and their importance for proxy applications, especially radiocarbon dating, a problem that exists completely independently of bioturbation.

**Fig. 2 Documentation of radiocarbon measured specimens and their assigned PI from 22.5 cm sediment depth in BC PS72/413-3.**



**a)** PI\_1 specimens pristine and translucent white, from this sample and other samples in the core section 20.5-23.5 cm revealed an GI age. **b)** PI\_2 specimens with an off-white shell lacking overgrowth reveal and MIS2 age. **c)** PI\_3 specimens with an off-white shell showing overgrowth reveal a MIS3 age.

**Data Availability Statement.** The datasets used and generated during the original paper and this study are available in the PANGAEA data repository, <https://www.pangaea.de/?q=doi:10.1594/PANGAEA.938246> , where the previously published datasets are also linked and referenced.

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**Author contributions**

JW designed the experiment, was in charge of the foraminifera work and the photographic documentation, and wrote the manuscript. JM and WG assisted in writing. JM and CV contributed lithostratigraphic information. HG and GM did the AMS dating. All co-authors contributed and commented on the manuscript.

**Competing Interest Declaration**

The authors declare no competing interests.

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