# Bottom water oxygenation changes in the Southwester Indian Ocean as an indicator for enhanced respired carbon storage since the last glacial inception – cp-2021-29 (10.5194/cp-2021-20 RC1)

We highly appreciate the comments and suggestions provided by the two anonymous referees, and wished to thank them for the time and efforts invested in evaluating our work. We feel that their constructive comments contributed to clarify and strengthen our argumentation.
While both referees find merit in our work, they also highlight two important issues. The first issue relates to the robustness of our age model, for which we provide clarification below (as well as in the revised manuscript). The second issue relates to potential variations in the $^{238}U/^{232}Th$ ratio of the lithogenic material delivered to the core sites and the impact this potential variability may bear on our aU records. Since both referees highlighted similar issues, we took the liberty to provide one consolidated response to address their shared concerns.

We have strived to incorporate the suggested changes and recommendations into the revised manuscript as detailed below in our point-by-point response.

In order to efficiently refer to our responses to the reviewers' comments, we have opted to continuously number our replies. The original referee comments are in black and our responses in green.

We sincerely hope that our clarifications have satisfactorily addressed the reviewers' concerns. We remain at disposal would further questions arise.

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Anonymous Referee #1

The authors present new records of redox-sensitive elements to reconstruct bottom water oxygenation changes from the last glacial inception to the Holocene. These records were obtained on a North South transect of marine sediment cores in the western Indian sector of the Southern Ocean. The authors provide records of exported biogenic silica in the same cores to determine whether the bottom water oxygen changes are linked to increased organic carbon sedimentation or circulation changes. These data therefore provide important information concerning the mechanisms involved in the air-sea partitioning since the last glacial inception.

The paper is thus within the scope of "Climate of the Past" and could be of great interest for the community.

Reply #1: We thank referee #1 for the positive assessment of our work.

However part of the methods needs to be clearly explained.

The weakest part of the paper concerns the age models. For the sub-Antarctic core DCR-1PC the age model has been established in a previous paper (Crosta et al., 2020). However, it is necessary for the reader to see figures with

- the depth of the 14C dates and the tie-points on the aU, Mn/Ti and opal records to see where are the chronological constraints (could be added on figure 4 but it would be nice to see also the records that have been tuned)
- a depth/age plot.

In fact, the $^{14}C$ dates presented in Crosta et al. 2020 for this core may indicates a hiatus of ~5kyr between 33 and 41 cm, that would roughly correspond to isotopic stage 2. This possibility should be discussed when considering this time period.

Reply #2: We understand that the referee's argument relates to the decrease in sediment accumulation rate during this specific time interval. To the best of our knowledge, Crosta et al., 2020 did not report any age reversals, nor did they signal any major sedimentary disturbance between 33 and 41 cm. Furthermore, we were unable to find any sedimentological evidence supporting the presence of a hiatus during MIS 2. This being said, we cannot completely exclude the presence of a sedimentary hiatus, associated with the transient decrease in sediment accumulation prior to the last glacial termination and have included this potential caveat when discussing DCR-1PC's age model - "The $^{14}C$-dates indicate a possible sedimentary hiatus between 33 and 41 cm depth, which approximately corresponds to MIS 2."

As per referee #1's request, we now provide a figure illustrating the age vs depth relationship for each core (Fig. Rev1), as well as the age pointers outlined in Table 1. We note that Table 1 has been revised for the sake of clarity in the revised version of the MS (Table Rev1).

For the other cores, the dating strategy is not explained. Why correlating the core signals to benthic LR04-stack, while the sub-Antarctic core age model has been established by tuning with EPICA Dome C deuterium record? If there is a scientific reason to link the magnetic susceptibility records and the LR04-stack that have been aligned together, it has not been explained. Comparing the same/similar records of two neighbouring marine cores does not need a long explanation but any other tuning between various records requires at least a short explanation of the underlying assumptions.

Reply #3 – We certainly recognize that the strategy we followed to determine the different age models lacked clarity. Determining robust age models in Southern Ocean sediment records characterised by poor carbonate preservation is certainly a difficult task as referee #1 reckons.

We used published age models/age pointers wherever possible (DCR 1PC – Crosta et al., 2020; COR-1bPC – Oiwane et al., 2014).

Specifically for DCR-1PC, radiocarbon ($^{14}C$) measurements were carried out using Accelerator Mass Spectrometry (AMS) on planktic foraminifera *Globigerina Bulloides and Neogloboquadrina pachyderma (sinistral)*. Treatment of samples was according to the protocol used by Yokoyama et al., 2007, 2010 with graphite targets measured at the AMS facilities at the University of Tokyo. Calibration for $^{14}C$ was performed using CALIB7.02 software using the Marine13 calibration curve (Reimer et al., 2013) after a regionally-informed marine reservoir age correction of 890 ± 100 years (Butzin et al., 2005). MARINE13 was applied here because MARINE20 is not recommended for polar regions with variable sea-ice extent (Heaton et al., 2020).

For COR-1bPC, the age model is based on 23 calibrated $^{14}C$-measurements on planktic foraminifera neogloboquadrina pachyderma (sinistral) (Oiwane et al. 2014). The samples were treated according to the protocol of Yokoyama et al., 2007, 2010) with graphite targets measured at the AMS facilities at the University of Tokyo. All dates were corrected for the regional reservoir age (890 yr) (Bard, 1988) and converted to calendar years (cal yr BP) using the calibration program CALIB 6.1.0 (Stuiver and Reimer, 1993).

Regarding the PS cores, preliminary age pointers were based either on then available radiocarbon dates (Xiao et al., 2016) and/or biostratigraphic constraints. The radiocarbon measurements were carried out on the sedimentary humic acid fraction using AMS. Radiocarbon ages were converted to calendar years using CALIB4.2 (Stuiver et al., 1998) after applying a reservoir age correction of 810 years (Bard, 1988).

The preliminary age models were first refined by graphically aligning biogenic opal ($BSiO_2$) concentration measurements to the LR04 d18O benthic stack, assuming an in-phase relationship (Fig. Rev2). This approach inherently assumes that sedimentary $BSiO_2$ concentrations/export fluxes are modulated by climate variability in the Southern Ocean (e.g. Hasenfratz et al., 2019) and more specifically in the Indian sector of the Southern Ocean (Kaiser et al., 2021). Similarly, the sedimentary MagSusc signal contains a coherent climate-related component and may thus be suitable for initial age model tuning (e.g. Weber et al., 2012, 2014) (Fig. Rev3). We certainly recognize that these assumptions remain a subject of debate.

These age solutions were then further refined by graphically aligning the XRF Ca/Ti and Ti records to the EPICA Dome C (EDC) dust record (Lambert et al., 2012) assuming an in-phase relationship between both proxies and archives (e.g. Martinez-Garcia et al., 2014; Lamy et al., 2014). Again, these assumptions may raise questions, as marine and ice core records may be transiently decoupled during climate transitions of the last glacial cycle (e.g. Thöle et al., 2019). We note however, that similar assumptions underlie the development of all five records and thus, all records may be affected by similar uncertainties.
Finally, we have critically tested our age models by comparing our solutions to independently defined stratigraphies. Specifically, our age model for PS2606-6 is very similar to the stratigraphic framework published by Ronge et al., 2020. The age model for core PS2603-3, which arguably contains the fewest tie-points, was critically assessed using an independent approach based on constant rate supply (CRS) (Geibert et al., 2019). Both approaches provided very similar ages, with age offsets < 1.5 kyrs for the last 20 kyrs. In summary, we recognize that our age models may certainly be perfectible, but we feel that given the constraints and limitations, our solutions are probably realistic and permit meaningful regional comparisons on multi-millennial timescales.

The introduction is well written and the lines 59 to 69 clearly present the goal of this study. However it is disappointing to have a very simplified presentation of the role of iron in the Southern Ocean. This study concerns the Indian sector of the Southern Ocean, not the Atlantic sector and dust is probably not the major source of iron at the cores locations (Tagliabue et al., 2017, 2014 and reference therein) at any time of the last glacial cycle.

Reply #4: We certainly agree with referee #1 that the introduction could be more regionally specific. The introduction was meant to illustrate the role aeolian Fe supply may bear on past changes in export production in the Southern Ocean and more generally on the global carbon cycle (and by inference climate).
However, we feel that discussing the role and the multiple potential sources of Fe in the Indian sector of the Southern Ocean in detail lies beyond the scope of the present manuscript and will be treated separately. Indeed, the manuscript focuses on understanding the factors controlling past changes in oxygenation and not, specifically, the factors modulating past changes in export production. We indeed show that deep ocean oxygenation varied coherently along our meridional transect of cores, despite very different export production patterns between the SAZ and AZ.

For bottom water oxygenation proxies, the authors indicate that they considered two different $^{238}U/^{232}Th$ ratio, 0.5 for cores within CDW with a large NADW component and 0.27 for the deeper and southern core PS2603-3 influenced by AABW and thus Antarctic continental crust. Within the discussion, the authors consider changes in the deep Southern Ocean circulation during the last climatic cycle, with shoaling of the NADW influence (Govin et al., 2009 should be cited for the circulation changes within the Indian sector of the Southern Ocean during the glacial inception). The authors should thus consider a possible decrease of the $^{238}U/^{232}Th$ ratio for the shallower cores during the glacial stage. It might not change significantly their results but it would be nice that they indicate the corresponding uncertainty.

Reply #5: Very good point.
The rationale underlying us selecting a temporally invariant $^{238}U/^{232}Th$ ratio for the lithogenic material (i.e. 0.5, Henderson and Anderson, 2003) relates to the possibility to compare our records to those published previously for the region (e.g. François et al., 1993; Dezileau et al., 2000, 2002). This value reflects the average composition of upper continental crust material (Wedepohl, 1995; Rudnick and Gao, 2003) and the lithogenic $^{238}U/^{232}Th$ ratio has been shown to vary little (10-15%) throughout pelagic regions of the Southern Ocean, away from Antarctica (François et al., 1993; Anderson et al., 1998). Applying this specific value to the southernmost core (PS2603-3) generated negative aU concentrations, suggesting that lithogenic material originating from Antarctica (possibly supplied to the core sites via IRDs), warranted using a different value for the lithogenic background.

Although the detrital U/Th ratio may have fluctuated in response to changing detrital sources, for example during glacial intervals, the authigenic component is typically > 60% of the total U, so this correction remains small (Fig. Rev4 and Fig. Rev5). As such, a decrease in the $^{238}U/^{232}Th$ value would indeed affect the absolute aU concentrations, but not the general downcore patterns.

What's more, our interpretation is supported by the Mn/Ti records (where available). The anti-phased pattern of both proxies provides further, independent support corroborating the robustness of the aU records, in spite of potentially changing supply of detritic material through time.

As such, we remain convinced that the temporal variability in aU for all cores are primarily driven by changes in bottom water oxygenation.

Govin et al., 2009 has been cited in the revised MS.

Other questions and minor corrections are indicated with the manuscript line numbers in the following part.

Change Sigman et al., 2020 to Sigman et al., 2021

Reply #6: The reference was modified as suggested

All the figures have a 2 before their number, to be suppressed.

Reply #7: Amended

Line 210 to 214, aU do not peaks at peak glacial conditions but at the transition to termination 1

Reply #8: sentence has been modified as follows: "…before reaching highest values at the end of peak glacial conditions just before the start of deglaciation."

Line 254 to 270: the authors could also consider the possible hiatus in the core with a missing isotopic stage 2.

Reply #9: We added the following clarification: "As the $^{14}C$-dates in core DCR-1PC, and more specifically, the transient decrease in sediment accumulation, may indicate a possible hiatus during the time interval corresponding to MIS 2, the comparatively early decrease in aU could alternatively be explained by the absence of this critical sedimentary interval."

Line 286: I do not understand the sentence: in the Polar frontal zone the nutrient availability was reduced compared to interglacial period but the nutrient availability is always higher in the Polar frontal zone than closer to the Subantarctic front. Again consider also a possible hiatus, as indicated by $^{14}C$ data.

Reply #10: sentence was modified to take the possible presence of a sedimentary hiatus into consideration

Line 306 "alternative" , n missing

Reply #11: Amended

Line 315 Is it the sampling resolution or the uncertainty of the age models that precludes to assess the potential time lag between cores?

Reply #12: The sampling resolution is probably insufficient and the time interval related to the diagenetic aU peak emplacement cannot be robustly defined. As such a potential time lag cannot be assessed reliably in sedimentary records characterised by relatively low sedimentation rates.

Changed text to: "However, as the timing of aU peak emplacement cannot robustly be defined and the sampling resolution may be insufficient, the potential time lag between the onset of the aU decrease and the sharp rise in opal production and deposition cannot reliably be assessed."

Line 316 to 325 the increase in aU seems to be at the beginning of the Holocene not during the deglaciation, as well as the opal peak in the PS2603-3. Do the authors consider a possible 5kyr error on the age scale at that time? We really need to see the records that were tuned to benthic LR04 record or EPICA Dome C deuterium and the tie points considered.

Reply #13: The statement related to the ACR was indeed too speculative given our age model constraints and has consequently been removed.

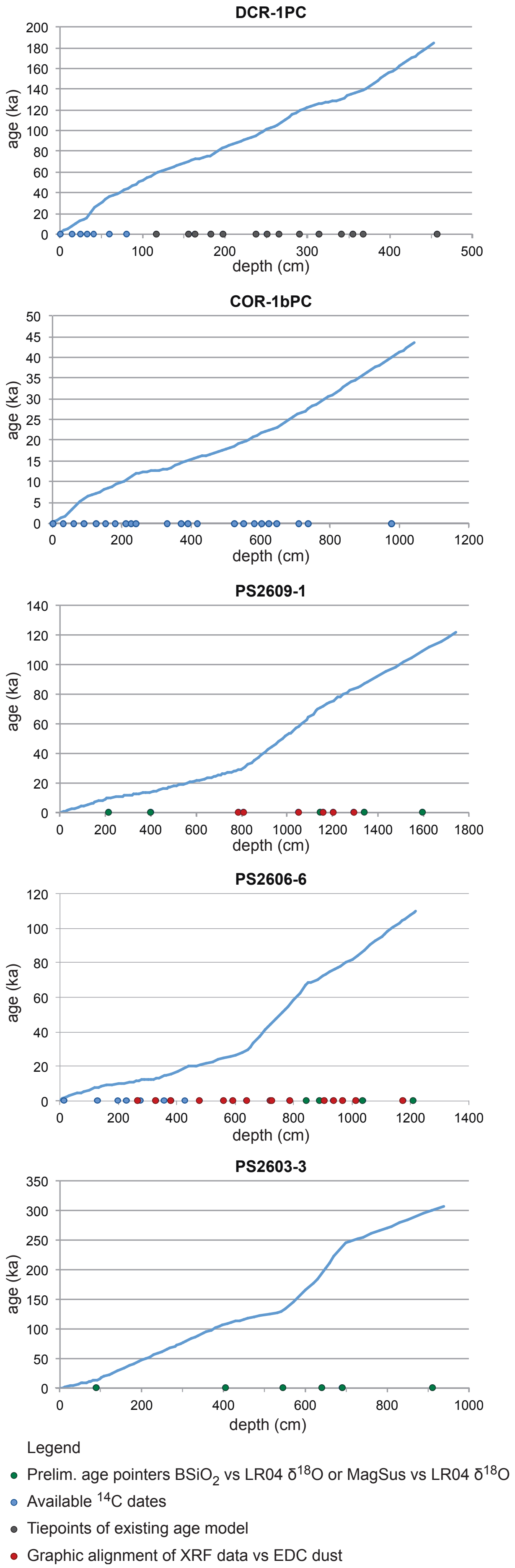


Fig. Rev.1: Age vs depth for each core.

Table Rev.1: Tie points of cores PS2609-1, PS2606-6, and PS2603-3. Colors according to Fig. Rev1.

**Tie points PS2609-1**

| Depth (cm) | Age pointers (ka) | based on |
|---|---|---|
| 0 | 0 | |
| 215 | 10 | Ca peak |
| 400 | 14 | MagSus vs LR04; $BSiO_2$ vs LR04; Si/Ti vs LR04 |
| 785 | 28.68 | Ti (XRF) vs EDC dust |
| 808 | 29.88 | Ti (XRF) vs EDC dust |
| 1050 | 58.2 | Ti (XRF) vs EDC dust |
| 1145 | 71 | MagSus vs LR04; Fe vs LR04 |
| 1157 | 72.25 | Ti (XRF) vs EDC dust |
| 1202 | 75.87 | Ti (XRF) vs EDC dust |
| 1293 | 83.6 | Ti (XRF) vs EDC dust |
| 1340 | 87 | MagSus vs LR04; Fe vs LR04 |
| 1595 | 109 | MagSus vs LR04; Fe vs LR04 |

**Tie points PS2603-3**

| Depth (cm) | Age pointers (ka) | based on |
|---|---|---|
| 0 | 0 | |
| 90 | 14 | $BSiO_2$ vs LR04; rouxia lenenterae |
| 405 | 109 | $BSiO_2$ vs LR04; hemidiscus karstenii |
| 545 | 130 | $BSiO_2$ vs LR04 |
| 640 | 191 | $BSiO_2$ vs LR04; rouxia constricta |
| 690 | 243 | $BSiO_2$ vs LR04 |
| 910 | 300 | $BSiO_2$ vs LR04 |

**Tie points PS2606-6**

| Depth (cm) | Age pointers (ka) | based on |
|---|---|---|
| 0 | 0 | |
| 14 | 1.92 | $^{14}$C - Xiao et al. (2016) |
| 128 | 8.08 | $^{14}$C - Xiao et al. (2016) |
| 198 | 10.06 | $^{14}$C - Xiao et al. (2016) |
| 228 | 10.39 | $^{14}$C - Xiao et al. (2016) |
| 266 | 11.51 | Ca/Ti (XRF) vs EDC dust |
| 275 | 12.12 | 14C - Xiao et al. (2016) |
| 328 | 12.79 | Ca/Ti (XRF) vs EDC dust |
| 357 | 14.52 | $^{14}$C - Xiao et al. (2016) |
| 380 | 15.07 | Ca/Ti (XRF) vs EDC dust |
| 427 | 19.68 | $^{14}$C - Xiao et al. (2016) |
| 478 | 20.56 | Ti (XRF) vs EDC dust |
| 559 | 24.67 | Ti (XRF) vs EDC dust |
| 591 | 26.20 | Ti (XRF) vs EDC dust |
| 639 | 29.20 | Ti (XRF) vs EDC dust |
| 719 | 44.39 | Ti (XRF) vs EDC dust |
| 725 | 45.44 | Ti (XRF) vs EDC dust |
| 786 | 55.27 | Ti (XRF) vs EDC dust |
| 844 | 67.90 | MagSus vs LR04; Ti, Ca (XRF) vs EDC dust |
| 889 | 71 | MagSus vs LR04 |
| 905 | 73.30 | Ca/Ti (XRF) vs EDC dust |
| 936 | 75.87 | Ti (XRF) vs EDC dust |
| 968 | 78.93 | Ca/Ti (XRF) vs EDC dust |
| 1013 | 83.6 | Ca/Ti (XRF) vs EDC dust |
| 1036 | 87 | MagSus vs LR04; Ti, Ca (XRF) vs EDC dust |
| 1174 | 104.69 | Ca/Ti (XRF) vs EDC dust |
| 1210 | 109 | MagSus vs LR04 |

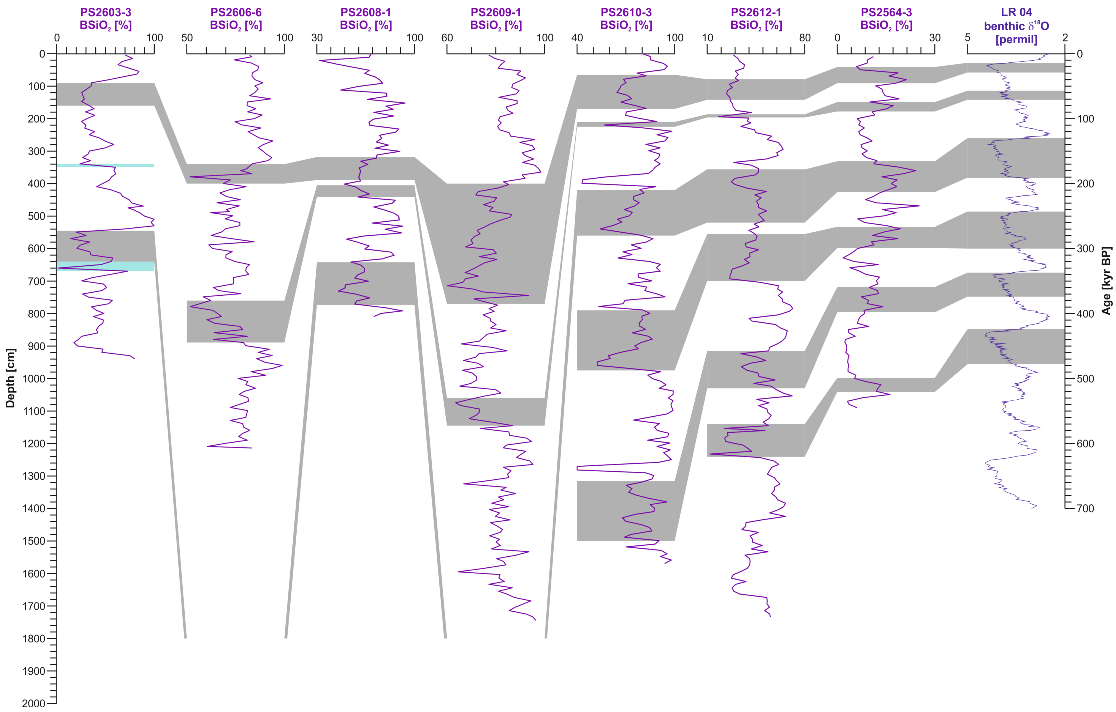


Fig. Rev2 Preliminary stratigraphic correlation between the dowcore BSiO2 data for the PS cores and the LR04 benthic d18O stack (Lisiecki and Raymo, 2005).

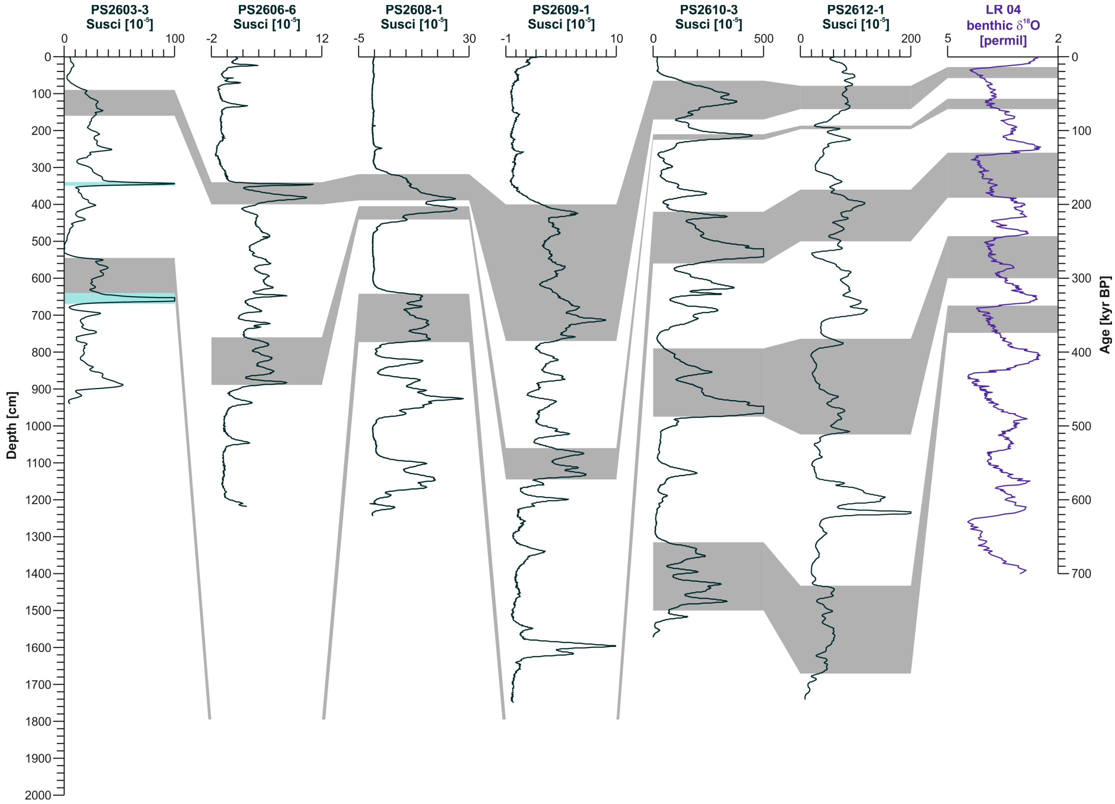


Fig. Rev3 Preliminary stratigraphic correlation between the dowcore MagSusc data for the PS cores and the LR04 benthic d18O stack (Lisiecki and Raymo, 2005).

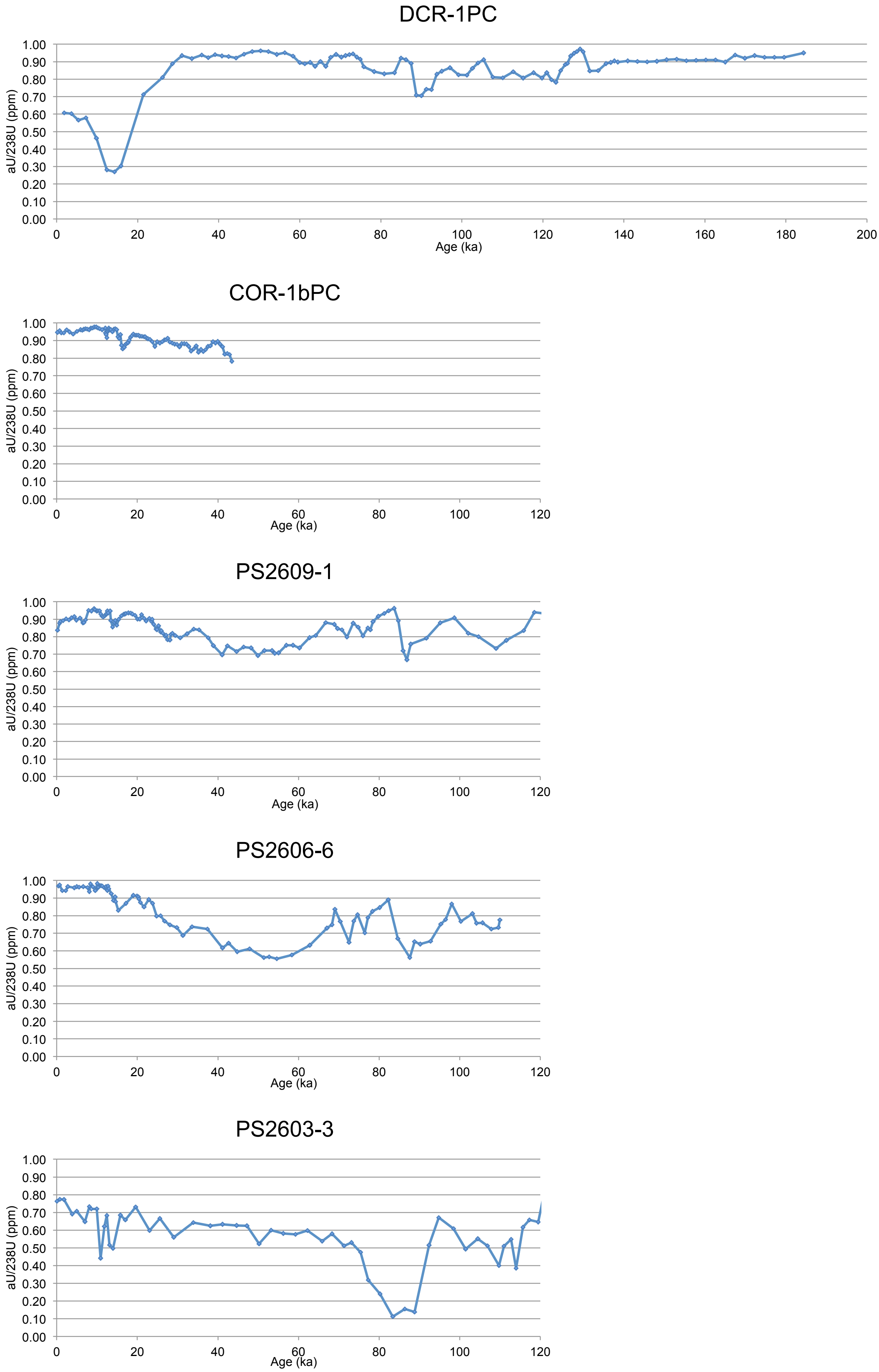


Fig Rev4: Authigenic component of the total U in all cores.

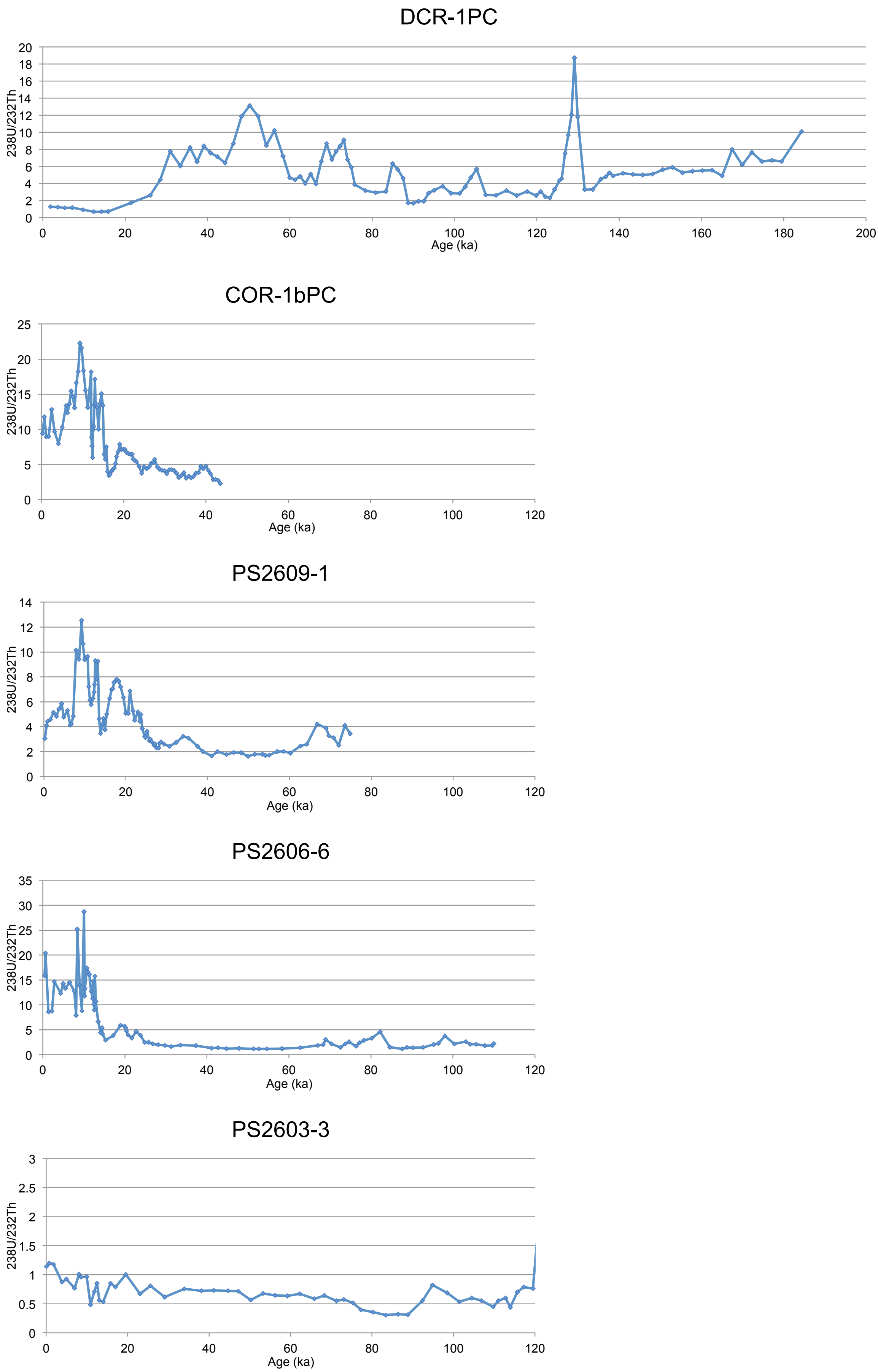


Fig Rev5: Changes in $^{238}U/^{232}Th$ over time in all cores.