Supplementary material for:

**Deglacial patterns of South Pacific Overturning inferred from 231Pa/230Th**

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**Supplementary text**

**Impact of biogenic opal**

Unlike the deep-water sediment cores from ~2000 m to ~4300 m (SO213-82-1 down to SO213-76-2), PS75/104-1 (835 m), which is not discussed in the main article, is bathed by newly formed Antarctic Intermediate Water (AAIW) and thus records waters that recently passed an area of high silicate production1. The noticeable decrease in the 231Pa/230Th-ratio of PS75/104-1 at ~20 ka might therefore not only record changes in circulation strength, but also to a certain extent enhanced 231Pa-scavenging in the opal-rich waters of AAIW-formation. This process would lower the 231Pa/230Th-ratio2 and thus might erroneously indicate enhanced overturning once the waters reach our core location. South of 45° S, in the area covered by our New Zealand Margin sediment cores, pCFC-data (partial pressure of chlorofluorocarbon-11) indicate an average age of Southwest Pacific AAIW of just 21-22 years3. If AAIW ages were similar over the past, this travel time would be too short to reset the 231Pa/230Th-signal. Hence, we assume that the signal recorded by PS75/104-1 also reflects the pattern of opal productivity in the formation area of Southwest Pacific AAIW, instead of being a pure circulation signal. This reasoning is corroborated by opal flux rates and 231Pa/230Th-ratios from the Southern Ocean, south of the Antarctic Polar Front4, which indicate the most pronounced increase in opal flux, parallel to the observed decrease in PS75/104-1 231Pa/230Th-ratios (~17.2 – 15.5 ka). Hence, although the opal-values of PS75/104-1 are constantly below 1% (*https://doi.pangaea.de/10.1594/PANGAEA.889934*), we argue that the upstream opal-production affected the AAIW 231Pa/230Th-signal at our core site.

East Pacific Rise (EPR) record PS75/059-2 on the other hand shows higher glacial opal concentrations (~10%) compared to low Deglacial and Holocene values (3-5%). We assume that the glacial northward displacement of the Antarctic Polar Front (APF)5, shifted the area of higher opal production into the vicinity of PS75/059-2. During Termination 1 and the Holocene, the southward movement of the APF led to lower opal concentrations. Hence, we assume that after ~18 ka, 231Pa/230Th in PS75/059-2 was not driven by opal concentrations in the first order but can act as an overturning proxy for deep-water at the EPR.

We see no significant impact of opal on the NZM sediment cores between 2066 m and 4339 m water depth. Hence, we are confident to use the 231Pa/230Th-proxy to reconstruct Southwest Pacific overturning.

***Hummingage* age-depth model**

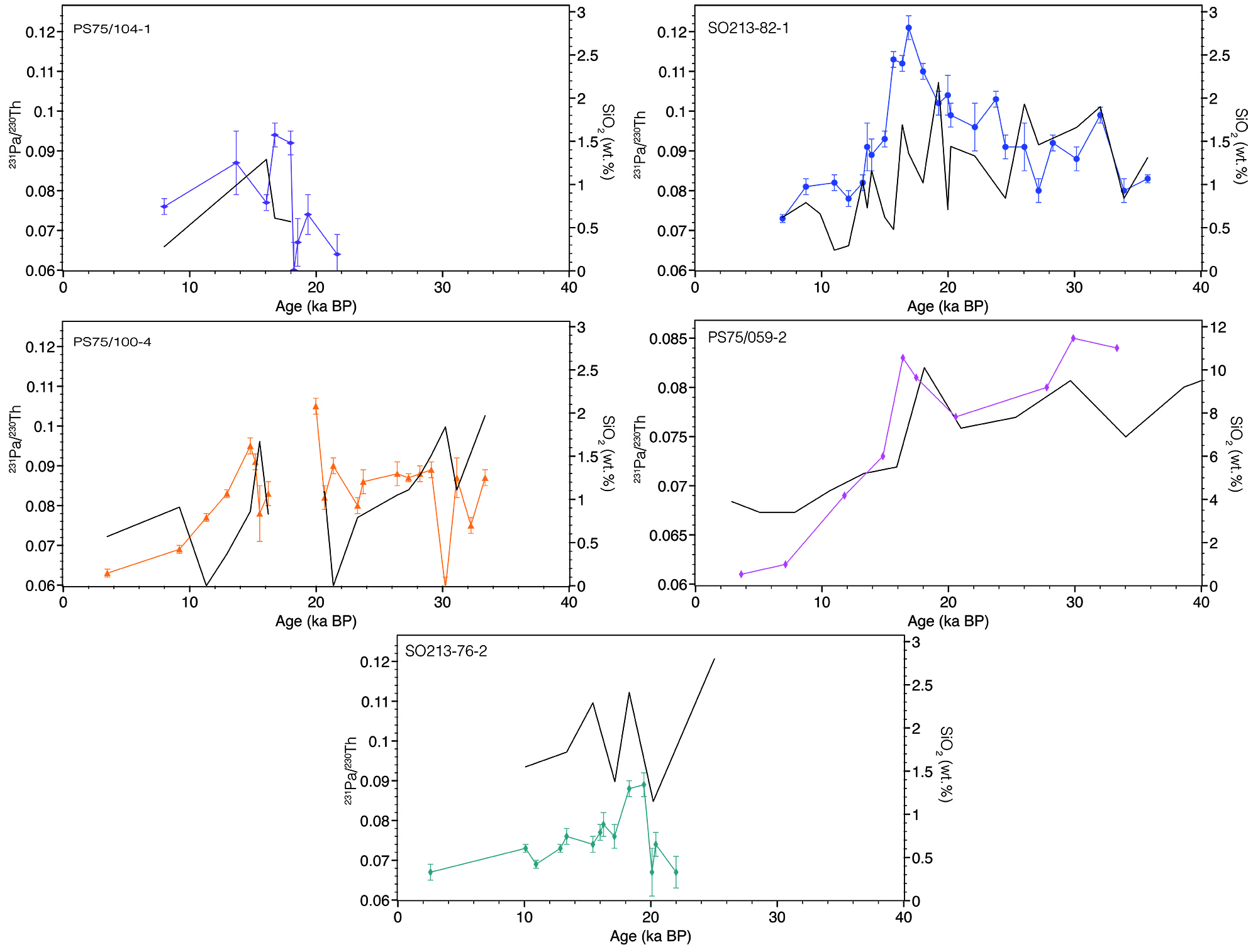
In its current version, *hummingage* requires Gaussian errors of the input age data, which is a fair assumption on our already calibrated data. *Hummingage* applies a multi-segment linear regression on the accumulation rate of the sediment data. The decision on the optimal number of segments is made with the objective support of the BIC (Bayesian Information Criterion)6. The BIC implements the concept of Occams’s Razor7, which suggest choosing the hypothesis requiring the fewest assumptions among competing hypotheses describing a phenomenon (equally) well. Practically the BIC is an optimal compromise between minimizing the fit residuals and dividing the data into not more segments as needed. For our data, the BIC suggested to divide the sequence in either two or three segments.

Following the linear regression on the accumulation rate *hummingage* applies a Bayesian tuning to find a best fitting curve by interpreting the regression as prior probability and ask for the posterior probability of this regression given the observed data. Following a Gaussian assumption, it turned out that the best fitting curve is the weighted average of the regression line and the original data, whereas the weights are given by the regression error and the individual data errors.

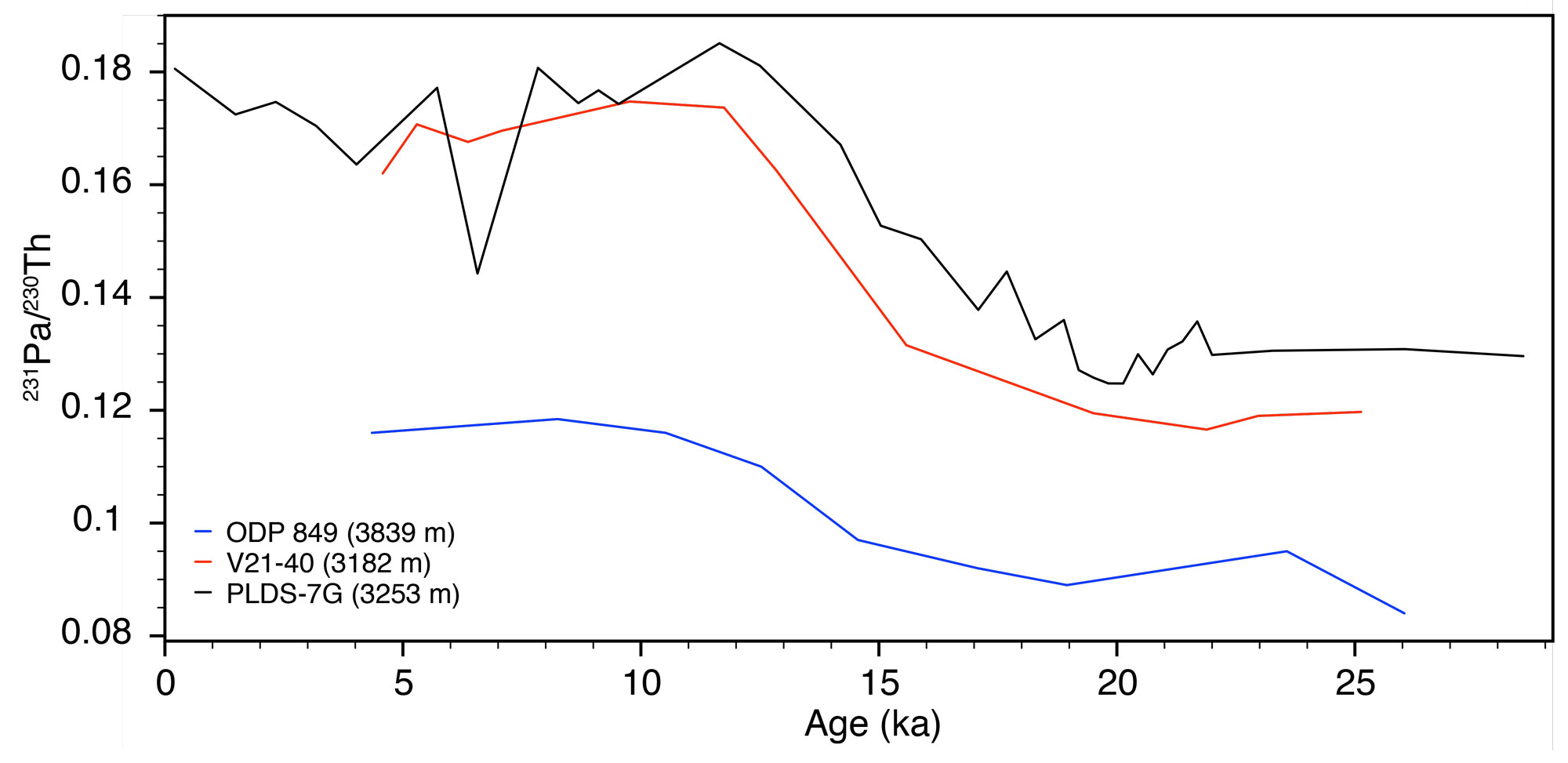
Because of the novelty of the *hummingage* method we also applied the widely used *Bacon* method to our data (Fig. S2). Since our data have been already calibrated, we disabled the calibration function in *Bacon* (cc=0). *Bacon* also divides the original data into segments and for our data it suggests roughly to use segments in the order of 10. Following, it is the subjective decision of the user, how many segments to choose until the curve “looks good”. One guideline to choose the best number of segments is to assure that the MCMC algorithm used by *Bacon* mixes well and finally, we decided to use 10, 11 or 12 segments. Lower numbers of segments show bad MCMC mixing and higher numbers of segments introduce unrealistic curvatures.

As can be seen from Figure S2, both the *hummingage* model and the *Bacon* model yield very similar results, especially also the errors are quite similar. This is an important point, because according to Trachsel et al.8, the strength of the Bayesian age-depth models, in comparison with the standard methods, is a better representation of the errors and thus a more reliable estimation of the age-depth relation. Thus, in our case, with the pre-calibrated data, *hummingage* is a real alternative, is easy to use online, and provides similar results to the sophisticated *Bacon* model. Finally, we decided to use the interpolated (1 cm) model output from *hummingage* for our analysis.

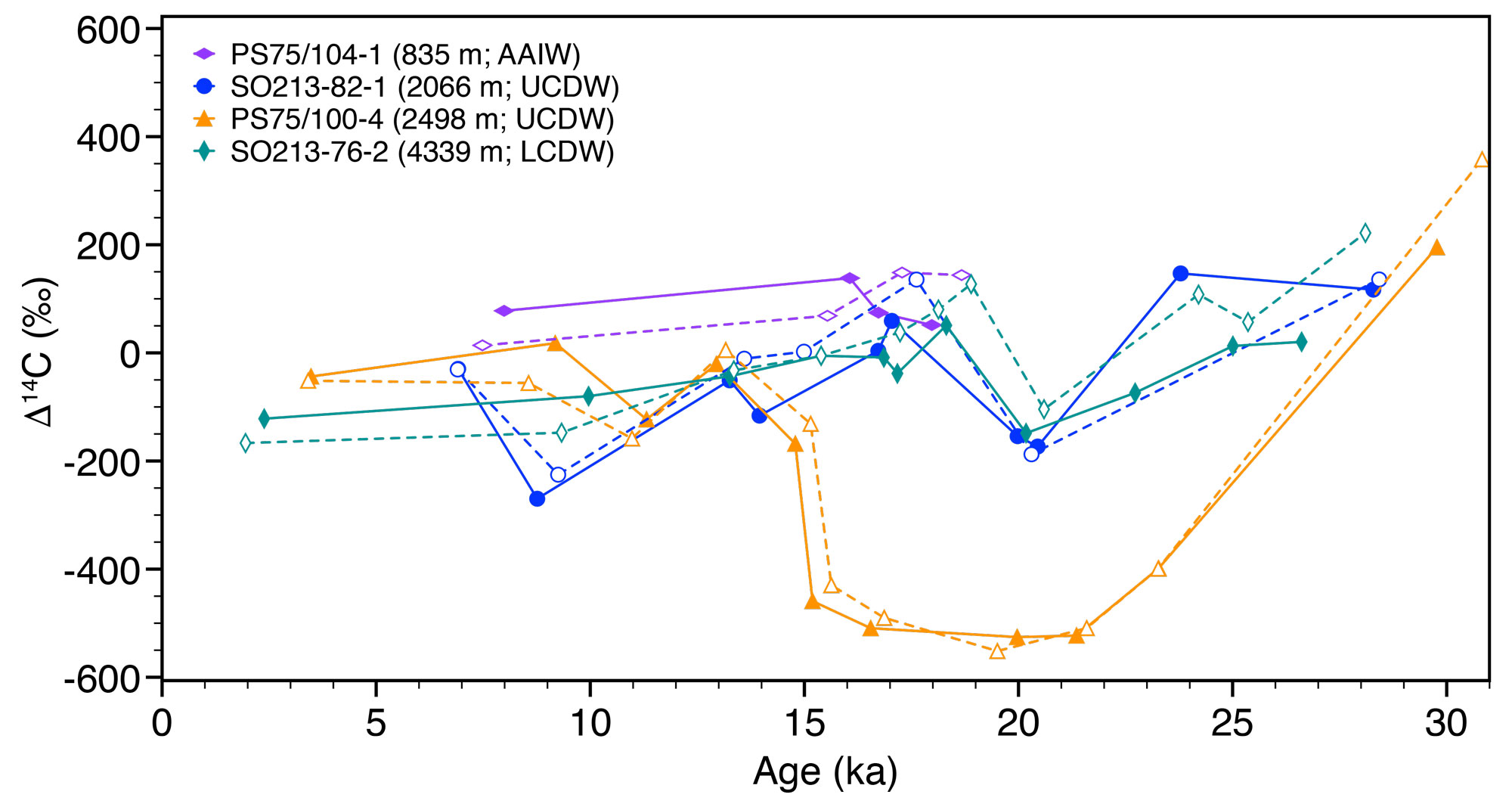
**Supplementary figures and tables**

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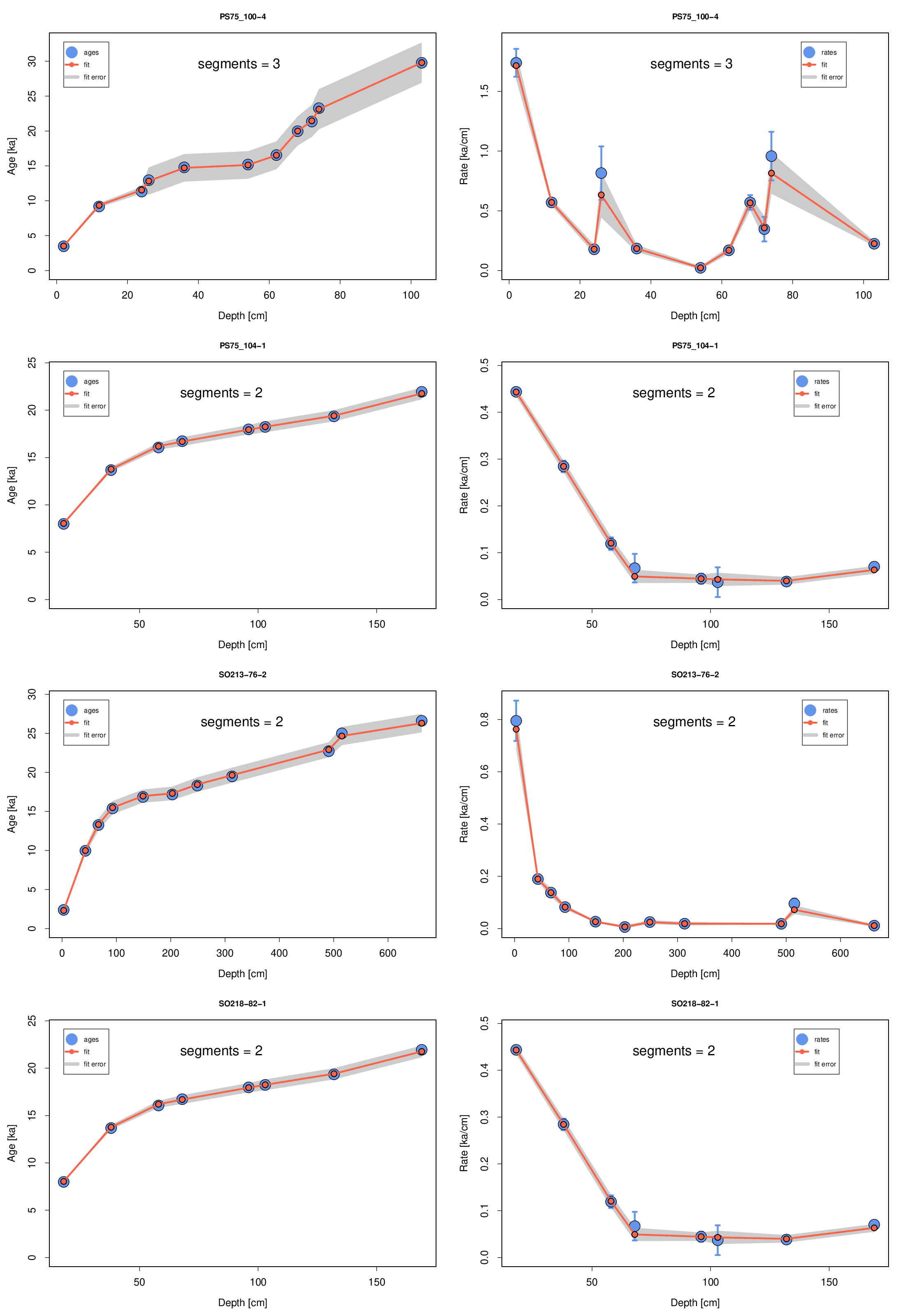
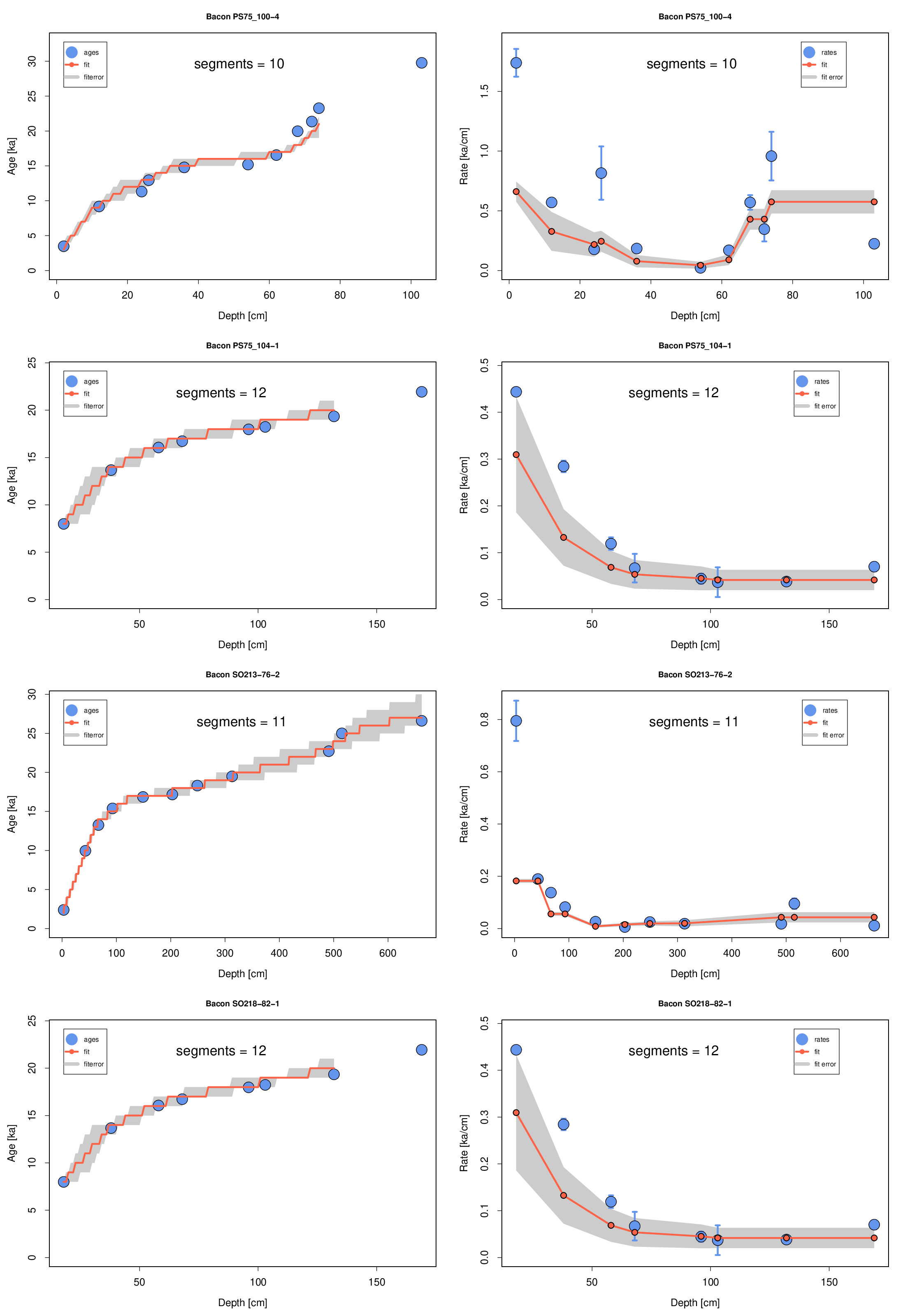
**Figure S1:** Downcore 231Pa/230Th records (colored) vs. SiO2 (black). Note the change of scale in the y-axis for the opal content for the Southern Ocean core PS75/059-2.



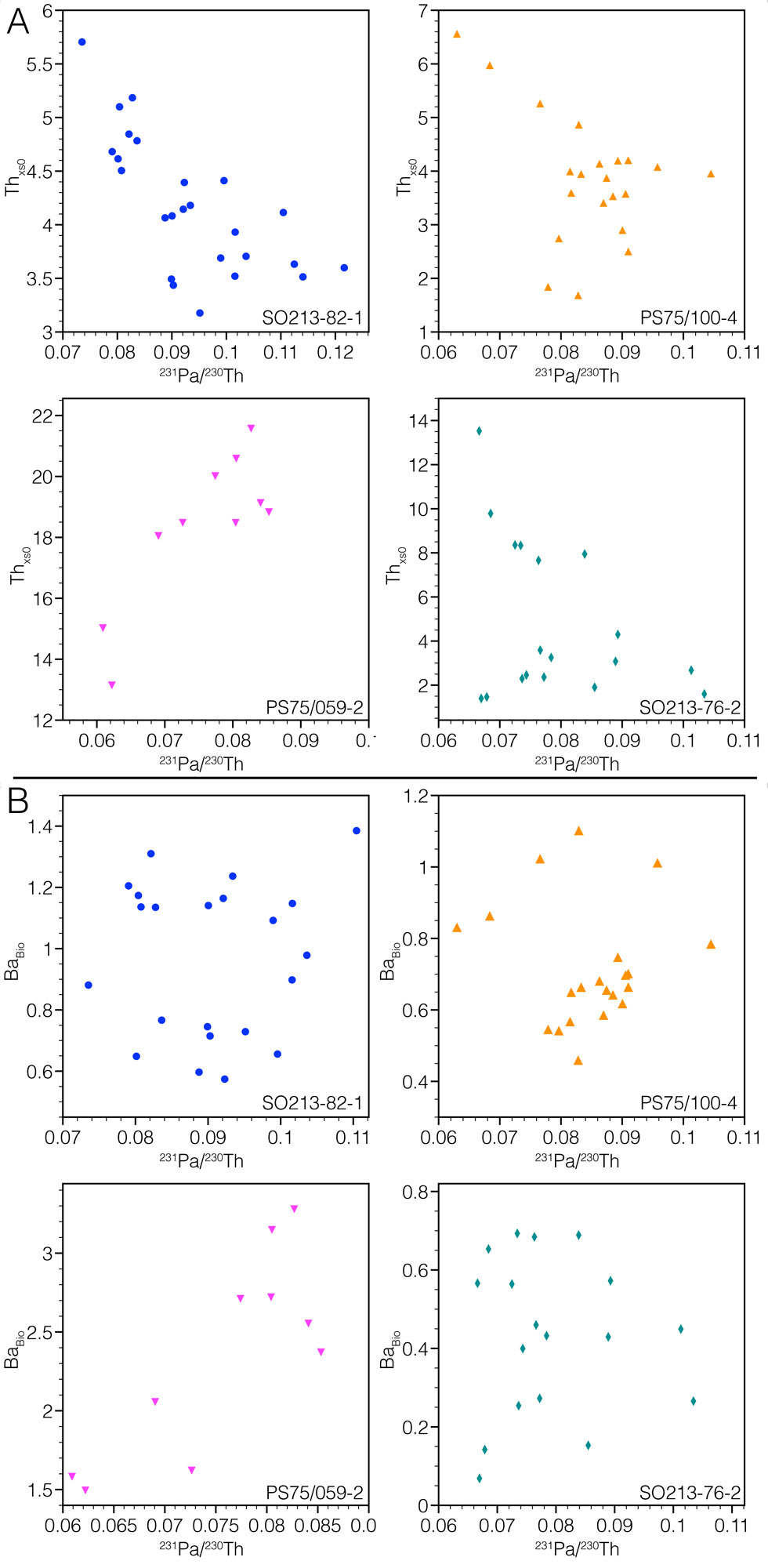
**Figure S2:** Records of Equatorial Pacific 231Pa/230Th along the East Pacific Rise23-25.



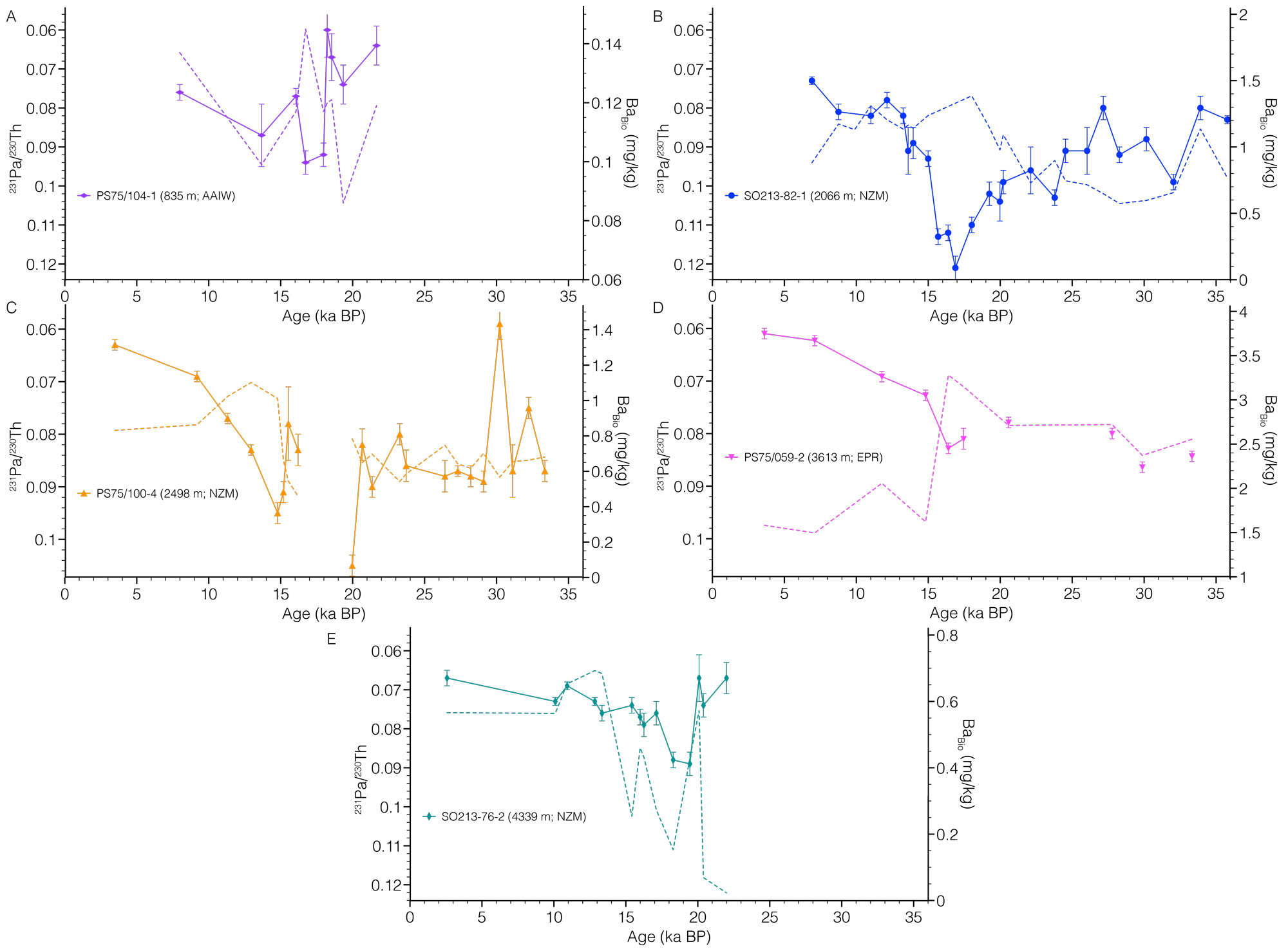
**Figure S3:** Comparison of 14C-records based on the Ronge et al.9 age models (broken lines) and our updated 14C-based age models (complete lines).

**Figure S4:** Bayesian approach to estimate the quality of our age models, using our *hummingage* (left) and the established *Bacon-*script (right).

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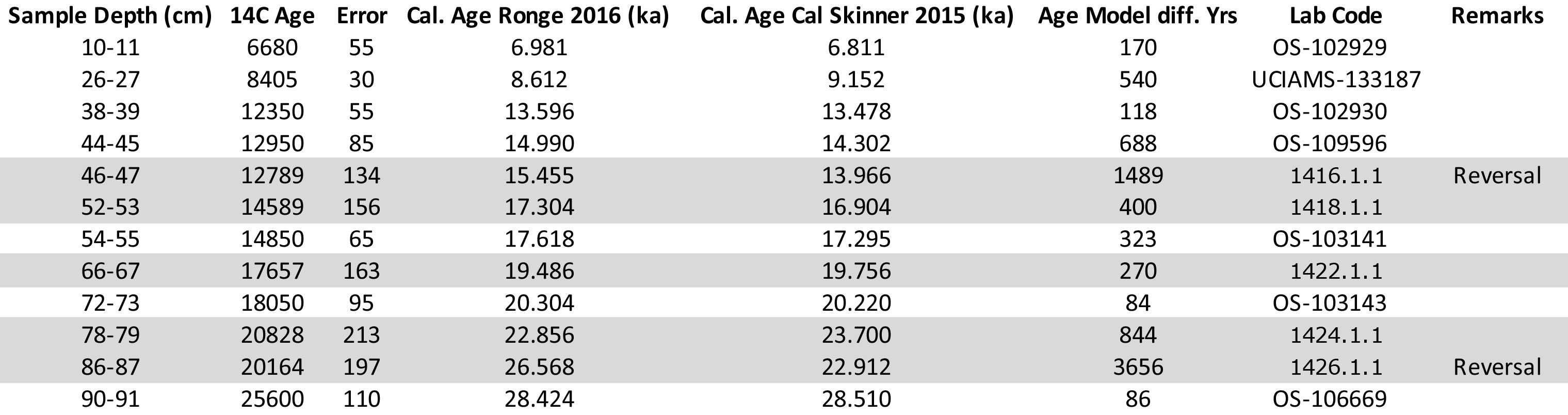
**Figure S5:** Comparison of 231Pa/230Th to Thxso **(A)** and BaBio **(B)** for all deep-water sediment records, measured on the same samples



**Figure S6:** Comparison of 231Pa/230Th and BaBio for all sediment records, measured on the same samples.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Station** | **Lat** | **Long** | **231Pa/230Th** | **Depth (m)** | **Reference** |
| V27-263 | 35.02 | -40.92 | 0.037 | 3704 | 10 |
| KNR140 31GGC | 30.90 | -74.50 | 0.066 | 3410 | 10 |
| RC13-189 | 1.86 | -30.00 | 0.056 | 3233 | 11 |
| V30-40 | -0.20 | -23.15 | 0.044 | 3706 | 11 |
| RC16-66 | -0.76 | -36.62 | 0.041 | 4424 | 11 |
| MD09-3257 | -4.24 | -36.35 | 0.067 | 2344 | 12 |
| MD95-2037 | 37.10 | -32.00 | 0.096 | 2159 | 13 |
| KN140-2-51GGC | 32.78 | -76.28 | 0.068 | 1790 | 14 |
| ODP 1063 | 33.69 | -57.61 | 0.057 | 4584 | 15 |
| 12JPC | 29.75 | -72.90 | 0.059 | 4250 | 16 |
| M35003 | 12.09 | -61.24 | 0.109 | 1300 | 16 |
| IODP 1313 | 41.00 | -32.96 | 0.051 | 3414 | 16 |
| ODP 1055 | 32.78 | -76.29 | 0.065 | 1798 | 17 |
| 55GGC | 4.90 | -42.90 | 0.045 | 4556 | 17 |
| 58GGC | 4.80 | -43.00 | 0.045 | 4341 | 17 |
| 71GGC | 4.40 | -43.70 | 0.059 | 3164 | 17 |
| 82GGC | 4.30 | -43.50 | 0.051 | 2816 | 17 |
| C2 PC-2121009 | -24.30 | -43.20 | 0.098 | 781 | 17 |
| MD3253 | -2.35 | -35.45 | 0.042 | 3867 | 18 |
| MD3254 | -2.80 | -35.42 | 0.042 | 3715 | 18 |
| MD09-3256Q | -3.55 | -35.38 | 0.047 | 3537 | 18 |
| MD3242 | -4.22 | -37.83 | 0.090 | 1008 | 18 |
| GeoB3936-1 | 12.72 | -59.00 | 0.078 | 1854 | 18 |
| GeoB3935-2 | 12.61 | -59.39 | 0.082 | 1558 | 18 |
| GeoB3937-2 | 12.56 | -58.77 | 0.079 | 1654 | 18 |
| OCE326-GGC5 | 33.70 | -57.60 | 0.056 | 4550 | 19 |
| GeoB16202-2 | -1.91 | -41.59 | 0.051 | 2248 | 20 |
| JC094-GVY14 | 15.46 | -50.99 | 0.065 | 2714 | 21 |
| EW9209 1JPC | 5.91 | -44.20 | 0.043 | 4056 | 21 |
| ODP 1059 | 31.67 | -75.42 | 0.061 | 2985 | 22 |
| ODP 1060 | 30.76 | -74.57 | 0.054 | 3481 | 22 |
| ODP 1061 | 29.98 | -73.60 | 0.057 | 4038 | 22 |
| ODP 1062 | 28.25 | -74.41 | 0.052 | 4761 | 22 |
| GeoB1515 | 4.24 | -43.67 | 0.051 | 3129 | 22 |
| GeoB1523 | 3.83 | -41.62 | 0.062 | 3292 | 22 |

**Table S1:** Sample details and references for W-Atlantic data used in Figure 1.



**Table S2:** Radiocarbon ages for sediment core SO213-82-1. Samples marked by grey shading indicate new measurements conducted for this study. Other samples were previously measured by Ronge et al.9. Cal. Age Ronge (2016) indicates calendar ages according to the 14C-independent method by Ronge et al. 9. Cal. Age Skinner 2015 is the 14C-derived age model, with surface reservoir ages accounted for according to Skinner et al.26. Age Model diff. is the difference in years between both methods.

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