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Dear Dr. Paul / Dear André,

Below you will find our point-to-point response to the critique raised by two referees, that were constructive and very helpful. Inversely, we regret not having an opportunity yet to include a response to the "extended comment" that Bard & Heaton recently announced to submit to C.P.

Following the advice of Ref. #1 and #2 we have carefully revised and streamlined many sections of our manuscript either following directly the comments of the two referees and/or taking care of their legitimate critique by broadening our empirical evidence and arguments in support of our strategy, interpretations, and conclusions, as outlined in detail below. For a better insight we submit a revised version of both our merged manuscript and the Supplementary Materials, where our recent changes are marked in RED.

We thank you for your great efforts to handle this manuscript that have provided us with the opportunity of manuscript revision, that is, for your help to improve on our manuscript and the quality of our working hypotheses. In turn, we hope and are confident that our manuscript may now satisfy the needs for publication in C.P.

Sincerely,
Michael Sarnthein and Co-authors

In particular we follow your recommendation to consider the following issues:

(1) As a highlight in its own right, to present in a dedicated Results section the "shift to the U/Th modeled Suigetsu chronology" (review #1)/the "new findings regarding the age scale of the target atmospheric (Suigetsu) 14C record" (review #2). This would basically correspond to part 1 of the paper (or a hypothetical series of two papers) as proposed by referee #1.

We now upgrade Section 2 of our manuscript to a "Results section" that further stresses our new findings regarding the age scale of the atmospheric (Suigetsu) 14C reference record.

Here Subsection 2.2 was renamed to "Suigetsu atmospheric ^{14}C record: Shift to a chronology based on U/Th model ages"

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(2) ,,,,,, to extend the Discussion section "to expand a bit more to adress a few
more points as other explanations for marine 14C plateaus" and include figures S2
and S3 in the main text (review #1) and "refocus on the advantages and disadvantages
of the 14C plateau tuning technique" and the comparison of the resulting surface
ocean reservoir ages to models, existing databases and results from other techniques
(review #2). This extended Discussion would correspond to part 2 of the paper as
proposed by referee #1.
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We now start our Results section by a new two-page subsection 2.1 named “Suite of planktic ^{14}C plateaus: Means to separate global atmospheric from local oceanographic forcings”. In this way we try to meet explicitly potential weak points (but disagree with the term “disadvantages”) of the ^{14}C plateau tuning technique. Detailed comparisons to other reconstruction methods of ^{14}C reservoir ages have already been detailed in subsection 1.2 of the Introduction, a section we do not like to repeat, but slightly enlarge. On the other hand, previous Subsection 3.3 on the definition and origin of Zoophycos burrows is now deleted. Also, Subsection 3.2 (comparison of reconstructed and modeled ocean reservoir ages) is slightly enriched by a reference to results from other reconstruction techniques that – in our view -- have produced less helpful results.

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Points (1) and (2) would follow up on the suggestions by referee #1 without actually
splitting the paper in two papers.
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We feel happy to keep basically, though with various necessary modifications, the present organization of our paper.

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At the same time, I strongly agree with referee #2 that the manuscript would need
some serious streamlining, reduction of redundancy and possibly removal of less
important sections.
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In harmony with ref. #2 we now streamlined the manuscript, e.g., by deleting a complete subsection (former #3.3). On the other hand, we had to insert a new Subsection 2.1 and many answers to questions of the reviewers, a dilemma with regard to manuscript length. Also, we see a genuine trait of any 'synthesis' paper to include both some recaps of important results already published and a test of the power of the plateau-tuning technique to produce global age markers, that is, to show major implications for our understanding of ocean circulation, climate, and the carbon cycle in the past that make the 'dry' report on a new dating technique more attractive for C.P. readers. Altogether, the length of our text remained constant.

,,

RESPONSE TO ANONYMOUS REFEREE #1

We thank for a very constructive and helpful review.

Response to specific comments

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The authors have gone to great lengths to try to organize the paper in a way that
helps to wrangle the many topics presented, but I think this paper would benefit
from being split into two (companion) papers.
```

We truly pondered to follow this interesting proposal. For two reasons, however, we see problems in its realization: (1) To be published in a journal named CP any dry report on a new marine dating method also needs to display some major implications in the field of paleoceanography (as now given in Sections 3.1–3.3) to be attractive for CP readers. (2) A subdivision of this manuscript and subsequent review process of two companion papers would be that time consuming that our manuscript might gradually lose timeliness.

```
,,, the paper could be simplified to enhance accessibility by deleting some of
the unnecessary words (hence, thus, moreover etc.).
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We are aware that native English readers may suffer from our wording being somewhat biased by a foreign mother tongue, where connectional adverbs appear helpful to generate a 'red thread' of reasoning, though perhaps somewhat colloquial. We went through the manuscript and deleted such words where we felt they did not add to the flow.

```
I think it is very important that they have used the introduction to address some of
the criticism that has been raised with the plateau tuning method. However, I think
this is an area that could be expanded a bit more to address a few more points such
as other explanations for marine 14C plateaus, including local shifts in air-sea gas
exchange or upwelling, and if so, how can we account for these.
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This is an important remark. We now broaden our Results section by a two-page long new subsection 2.1 named “*Suite of planktic ^{14}C plateaus: Means to separate global atmospheric from local oceanographic forcings*”. Based on this resumé we try to meet explicitly potential weak points of the ^{14}C plateau tuning technique (points that actually had already been discussed in our previous publications since Sarnthein et al., 2007).

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,,, it would be helpful to address why using the Suigetsu record for plateau tuning
is preferred to Intcal. It seems that correlation directly to Intcal may be more
conservative.
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As now added to our text (end of Subsection 1.2), we prefer the Suigetsu record, since it is based on original primary atmospheric data and results in small-scale spatio-temporal changes of reservoir age, whereas IntCal is mixing and smoothing a broad array of different data sources with comparatively coarse time resolution, including carbonate-based marine and speleothem records. Combining these diverse records results in various unsolved problems and assumptions that finally resulted in major differences between the IntCal 13 and 20 records.

```
(If the paper is split into two separate papers), , , , figures S2 and S3 should be
included in the main text of the synthesis paper. I found these figures particularly
helpful for visualizing the geographic spacing of Plateau tuned records and their
findings.
```

Figs. S2 and S3 are now included in the main text.

More detail included for sections 3.2-3.3 would also be welcome along with a picture/diagram of the Zoophycus burrow.

Following the suggestion of Ref.#2 we now have deleted the 'Zoophycos story' of former Subsection 3.3, in particular, since details are published in detail by Küssner et al., 2018.

Specific notes: Figure 1: It isn't clear in the figure caption what the difference is between the top and bottom panels.

In the figure caption we now specify that the top panel shows the record from 19–29 cal. ka and the bottom panel that from 10–20 cal. ka.

Figure 7: Please include the references for the records used in this figure.

As cited in the caption of (new number) Fig. 8, all references are given in Table 3 a-c.

It would also be helpful if I could match the data points in the x-y plot to the data points on the map, perhaps using symbols or colors.

All data now are labeled with the sea region wherefrom a sediment record was obtained.

Also, I'm not sure inclusion of the surface currents in panel b or in figure S3 are helpful, they make it a bit more difficult to see where the cores are located and to read the reservoir age differences - especially because the currents are available in figure S2.

We regard the arrows of surface currents (now Fig. 8) as important for a straight-forward comparison of different reservoir ages to different sea regions linked to different surface water currents in east-west direction, important to assess the limits of spatial extrapolation of reservoir ages.

Lines 601-603: Include the unit the corresponds to the foraminifera habitat depths.

Thanks: (m)

Section 3.4, Lines 656-663: Might be good to mention the interspecies 14C differences from Lindsay et al., 2015.

Thanks (ref. is now included).

Sections 3.5.1 and 3.5.2: In a few spots it would be helpful if the results from plateau tuning studies were more clearly emphasized. This would nicely highlight the important role that this technique has played in our understanding of LGM and HS1 MOC. This is done very nicely in section 3.5.3.

Thanks for an important suggestion. We now highlight some of the results of our new technique in the text, for instance, the formation of NADW during LGM, the HS-1 reversal of global MOC, and the reach of NPDW up to the South China Sea during HS-1.

Figure 9: This figure is a bit small and hard to see. The overlapping arrows can also be a bit confusing.

Indeed, opposed arrows for ocean currents are a bit confusing, since the east-west structures of the ocean are projected on a simple 2D meridional transect. Many arrows show opposed directions because of differential Coriolis forcing, especially so in the North Pacific and North Atlantic (as now specified in figure caption and text).

Overall, I find that this figure is critical for visualizing the findings from sections 3.51-3.5.2,

We hope to display this figure in landscape format spread over a full page of CP. This will require a discussion with the publishing editor.

, , it might be helpful to also include the modern MOC for comparison.

Today the display of a modern MOC may appear too repetitive since it has already been published in that many versions of textbooks.

,,,

RESPONSE TO ANONYMOUS REFEREE #2

General statements (paragraphs on page C1 - C2)

-->Thank you for numerous very helpful comments to improve the quality of our manuscript.

The method has not been extensively used outside the first author's group, which might be associated with some sceptisism towards this method.

-->It is common to novel hypotheses and techniques to take some time until their acceptance by a dominantly conservative community that even may try to suppress a new approach. By now, the approach of ^{14}C plateau tuning has been successfully applied to more than 20 records of marine sediment cores, yielding a consistent output from regions with high sedimentation rates (>10cm/ky).

This paper is therefore very welcoming as it presents new findings regarding the age scale of the target atmospheric (Suigetsu) 14C record, uncertainties of this age scale at plateau boundaries, and 14C reservoir age changes in the ocean.

-->The positive judgement of our efforts is acknowledged.

Assuming the robustness of the method, the authors suggest that it provides "precise" chronostratigraphic control for marine sediment cores

-->We now replace "precise" by "accurate", a term that meets more precisely the quality of our results.

In my view, all of these topics overload the paper, as the paper goes off too many tangents, and in fact blurs the main message(s) of the paper.

-->and:

The paper appears too "crowded", as a number of aspects are discussed: the state of the AMOC and PMOC during the LGM, global circulation changes during the last deglaciation, the global carbon cycle and a model-data comparison. These topics in fact merit their own studies, so I can just recommend once more to streamline the paper and remove redundancy.

-->In our view a 'synthesis paper' on a new, purely 'technical' approach needs to display the wealth of published and unpublished aspects and tangents that result from the technique, an effort that necessarily includes elements of previous publications but does not rank under redundancy. We consider it as genuine trait of a 'synthesis' to include both some recaps of important results already published and various tests of the value of the plateau tuning technique to produce global age markers. A synthesis needs to show major paleoclimatic implications that make the dry report on a new dating technique attractive to readers of CP.

Inversely, we followed the suggestion and deleted the subchapter on Zoophycos burrows. Also, we carved out a clearer separation of the RESULTS from the DISCUSSION AND IMPLICATIONS section.

, , , the paper should re-focus on the advantages and disadvantages of the 14C plateau tuning technique

-->and:

I however miss a more nuanced discussion of potential disadvantages of the technique and the underlying assumptions in places. For instance, when is the technique best applied? What are the underlying assumptions, and are there uncertainties associated with these assumptions? What resolution of the tuning record is required?

-->We follow this helpful suggestion and broaden our Discussion section by a one-page long recap of our previous publications in the new *Subsection 2.1* named "*Suite of planktic ^{14}C plateaus: Means to separate global atmospheric from local oceanographic forcings* ". In this way we address potential weak points of the ^{14}C plateau tuning method. We explicitly reject the referee's term "disadvantages". Subsection 2.1 also recaps some technical needs (e.g., minimum sedimentation rates of 10 cm/ky of hemipelagic deposits, minimum ^{14}C dating resolution of ~100-150 yr, as published in Sarnthein et al., 2007).

This would mean to significantly shorten or remove the bioturbation section and/or repetitions of previous published work e.g. on the carbon cycle.

-->The bioturbation section has now been deleted. Other recaps are maintained, as necessary parts of this synthesis paper.

The paper appears too "crowded", as a number of aspects are discussed: , , , , so I can just recommend once more to streamline the paper and remove redundancy.

-->Our philosophy on the traits of a 'synthesis paper' has been outlined above.

, , , so it should be more clearly highlighted what are the new findings

-->Thanks for a good suggestion. These are 'new findings' since our last synthesis paper 2015:

- Switch to U/Th-based model ages for ^{14}C plateaus boundaries in 18/20 sediment cores,
- Inclusion of ^{14}C records from nine new sediment cores into our synthesis,
- Global data-model intercomparison for LGM and Heinrich-1 surface waters,
- Generation of global deep-water transects.

-->The listing is now incorporated in the text at the end of the Introduction and in Section 3.1.

<u>--> Response to 'major points' and specific questions</u> (page C3-C4-C5)

(1) Comparison with latest compilation of surface ocean reservoir age variations of Skinner et al. (2019) and Stern and Lisiecki (2013). The authors have synthesized surface ocean reservoir age records based on the 14C plateau tuning technique that are interpreted for potential driving mechanisms and implications regarding changes in atmospheric CO2. However, it is not clear why other reservoir age estimates have been neglected for instance those based on paired tephra-foraminifera 14C analyses (Skinner et al., 2015; Sikes and Guilderson, 2016) or those resulting from stratigraphic tie points (e.g., Waelbroeck et al., 2001). The fact that these estimates are low in resolution, should not diminish their veracity. I strongly recommend that plateau-tuned surface ocean reservoir age estimates are compared with results from other techniques, in particular Skinner et al. (2019).

-->Detailed comparisons to other methods for tie points to reconstruct past variations in surface ocean reservoir age were given in Subsection 1.2 of the Introduction, in particular in "paragraph 2", that we do not like to repeat in the discussion. Now, however, no problem to enrich the paragraph by additional remarks and references to authors listed by Ref.#2.

-->• To be fair, the paper of Skinner et al. (2019) appeared only two weeks after our manuscript submission. Of course, we appreciate to read that these authors -- like ourselves -- now fully recognize the concept of strongly variable spatiotemporal patterns of surface water reservoir age. We feel happy to include into our discussion the results of this single-core study, that also includes detailed (though in part somewhat debatable) alignment of paleoclimate records.

-->• We agree, each low-resolution age tie point *per se* has full veracity. Being spaced over 5-10 ky, however, these tie points cannot depict the actual dramatic short-term variability of res. ages now revealed for glacial-to-deglacial records by means of ^{14}C plateau tuning, hence won't provide the accurate timing of paleoclimatic events needed for proper age correlation.

-->• Stern and Lisiecki (2013) indeed had been cited in "§2", but unfortunately deleted in a "streamlining action" prior to our manuscript submission. Based on pers. comm. with L. Lisiecki (Cambridge, 9-2018), however, we (M.S.) learned that the uncertainty range of their age assignments for the LGM amounts to ±1.5–±2.0 kyr, a range problematic for any proper correlation of multi-centennial-scale events in paleoceanography.

-->• Valuable age tie points and reservoir ages were derived from ^{14}C ages of planktic foraminifera paired with ^{14}C dated tephra layers as cited in "§2" of Subsection 1.2. Most of these tie points, however, are far too wide-spaced in peak glacial-to-early deglacial sediment records to meet the need to specify millennial-scale LGM-to-deglacial changes in ocean circulation, which may involve wrong age correlations. A rare deglacial suite of four tephra-based reservoir ages off Chile (Siani et al., 2013) was clearly reproduced, its variability, however, was much refined by ^{14}C plateau-based reservoir ages (Küssner et al. (subm.). Accordingly, we now broaden our discussion of tephra-based ages in "§2". -- Tephra-based results of Waelbroeck et al., 2001 and 2011 had been properly cited in our text.

2) Drivers of 14C plateaus: The causes of 14C plateaus are seemingly not well understand. The plateau tuning technique assumes that oceanic and atmospheric 14C records occur simultaneously, with identical duration and without any temporal offsets, and can unequivocally be identified in the often low(er)-resolution ocean records (see lines 216-217, or line 223). Do all of these conditions always apply?

-->and:

The authors outline that "air-sea gas exchange transfers the atmospheric 14C fluctuations into the surface ocean" (line 178-179), but it remains unclear how ocean degassing (of 14C-depleted CO2), sea ice and/or wind changes might have affected this one-to-one assumption.

-->We now added the new *Subsection 2.1* on the "*Suite of planktic ^{14}C plateaus: Means to separate global atmospheric* etc." to avoid this misunderstanding: Indeed, only plateaus during which local oceanograpy did not change significantly will correlate and without much delay or change in duration in view of the rapid atmosphere-surface ocean exchange. Thus, the possibility of local ocean effects necessitates the use of a complete suite of ^{14}C plateaus (and their estimates of reservoir age) to achieve a best-possible tuning of each sediment core. In this case one or two disturbed plateaus (out of up to 19) won't hinder valuable results for the others and, at the same time, provide evidence of local short-term oceanographic changes. Finally, our records show that reservoir ages generally vary with climate changes on time scales of 1000 and more years in contrast to generally much shorter atmospheric plateaus.

```
In my view, this poses serious challenges to the 14C plateau tuning technique
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-->These changes are at least as challenging for IntCal where a close correspondence between ^{14}C levels in the surface ocean and in the atmosphere is assumed to justify the use of ocean carbonate records for the reconstruction of atmospheric ^{14}C. A comparison of IntCal13, IntCal20, and MarineCal20 for the time period older than 14 cal. ka shows how much work still needs to be done and how plateau tuning can contribute valuable data. In contrast to Marine Cal20 and IntCal where the timescale of the ocean record is largely based on climate wiggle matching beyond 14 cal ka our plateau tuning is based on atmospheric wiggle matching.

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,,,, These potential caveats are not fully discussed.
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-->To meet this objection we now added the new *Subsection 2.1.*

```
recommend to address potential disadvantages , , , ,
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-->and:

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the community has not really embraced this technique yet.
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-->The tuning technique does not have "disadvantages", rather potential weak points that need consideration. At least the technique is better than most other ways to produce R data with high spatial and centennial-to-millennial-scale resolution.

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It might also be beneficial to tone down some of the overselling language.
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-->We agree, it never is good to oversell. E.g., we may replace "far" by "a bit" superior.

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,,, the method works "wherever [sediment is] retrieved in the global ocean"
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-->Indeed, we need to specify and say: "wherever cores with high hemipelagic sedimentation rates are sampled"

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Furthermore, the authors seem to make clear that the assumption "[. . . ] these
plateau/jump structures are real and widely reproducible in marine sediment records"
(lines 245-246) remains a speculation.
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-->The objection that our assumption remains a speculation is simply not true. Our assumption is, as stated, general and common with those of IntCal. Each new sediment record that, after high-resolution dating, provides a suite of jumps and plateaus that can be correlated with the atmospheric master curve and our planktic records, confirms the practical applicability of the assumption. These findings are no "speculation" but apply to ^{14}C records of by now 20 (plus one more recent, yet unpublished) sediment cores from the global ocean.

-->Yet, we agree, "one always needs to be cautious". Therefore, we insert a "most likely" because signs of local disturbing influences must always be looked for.

```
Line 395-398 and line 477-483: The authors compare the timing of atmospheric 14C
plateaus with major changes in the atmospheric CO2 record in order to emphasize
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the impact of ocean outgassing on the atmospheric CO2 record. Their arguments based on this comparison is inherently weak, as a number of 14C plateaus are not associated with a major shift in atmospheric CO2. This should be acknowledged and discussed in more detail.

-->In (former) L. 501-507 we had already acknowledged the weakness of our understanding of several causal links that might have controlled the origin of atmospheric plateaus and jumps. We broached pulsed ocean outgassing as one amongst various other forcings and now terminated (present) Subsection 2.3 with the following sentence (now L. 531):
<<However, there is still little information on the origin of several other peak glacial ^{14}C plateaus 17.5–29 cal. ka. The actual linkages of these plateaus to events in ocean MOC still remain to be uncovered.>>

What causes a temporal agreement between the two, why would the same process not operate at other times of 14C plateaus? What does this tell about the mechanisms driving atmospheric 14C plateaus, and in particular the assumed synchronicity between atmospheric and oceanic 14C changes?

-->Reformulated *Subsection 2.3* tries to make clear that due to the many factors involved it is often not possible to pinpoint a single dominant forcing of an atmospheric ^{14}C plateau. In some plateaus we can recognize the role of ^{14}C production (via ^{10}Be), while three others coincide with changes in CO_2 level shown by ice cores that indicate ocean outgassing and oceanic changes. The difference in length between the plateaus and the outgassing spikes suggests that the spikes were part of longer lasting oceanic processes. Such processes may also be the origin of other plateaus without a recognizable CO_2 signal. We here demonstrate that in some cases the origin of atmospheric ^{14}C changes can be identified. Increased use of plateau tuning may provide data that will allow identification of further determining factors.

-->Also, the fairly fast air-sea transfer of atmospheric ^{14}C signals that leads to a quasi-synchronicity was displayed at (former) L. 102-110.

3) Data in preparation by Küssner et al. and Ausin et al. or pers. communication 2018 (Line 263): The authors have compiled all existing 14C datasets obtained via the plateau tuning technique (mostly by the group involving the first author), among which are also two new datasets (Küssner et al. and Ausin et al.). I find it hard to follow the findings obtained from these datasets, as crucial metadata is lacking for these cores.

-->Küssner and Ausin are coauthors of this manuscript. In the meantime, the manuscript of Küssner et al. that we regard as important brick of this synthesis, has now been submitted to P&P. Also, the datasets of Küssner et al. are stored at PANGAEA.de, saved by a password until acceptance of this manuscript for publication.

-->For the ^{14}C record of Ausin et al., we may refer to their records and results as "unpubl. data". Unfortunately, the manuscript of Ausin et al., perhaps particularly interesting to Ref.#2, will be ready for submission only later this spring.

4) Revision of the Suigetsu age scale: I consider this an important contribution of the paper to the community but I do not find Fig. 5 very informative. What role do siderite layers play (they are not mentioned in the main text)? And how does the figure show age uncertainties, as indicated in lines 352-254. Further elaboration is needed here.

--> Our text is supplemented in Section 2.2 and the caption of Fig. 5.

Also in lines 385-388, what are the age uncertainties of the Mono Lake and Laschamp paleomagnetic excursions? They should be considered when assessing and comparing different age scales.

-->We now refer to data of Lascu et al. (2016).

```
Why was plateau 2b chosen as test case? How successful is the comparison for any
other of 10+ 14C plateaus?
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-->Unerring question! In contrast to optical varve counts reaching back to >40 cal. ka, the base of ^{14}C Plateau 2b marks the oldest tie point captured by XRF-based varve counts. Marshall et al. (2012) showed that the difference between optical and XRF-based varve numbers is modest back to ~15 varve ka. Before, it has risen dramatically back to 17 ka.

```
I am surprised to see in Table 3 that some plateaus are combined to one long
plateau, e.g. 6-7-8. What is the basis for that?
```

-->All right, we need to mention: Table 3 is grouping the ^{14}C plateaus of some climate units that can be reproduced by the time slots employed for the model-based res. ages of Muglia et al. Within these slots, the plateau-based res. ages are largely constant.

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5)  Zoophycos burrows (lines 562-576): This whole section is somewhat dubious and
not very clearly written. I wonder how useful it is for the review of the 14C
plateau tuning technique. The authors seem to suggest that 14C plateaus in host
sediments can flag 14C outliers as such, but it is not clear how initial 14C
measurements a priori exclude bioturbated material for dating. This should be
explained in detail. It is entirely unclear how Zoophyros burrows "help to
corroborated changes in MOC and climate". In general, I think that the paper goes
off another tangent here. The authors could consider removing this section in my
view.
```

-->The section on Zoophycos burrows has now been removed. Küssner et al., 2018, already gave all details on the principles how to separate foram tests of Z. burrows from those of the ambient host sediment.

```
6) Model comparison with Muglia et al. (2018): The authors compare their datasets
with the model output of Muglia et al. (2018). Given that other modelling studies
exist that studied past ocean reservoir ages variations (e.g., Franke et al., 2008;
Butzin et al., 2017), it is unclear why this particular study has been chosen. What
characterizes the model run of Muglia et al. (2018), and in particular the modeled
AMOC?
```

-->The choice of model data of Muglia et al. was linked to (1) the simple availability of pertinent recent model data and explanations, kindly provided by Juan Muglia as coauthor. (2) Butzin informed me, when testing his data as alternative dataset and preparing this manuscript in spring 2019, that his dataset (then not particularly successful by comparison with our dataset) was outdated and that his group was preparing a major improvement of their model concept. (3) With regard to res. ages modeled by Franke et al. (2008), we see major age differences found both for high-latitude and upwelling regions. -- In summary, we now introduce three different modelling studies at display and their availability for our test (new L.588-607).

```
How were the simulations forced and what were the LGM boundary conditions? A
comparison between the data and model results would be better facilitated by global
plots of surface ocean reservoir ages.
```

-->To avoid extending the manuscript up to 'textbook' length, we now just add a brief remark on the background of the model simulations.

Is the distribution realistic? It is impossible for the reader to follow statements such as "with estimates of 13 Sv appearing somewhat more consistent with our results." (line 714-715) without any further elaboration or figures.

-->We now give a short explanation for our choice of MOC strength for the LGM: Validation test by Muglia et al. (2018) through a model-data comparison of radiocarbon data compiled by Skinner et al. (2017).

Is the time interval used for comparison the same between 14C data and model data? How was the LGM 14C data obtained? Were several plateaus averaged?

-->Time intervals and average of several plateaus are given in Table 3, as listed in Fig. 8 caption. Both model-based and observed reservoir ages focus on the Late LGM, 21-18.7 cal. ka (14C plateaus no. 4-5).

Response to 'minor comments'

The following long and/or complicated sentences are hard to follow and should be revised: lines 135-144, line 228-232, lines 302-307, line 357-361, line 461-466, and lines 646-649.

-->We now tried to simplify the sentences demurred by the reviewer.

Line 110-113: should cite paper(s) on coral reservoir ages here.

-->Without expanding our manuscript up to 'textbook' length we now add a few refs in addition to Adkins & Boyle, 1997.

Line 116: "that finally turned out to be the most valuable tracer of oceanography" This is in the eye of the beholder, and should be rephrased to "became a valuable tracer for xxx/tool in oceanography"

-->As authors we may regard it legitimate to present these findings in our eye as beholders.

Line 118: "benthic carbonate particles" should be "benthic foraminifera", also "reflect" might be a better word for "sum" here. -- o.k.

Line 121: Remove "the 14C level of" -- o.k.

Line 135: "provided" instead of "given" -- o.k.

Line 143-144: unclear what iv refers to.

-->Item 'iv' is now reworded to a separate sentence that spells out the great need for a generally accepted high-precision atmospheric reference record , , ,

Line 173: jumps --> o.k.

Line 286: remove "developed a special computer program"

--> o.k.(paragraph was deleted)

Line 442: remove "ones of" --> o.k.

Line 450: consider "propagated error of calendar age uncertainty of a plateau boundary and the uncertainty in its determination"

-->We agree but do not follow the idea to include the fishy statement "*and the uncertainty in its determination*".

Line 484: Use (Skinner et al., 2010; Burke and Robinson, 2012) as Southern Ocean reference. --> o.k.

Line 509: “assess” instead of “rate”

-->We prefer "rate".

Line 639-641: This statement is unclear. Please specify. Do you mean the influence from eddies, AABW formation or the interference of bathymetry with ocean currents? -

-->o.k.: We mean a variability linked to small-scale frontal systems, upwelling cells, and the interference of ocean currents with small-scale bathymetry.

Line 649-640: Rephrase. “test” instead of “weigh more correctly”? --> o.k.

Fig. 1. It is unclear what the 1:1 line means

--> The 1:1 line shows a gradient of one ^{14}C yr per cal. yr

Fig. 6. (c) in figure should probably be (b) --> o.k., thank you!

xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx

MANUSCRIPT WITH AUTHORS' CHANGES ARE MARKED UP in RED

Plateaus and jumps in the atmospheric radiocarbon record – Potential origin and value as global age markers for glacial-to-deglacial paleoceanography, a synthesis

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ABSTRACT

Changes in the geometry of ocean Meridional Overturning Circulation (MOC) are crucial in controlling changes of climate and the carbon inventory of the atmosphere. However, the accurate timing and global correlation of short-term glacial-to-deglacial changes of MOC in different ocean basins still present a major challenge. A possible solution is offered by the fine structure of jumps and plateaus in the record of radiocarbon (^{14}C) concentration of the atmosphere and surface ocean that reflects changes in atmospheric ^{14}C production as well as in the ^{14}C exchange between air and sea and within the ocean. Boundaries of atmospheric ^{14}C plateaus in the ^{14}C record of Lake Suigetsu, now tied to Hulu U/Th model-ages instead of optical varve counts, provide a stratigraphic 'rung ladder' of ~30 age tie points from 29 to 10 cal. ka for correlation with and dating of planktic oceanic ^{14}C records. The age differences between contemporary planktic and atmospheric ^{14}C plateaus give an estimate of the global distribution of ^{14}C reservoir ages for surface waters of the Last Glacial Maximum (LGM) and deglacial Heinrich Stadial 1 (HS-1), as shown by about 20 planktic ^{14}C records. Clearly elevated and variable reservoir ages mark both upwelling regions and high-latitude sites covered by sea ice and/or meltwater. ^{14}C ventilation ages of LGM deep waters reveal opposed geometries of Atlantic and Pacific MOC. Similar to today, Atlantic deep-water formation went along with an estuarine inflow of old abyssal waters from the Southern Ocean up to the northern North Pacific and an outflow of upper deep waters. Vice versa, ^{14}C ventilation ages suggest a reversed MOC during early HS-1 and a ~1500 year-long flushing of the deep North Pacific up to the South China Sea, when estuarine circulation geometry marked the North Atlantic, gradually starting near 19 ka. Elevated ^{14}C ventilation ages of LGM deep waters reflect a major drawdown of carbon from the atmosphere. Inversely, the subsequent, massive age drop and related change in MOC induced 3 to 4 major events of carbon release to the atmosphere as recorded in Antarctic ice cores. These new features of MOC and the carbon cycle provide detailed evidence in terms of space and time needed to test and refine ocean models that, in part because of insufficient spatial model resolution and reference data for testing the model results, still poorly reproduce them.

1. INTRODUCTION

1.1 A variety of terms linked to the notion '^{14}C age'

The ^{14}C concentration in the troposphere is mainly determined by ^{14}C production, atmospheric mixing, moreover, air-sea gas exchange, and ocean circulation that vary over time (e.g., Alves et al., 2018; Alveson et al., 2018). The ^{14}C content of living terrestrial plants is in equilibrium with the atmosphere via processes of photosynthesis and respiration, and accordingly, the ^{14}C of terrestrial plant remains in a sediment section directly reflects the amount of radioactive decay, thus the time passed since the plant's death, and the ^{14}C composition of the atmosphere during the time of plant growth.

Contrariwise, ^{14}C values of marine and inland waters are cut off from cosmogenic ^{14}C production in the atmosphere, hence depend on the carbon transfer at the air-water interface and the result of local transport and mixing of carbon in the water. For surface waters, the air-sea transfer is relatively fast and effective involving a time span of ten years and less (e.g., Nydal et al., 1998). Yet, vertical and horizontal water mixing results in surface ocean ^{14}C concentrations on average 5 % lower than those in the contemporaneous atmosphere, a difference expressed as 'Marine Reservoir Age' (or 'reservoir effect' *sensu* Alves et al., 2018). These 'ages' reflect the local oceanography and are highly variable through time. They may range from near zero up to values of more than 700 yr, in some regions up to 2500 yr, induced, for example, by old waters upwelled from below (e.g., Stuiver and Braziunas, 1993; Grootes and Sarnthein, 2006; Sarnthein et al., 2015). Apart from U/Th dated corals (many papers on their reservoir age since Adkins and Boyle, 1997) the ^{14}C age of planktic foraminifers is the most common tracer of surface water ages in marine sediments, a rough estimate of the time passed since sediment deposition. Initially, marine geologists were most interested in this ‘simple’ age value. Soon, however, they were confronted with age inconsistencies that implied a series of unknowns, in particular the ^{14}C ‘reservoir age’ that finally became a most valuable tracer for oceanography.

In turn, ^{14}C records of benthic foraminifers in deep-sea sediments reflect the time of radioactive decay since their deposition with the apparent ‘ventilation age’ of the deep waters in which they lived. Ventilation age is primarily the time span from the moment when carbon dissolved in the (later) deep waters lost contact with the atmosphere and the somewhat reduced ^{14}C level of surface waters until the precipitation of benthic carbonate. Details on the derivation of ventilation ages are provided in Cook and Keigwin (2015) and Balmer and Sarnthein (2018). In addition, however, ventilation ages depict hardly quantifiable lateral admixtures of older and/or younger water masses, moreover, ^{14}C-enriched organic carbon supplied by the biological pump, thus are called ‘apparent’. Today, the apparent transit times of carbon dissolved in the deep ocean range from a few hundred up to ~1800 ^{14}C yr found in upper deep waters of the northeastern North Pacific (Matsumoto, 2007).

Over the last decades, it turned out that both the reservoir ages of surface waters and the ventilation ages of deep waters present robust and high-resolution tracers essential for drawing quantitative conclusions on past ocean circulation geometries, marine climate change, and the processes that drive both past ocean dynamics and carbon budgets, given the ages rely on a number of robust age tie points. Obtaining such tie points presents a problem, since any attempt to date a deep-sea sediment record by means of ^{14}C encounters a number of intricacies of how to disentangle the effects of global atmospheric ^{14}C variations due to past changes in cosmogenic ^{14}C production and carbon cycle from (i) local depositional effects such as sediment hiatuses and winnowing, differential bioturbational mixing depth, and sediment transport by deep burrows, (ii) the effects of local atmosphere-ocean exchange and ocean mixing resulting in reservoir and ventilation ages that change through time and space (e.g., Alves et al. 2018; Grootes and Sarnthein, 2006), and (iii) from the final target, quantitatively 'pure' ^{14}C ages due to radioactive decay. These problems are exacerbated by the need for a generally accepted high-precision atmospheric reference record for the period 14–50 cal. ka, beyond tree ring calibration,

By now, ^{14}C-based chronologies of deep-sea sediment records, used to constrain and correlate the age of glacial-to-deglacial changes in ocean dynamics and climate on a global scale, are often of unsatisfactory quality when they are based on (i) age tie points spaced far too wide (e.g., using DO-events 1, 2, and 3 only and/or sporadic tephra layers for the time span 30–14 cal ka), (ii) disregarding atmospheric ^{14}C plateaus, (iii) the risky assumption of ±constant planktic ^{14}C reservoir ages and other speculative stratigraphic correlations/compilations, and (iv) ignoring small-scale major differences in low-latitude reservoir age. Likewise, clear conclusions are precluded by an uncertainty range of 3-4 kyr sometimes accepted for tie points during the glacial-to-deglacial period (Stern and Lisiecki, 2013; Lisiecki and Stern, 2016), where significant global climate oscillations occurred on decadal-to-centennial time scales as widely shown on the basis of speleothem and ice core-based records (Steffensen et al., 2008; Svensson et al., 2008; Wang et al., 2001).

Thus marine paleoclimate and paleoceanographic studies today focus on the continuing quest for a high-resolution and global, hence necessarily atmospheric ^{14}C reference record that is marked by abundant, narrow-standing tie points on the calibrated (cal.) age scale. Such pertinent tie points are provided by a suite of reproducible 'plateaus' and 'jumps' that mark the atmospheric ^{14}C record (Figs. 1 and S1; Sarnthein et al., 2007 and 2015; Bronk Ramsey et al., 2012 and 2019; Schlolaut et al., 2018; Umling and Thunnell, 2017), hence form the basis of this synthesis.

1.2 Review of tie points used to fix calibrated and reservoir ages in marine ^{14}C records

The tree ring-based calibration of ^{14}C ages provides a master record of decadal changes in atmospheric ^{14}C concentrations back to ~14 cal. ka (Reimer et al., 2013 and 2020) with floating sections beyond (from ~12.5–14.5 cal. ka and around 29–31.5 and 43 cal. ka; Turney et al., 2010, 2017, Reimer et al., 2020). The evolution of Holocene and late deglacial ^{14}C ages with time is not linear but reveals variations with numerous distinct jumps (= rapid change) and (short) plateau-shaped (slow or no change or even inversion) structures indicative of fluctuations in atmospheric ^{14}C concentration. Prior to 8500 cal. yr BP, various plateaus extend over 400–600 cal. yr and beyond (Fig. 2). Given the quality of the tree ring calibration data, these fluctuations can be considered real, suitable for global correlation (Sarnthein et al., 2007, 2015; Sarnthein and Werner, 2018). Air-sea gas exchange transfers the atmospheric ^{14}C fluctuations into the surface ocean where they can provide high-resolution tie points to calibrate the marine ^{14}C record and marine reservoir ages back to ~14 ka (via the so-called ^{14}C wiggle match approach). In the near future, however, it is unlikely that a continuous tree ring-based record will become available to trace such atmospheric ^{14}C variations further back, over the period 14–29 cal. ka crucial for the understanding of last-glacial-to-interglacial changes in climate. Hence various other, less perfect ^{14}C archives have been employed for this period to tie past changes in atmospheric ^{14}C concentration/age to an 'absolute' or 'calibrated' (e.g., incremental and/or based on speleothem carbonate) age scale. This record can then be used to constrain the widely unknown evolution of ^{14}C reservoir ages of surface waters for various regions of the ocean.

Suites of ^{14}C ages of paired marine and terrestrial plant-borne samples, e.g. paired planktic foraminifers and wood chunks, provide most effective but rarely realizable absolute-age markers and reservoir ages of local ocean surface waters (Zhao and Keigwin, 2018; Rafter et al., 2018; Schroeder et al., 2016; Broecker et al., 2004). Likewise successful appears the alignment of ^{14}C-dated variations in downcore sea-surface temperatures (SST) with changes in hydroclimate as recorded in age-calibrated sedimentary leaf-wax hydrogen isotope (δD) records from ancient lakes (Muschitiello et al., 2019), assumed to be coeval. Further tie points are derived from volcanic ash layers (Waelbroeck et al., 2001; Siani et al, 2013; Davies et al., 2014; Sikes and Guilderson, 2016), paired U/Th- and ^{14}C-based coral ages (Adkins and Boyle, 1997; Robinson et al., 2005; Burke and Robinson, 2012; Chen et al., 2015), and the (fairly fragmentary) alignment of major tipping points in ^{14}C dated records of marine SST and planktic $\delta^{18}O$ to the incremental age scale of climate events dated in polar ice core records (Waelbroeck et al., 2011). Such well-defined tie points, however, are wide-spaced in peak glacial-to-early deglacial ice core records, too wide for properly resolving a clear picture of the spatiotemporal pattern of marine paleoclimate events. Finally, various data compilations tentatively rely on the use of multiple age correlations amongst likewise poorly dated marine sediment records, an effort necessarily problematic.

Skinner et al. (2019) recently combined new and existing reservoir age estimates from North Atlantic and Southern Ocean to show coherent but distinct regional reservoir age trends in subpolar ocean regions, trends that indeed envelop the range of actual major small-scale and short-term oscillations in reservoir age revealed by our technique of ^{14}C plateau tuning for the subpolar South Pacific (Küssner et al., 2020 subm.).

In the absence of robust age tie points an increasing number of authors resort to ^{14}C reservoir age simulations for various sea regions by ocean General Circulation Models (GCM) (e.g. Butzin et al., 2017; Muglia et al., 2018) to quantify the potential difference between marine and atmospheric ^{14}C dates during glacial-to-interglacial times. Considering the complexity of the ocean MOC and the global carbon cycle it is not surprising that the results of a comparison of a selection of robust empiric vs. simulated ^{14}C reservoir ages are not that encouraging yet (as discussed further below).

Accepting a generally close link between ^{14}C concentrations in the troposphere and in the surface ocean, the fine structure of planktic ^{14}C records with centennial-scale-resolution provides far superior (though costly) evidence, similar to that of tree rings, to furnish a series of age tie points with semi-millennial-scale time resolution for a global correlation of glacial-to-deglacial marine sediment sections. These suites of tie structures can link the marine sediment records to a reference suite of narrow-standing jumps and boundaries of the apparent plateaus robustly identified in the atmospheric ^{14}C record of Lake Suigetsu, the only long, continuous record based on terrestrial plant remains (Bronk Ramsey et al., 2012, 2019) provided that common ^{14}C variations are robustly identified in both atmospheric and marine records. Prior to the reach of the tree ring-based age scale ~14 cal. ka, the absolute age of these atmospheric ^{14}C structures can be either calibrated by incremental (microscopy- or XRF-based) varve counts (Schlolaut et al., 2018; Marshall et al., 2012) or by a series of paired U/Th- and ^{14}C-based model ages correlated from the Hulu Cave speleothem record (Bronk Ramsey, 2012 and 2019; Southon et al., 2012; Cheng et al., 2018). The difference between these calibrations (Fig. 3) is discussed below. The difference, however, is of little importance neither for the tuning of planktic to corresponding atmospheric ^{14}C plateaus nor for the derivation of planktic reservoir ages that present the highly variable offset of the ^{14}C age of a planktic plateau from that of the correlated atmospheric plateau. The offset is deduced by subtracting the average ^{14}C age of an atmospheric ^{14}C plateau from that of the correlated planktic ^{14}C plateau, independent of any absolute age value assigned. s

A basic philosophical controversy exists whether the apparent jump and plateau structures in the Suigetsu and planktic ^{14}C records reflect real ^{14}C fluctuations or statistical noise. In the 'null hypothesis' the ^{14}C values shaping plateaus of the calibration curve are regarded as result of mere statistical scatter. Thus, the record of atmospheric ^{14}C ages against time would form a simple continuous rise resulting from radioactive decay and the advance of time, such as suggested by a fairly straight progression of the highly resolved deglacial Hulu Cave ^{14}C record plotted vs. U/Th ages (Southon et al., 2012; Cheng et al., 2018).

This null hypothesis is contradicted by the 'master record' of tree ring data (Fig. 2; Reimer et al., 2013 /2020). Unequivocally it shows fluctuations in atmospheric ^{14}C concentration on the order of 2–3 % over the last 10 kyr (Stuiver and Braziunas, 1993) and even larger back to ~14 ka (Reimer et al., 2013, 2020). Though not resolved in speleothem data these plateau/jump structures most likely are real and widely reproducible in marine sediment records. Under glacial and deglacial low-CO_2 conditions beyond 14 ka, when climate and ocean dynamics were less constant than during the Holocene, atmospheric ^{14}C fluctuations were, most likely, even stronger than those reported by Stuiver and Braziunas and ^{14}C plateaus and jumps accordingly larger. Also, plateau-jump structures are becoming increasingly evident in the evolving atmospheric calibration record (Reimer et al., 2020).

Thus, the age-defined plateaus and jumps in the Suigetsu atmospheric ^{14}C calibration curve may most likely be regarded as a suite of ‘real’ structures, extending the tree ring record for Holocene and B/A-to-Early Holocene times (Fig. 2) into early deglacial and LGM times. In part the plateau/jump structures may be linked to changes in cosmogenic ^{14}C production, as possibly shown in the ^{10}Be record (Fig. 4; based on data of Adolphi et al., 2018), and – presumably more dominant – to short-term changes in ocean mixing and the carbon exchange between ocean and atmosphere. The exchange is crucial, since the carbon reservoir of the ocean contains up to 60 (preindustrial) atmospheric carbon units (Berger and Keir, 1984). The apparent contradiction with the smooth Hulu Cave ^{14}C record (Southon et al., 2012; Cheng et al., 2018) may possibly be explained by the Hulu Cave speleothem precipitation system acting as a low-pass filter for fluctuating atmospheric ^{14}C concentrations (statistical tests of Bronk Ramsey et al., pers. comm. 2018) and, to a very limited degree, by the obvious scatter in the Suigetsu data. That scatter, however, appears insufficient to feign plateaus in view of the evidence based on tree ring-based plateaus (Fig. 2). The filter for Hulu data possibly led to a loss especially of short-lived structures in the preserved atmospheric ^{14}C record, though some remainders were preserved in the ^{14}C records of Hulu Cave (Fig. 1). So we rather trust in the amplitude of Suigetsu 14C structures, but trust in the timing of Hulu Cave data as discussed below.

Like a 'rung ladder' the age-calibrated suite of ^{14}C plateau boundaries and jumps is suited for tracing the calibrated age of numerous plateau boundaries in glacial-to-deglacial marine ^{14}C records likewise densely sampled, even when some rungs have been destroyed by local influences on gas exchange or ocean mixing. Also, one may record the average offset of planktic ^{14}C ages from paired atmospheric ^{14}C ages, i.e. the planktic reservoir age, for each single ^{14}C plateau (Sarnthein et al., 2007, 2015). We prefer the Suigetsu record to IntCal, since it is based on original primary atmospheric data and results in small-scale spatio-temporal changes of reservoir age, whereas IntCal is mixing and smoothing a broad array of different data sources with comparatively coarse age resolution, including carbonate-based speleothem and marine records. For the first time, this suite of tie points may facilitate a precise temporal correlation of all sorts of changes in surface and deep-water composition on a global scale, crucial for a better understanding of past changes in ocean and climate dynamics.

1.3 Items discussed in this synthesis

The Results Section is summarizing

(1) Some means to separate atmospheric and oceanic forcings, that overlap in controlling the structure of a planktic ^{14}C plateau.

(2) Choice of a U/Th-based reference time scale (Bronk Ramsey et al. 2012; Cheng et al., 2018) instead of the earlier varve-counted version (Schlolaut et al., 2018) to date the

short-term structures in the global atmospheric ^{14}C record of Lake Suigetsu (Sarnthein et al., 2015).

(3) An extension of the suite of age tie points from 23 back to 29 cal. ka, values crucial for an accurate global correlation of ocean events over the period 10–29 cal. ka. Supplement Text no. 1 is discussing uncertainties in age-calibrated ^{14}C plateau boundaries and jumps of our redefined Suigetsu record (Bronk-Ramsey et al., 2012, 2019; Sarnthein et al., 2015) and their correlatives in ocean sediment cores.

(4) Attempts to explore the potential linkages of atmospheric ^{14}C plateaus and jumps to cosmogenic ^{14}C production and/or ocean dynamics.

The Discussion and Implications section includes the following topics:
(1) A global summary of our records of marine ^{14}C reservoir ages (Sarnthein et al. 2015) now amended by nine plateau-tuned records from the Southern Hemisphere (Balmer et al., 2016 and 2018; Küssner et al., 2018, and subm.) and northeast Atlantic (Ausin et al., unpubl.). In total, 18 (LGM) / 19 (HS-1) plus 3 wood chunk-based records (Broecker et al., 2004; Zhao et al., 2018) now depict the spatio-temporal variability of past ^{14}C reservoir ages of surface waters in different ocean regions.

(2) Comparison of our plateau-based reservoir ages with independent LGM estimates of surface water ^{14}C reservoir ages simulated by the GCM of Muglia et al. (2018). Differences between the results may help to constrain potential caveats in the boundary conditions and fine structure of model simulations. This section includes a discussion of some habitat- and season-specific ^{14}C reservoir ages characteristic of different planktic

foraminifera species, that monitor past changes in the local geometry of surface ocean dynamics (Sarnthein and Werner, 2018).

(3) A global overview of ^{14}C reservoir and ventilation ages of surface and deep waters that form a robust tracer of circulation geometries and the dissolved inorganic carbon (DIC) in different basins of the ocean (Sarnthein et al., 2013) and provide crucial insights into the origin of past changes in the global carbon cycle from glacial to interglacial times, an important correlative to model simulations.

In this way we highlight the important role the technique of ^{14}C plateau tuning and its revised cal. time scale are playing for global data-model intercomparison and a new understanding of Ocean MOC during the LGM and its reversal during HS-1.

2. RESULTS – AGE TIE POINTS BASED ON ^{14}C PLATEAU BOUNDARIES

2.1 *Suite of planktic ^{14}C plateaus: Means to separate global atmospheric from local oceanographic forcings*

The basic assumption of the ^{14}C plateau tuning technique is that the fine structure of fluctuations of the global atmospheric ^{14}C concentration record can also be found in the surface ocean. In a plot of ^{14}C age versus calendar age such fluctuations lead to a pattern of plateaus/jumps that correspond to decreases/increases in ^{14}C concentration. Here we refer to the derivation and interpretation of planktic ^{14}C plateaus, assuming a global atmospheric origin with local oceanographic forcings. The series of planktic ^{14}C plateaus and jumps are derived in cores with average sedimentation rates of >10 cm/ky and dating resolution of <100-150 yr. The plateau-specific structures in a sediment age-depth record form a well-defined suite for which absolute age and reservoir age are derived by means of a strict alignment to the reference suite of global atmospheric ^{14}C plateaus as a whole. Initially age tie points of marine $\delta^{18}O$ records showing (orbital) isotope stages #1-3 serve as stratigraphic guideline for the alignment. Planktic reservoir ages and their short-term changes are derived from the difference in average ^{14}C age between atmosphere and surface waters in subsequent plateaus. To stick as close as possible to the modern range of reservoir ages (Stuiver and Braziunas, 1993), tuned reservoir ages are kept at a minimum unless stringent evidence requires otherwise.

A close correspondence between ^{14}C concentrations in atmosphere and surface ocean is expected based on rapid gas exchange. In several cases, however, the specific structure and relative length of a planktic ^{14}C plateau may deviate from those of the pertinent plateau observed within the suite of atmospheric plateaus, thus indicate local intra-plateau changes of reservoir age. Though less frequent, these changes may indeed amputate and/or deform a plateau, then as result of variations in local ocean atmosphere exchange and oceanic mixing. Two saspects help to sort out short-term climate-driven intra- and inter-plateau changes in ^{14}C reservoir age: (i) The evaluation of the structure and reservoir age of an individual plateau is strictly including the age estimates deduced for the complete suite of plateaus. (ii) Our experience shows that deglacial climate regimes in control of changes in surface ocean dynamics generally occurred on (multi-) millennial time scales (e.g., YD, B/A, HS-1), whereas atmospheric ^{14}C plateaus hardly lasted longer than a few hundred up to 1100 yr (Fig. 1 and S1). Abrupt changes in gas exchange or ocean mixing usually affect one or only a few plateaus of the suite. -- Absolute age estimates within a plateau are derived by linear interpolation between the age of the base and top of an undisturbed plateau assuming constant sedimentation rates. The potential impact of short-term sedimentation pulses on ^{14}C plateau formation has largely been discarded by Balmer and Sarnthein (2016).

2.2 Suigetsu atmospheric ^{14}C record: Shift to a chronology based on U/Th model ages

Originally, we have based the chronology of ^{14}C plateau boundaries in the Suigetsu record (Sarnthein et al., 2015) on a scheme of varve counts by means of light microscopy of thin sections (Bronk Ramsey et al., 2012; Schlolaut et al., 2018). Over the crucial sediment sections of the Last Glacial Maximum (LGM) and deglacial Heinrich Stadial 1 (HS-1), however, the degree of varve quality / perceptibility in the Suigetsu profile is highly variable (Fig. 5). In parallel, varve-based age estimates have been derived from counting various elemental peaks in µXRF data, interpreted as seasonal signals (Marshall et al., 2012). The results obtained from these two independent counting methods and their interpolations widely support each other. The optical counts ultimately formed the backbone of a high-resolution chronology obtained by tying the Suigetsu ^{14}C record to the U/Th based time scale of the Hulu cave ^{14}C record (Bronk Ramsey et al., 2012). Recently, Schlolaut et al. (2018) amended the scheme of varve counts. Accordingly, Suigetsu varve preservation (i.e., the number of siderite layers per 20 cm thick sediment section) is fairly high prior to ~32 ky BP and over late glacial Termination I but fairly poor over large parts of the LGM and HS-1, from ~15 - 32 cal ka (17.3-28.5 m c.d. in Fig. 5). Here only less than 20-40 % of the annual layers expected from interpolation between clearly varved sections are distinguished by microscopy. Varve counts that use µXRF data (Marshall et al., 2012) can distinguish subtle changes in seasonal element variations, that are not distinguishable in thin section microscopy, hence result in higher varve numbers especially during early deglacial-to-peak glacial times. Yet, some subtle variations are difficult to distinguish from noise, which adds uncertainty to the µXRF-based counts. Thus, the results from either counting method are subject to uncertainties that rise with increased varve age (Fig. 5).

Bronk Ramsey et al. (2012) established a time scale based on ^{14}C wiggle matching to U/Th dated ^{14}C records of the Hulu Cave and Bahama speleothems. In part, this calibr-ated (cal.) age scale was based on Suigetsu varve counts, in part on the prerequisite of the best-possible fit of a pattern of low-frequency changes in ^{14}C concentration obtained from Suigetsu and Hulu Cave. The two ^{14}C records were fitted within the uncertainty envelope of the Hulu 'Old / Dead Carbon Fraction' (OCF/DCF) of ^{14}C concentration. The uncertainty of this model is debatable while the character of the Hulu DCF and thus, its uncertainty back in time is still incompletely understood. We surmise that the U/Th-based age model of Suigetsu may suffer from the wiggle matching of atmospheric ^{14}C ages of Lake Suigetsu with ^{14}C ages of the Hulu Cave (Southon et al., 2012) in case of major short-term changes in atmospheric ^{14}C concentration due to a memory effect of soil organic carbon in carbonate-free regions of the cave overburden. The speleothem-carbonate-based Hulu ages may have been influenced far more strongly by short-term changes in the local DCF than assumed, as suggested by major variations in a paired $\delta^{13}C$ record, that reach up to 5 ‰, mostly subsequent to short-term changes in past monsoon climate (Kong et al., 2005). The uncertainty regarding the assumption of a constant OCF/DCF (Southon et al. 2012; Cheng et al., 2018) may hamper the age model correlation between Hulu and Suigetsu records and the Suigetsu chronology.

To test and optimize the age calibration we compared the results of the two timescales independently deduced from varve counts with those of the U/Th-based model age scale using as test case the base of ^{14}C Plateau 2b, the oldest tie point constrained by μXRF-based counts. In contrast to 16.4 cal. ka, supposed by optical varve counts, μXRF-based counts suggest an age of ~16.9 cal. ka (Marshall et al., 2012; Schlolaut et al., 2018), which matches closely the U/Th-based estimate of 16.93 ka. This is a robust argument for the use of the U/Th-based Suigetsu time scale as 'best possible' age scale to calibrate the age of thirty ^{14}C plateau boundaries (Fig. 1). In its older part, the U/Th model time scale is further corroborated by a decent match of short-term increases in ^{14}C concentration with the low geomagnetic intensity of the Mono Lake and Laschamp events at ~34 and 41.1±0.35 ka (Lascu et al., 2016), independently dated by other methods. The new U/Th-based model ages of ^{14}C plateau boundaries are significantly higher than our earlier microscopy-based varve ages over HS-1 and LGM, a difference increasing from ~200 yr near 15.3 cal. ka to ~530 near 17 ka and 2000 yr near ~29 ka (Fig. 3).

Note, any readjustment of the calendar age of a ^{14}C plateau boundary does not entail any change in ^{14}C reservoir ages afore deduced for surface waters by means of the plateau technique (Sarnthein et al., 2007, 2015), since each reservoir age presents the simple difference in average ^{14}C age for one and the same ^{14}C plateau likewise defined in both the Suigetsu atmospheric and planktic ^{14}C records of marine surface waters, independent of the precise position of this plateau on the calendar age scale.

In view of the recent revision of time scales (Schlolaut et al., 2018; Bronk Ramsey et al, 2019) we now extended our plateau tuning and now also defined the boundaries and age ranges of ^{14}C plateaus and jumps for the interval ~23–29 cal. ka, which results in a total of ~30 atmospheric age tie points for the time span 10.5–29 cal. ka (Fig. 1; summary in Table 1; following the rules of Sarnthein et al., 2007 and 2015). Prior to 25 cal. ka, the definition of ^{14}C plateaus somewhat suffered from an enhanced scatter of raw ^{14}C values of Suigetsu. -- In addition to visual inspection, the ^{14}C jumps and plateaus were also defined with higher statistical objectivity by means of the first-derivative of all trends in the ^{14}C age-to-calendar age relationship (or –core depth relationship, respectively) by using a running kernel window (Sarnthein et al., 2015).

2.3 Linkages of short-term structures in the atmospheric ^{14}C record to changes in cosmogenic ^{14}C production versus changes in ocean dynamics

Potential sources of variability in the atmospheric ^{14}C record have first been discussed by Stuiver and coworkers in the context of Holocene fluctuations deduced from tree ring data (e.g., Stuiver and Braziunas 1993). -- Similar to changes in ^{14}C, variations in ^{10}Be deposition in ice cores reflect past changes in ^{10}Be production as a result of changes in solar activity and the strength of the Earth's magnetic field (Adolphi et al., 2018). Correspondingly, the changes in ^{10}Be also reflect past changes in the cosmogenic production of ^{14}C. If we accept to omit assumptions on the modulation of past ^{14}C concentrations by changes in the global carbon cycle we can calculate the atmospheric ^{14}C changes over last glacial-to-deglacial times with ^{10}Be and a carbon cycle model and convert them into ^{14}C ages (Fig. 4). This neglects, however, the influence of climate and carbon cycle changes over this period that necessarily modified the ^{10}Be-based ^{14}C record if included correctly into the modeling. Between 10 and 13.5 cal. ka, the ^{10}Be-modeled ^{14}C record displays a number of plateau structures that appear to match the Suigetsu-based atmospheric ^{14}C plateaus. Between 15 and 29 cal. ka, however, ^{10}Be-based ^{14}C plateaus are far more rare and/or less pronounced than those in the Suigetsu record. Most modelled plateaus are far shorter than those displayed in the suite of atmospheric ^{14}C plateaus of Lake Suigetsu (e.g., plateaus near to the top 2a, 2b, top 5a, and 9), except for a distinct equivalent of plateau no. 6a. On the whole, the modelled and observed structures show little coherence. This may indicate that any direct relationship between variations in cosmogenic ^{14}C production and the Suigetsu plateau record is largely obscured by the carbon cycle, uncorrected climate effects on the ^{10}Be deposition, and/or noise in the ^{14}C data. Also, a relatively high uncertainty of the measured ^{10}Be concentrations in the ice, (in many cases ~7%; Raisbeck et al., 2017), and a lower sample resolution in the order of 50 to 200 yr may contribute to the smoothed character of the ^{10}Be record in Fig. 4.

On the other hand, the 'new' U/Th-based cal. ages of plateau boundaries may suggest some reasonable stratigraphic correlations between peak glacial and deglacial change in atmospheric CO_2 and ^{14}C plateaus with millennial-scale events in paleoceanography (Fig. 6, Table 2): The suite of deglacial ^{14}C plateaus no. 2a, 1, and Top YD indeed displays a temporal match with three brief but major deglacial jumps in ocean degassing of CO_2 documented in the WDC ice core (Marcott et al., 2014). The two records have been independently dated by means of annual-layer counts in ice cores and U/Th ages of stalagmites. The match suggests that these atmospheric ^{14}C plateaus may largely result from changes in air-sea gas exchange, and in turn, from changes in ocean dynamics.

In particular, these events may have been linked to a variety of fast changes such as in sea ice cover in the Southern Ocean and/or in the salinity and buoyancy of high-latitude surface waters (Skinner et al., 2010; Burke and Robinson, 2012). These factors control upwelling and meridional overturning of deep waters, in particular found in the Southern Ocean (Chen et al., 2015) and/or North Pacific (Rae et al. 2014, Gebhardt et al., 2008).

Such events of changes in MOC geometry and intensity may be responsible for ocean degassing and the ^{14}C plateaus.

In an extreme case, ventilation ages in the Southern Ocean near New Zealand (SO213-76 in Fig. S2; Küssner et al., 2020 subm.) have short-term dropped around 18 cal. ka from 4000 to 1000 yr (Fig. 4c). Over this time, the ^{14}C level of the atmosphere was constant at 1.4 FMC (Fraction of Modern Carbon). Hence a ventilation age of 4000 yr is equal to ~60 % of the contemporaneous level of past atmosphere 1.4 FMC, at that time leading to 1.4 x 0.6 = 0.84 FMC. In turn, the ventilation age of 1000 yr was equal to 88 % of past atmosphere FMC. This implies an increase of local deep ocean ^{14}C to 1.4 x 0.88 = 1.232 FMC at this site. The concentration difference of ~0.4 FMC means a major ^{14}C shift in DIC at that very MOC key region of the deep Southern Ocean (Rae and Broecker, 2018) over 200 yr. This enhanced mixing of the Southern Ocean and a similar, slightly later mixing event in the North Pacific (MD02-2489; Fig. S2d) may have triggered – with phase lag – two trends in parallel, (1) a rise in atmospheric CO_2, in part abrupt (*sensu* Chen et al., 2015; Menviel et al., 2018), and (2) a gradual enrichment in ^{14}C depleted atmospheric carbon, reflected as ^{14}C plateau.

Plateau 6a matches a ^{14}C plateau deduced from atmospheric ^{10}Be concentrations, thus suggests changes in ^{14}C production. Other changes in atmospheric ^{14}C (plateaus 4 and 8) match short-term North Atlantic warmings during peak glacial and earliest deglacial times, similar to that at the end of HS-1 and during plateau 'YD', hence may reflect minor changes in ocean circulation and ocean-atmosphere exchange without major degassing of old ^{14}C depleted deep waters in the North Atlantic (Table 2, Fig. S2a). There is still little information, however, on the origin of several other peak glacial ^{14}C

plateaus 17.5–29 cal. ka. The actual linkages of these plateaus to events in ocean MOC still remain to be uncovered.

3. DISCUSSION and IMPLICATIONS

3.1 ^{14}C plateau boundaries – A suite of narrow-spaced age tie points to rate short-term changes in marine sediment budgets, chemical inventories, and climate 29–10 cal. ka

In continuation of previous efforts (Sarnthein et al., 2007 and 2015) the tuning of high-resolution planktic ^{14}C records of ocean sediment cores to the new age-calibrated atmospheric ^{14}C plateau boundaries now makes it possible to establish a ‘rung ladder’ of ~30 age tie points covering the time span 29 – 10.5 cal. ka. These global tie points have a time resolution of several hundred to thousand years, and can be used to constrain the chronology and potential leads and lags of events that occurred during peak glacial and deglacial times (Fig. 1). The locations of the 18 (20) cores are shown in Fig. 7. The time histories of the benthic and planktic reservoir ages are summarized in Figs. 8 and S2 and the information these provide is discussed below.

Six prominent examples showing the power and value of additional information obtained by means of the ^{14}C plateau-tuning method are:

(i) Signals of the onset of northern hemisphere deglaciation can now be distinguished in detail from the subsequent beginning of deglaciation in the southern hemisphere and reveal that changes began ~1400 yr earlier in the north (Fig. S2) (Kawamura et al., 2007; Küssner et al., 2020 subm.; in harmony with Schmittner and Lund, 2015).

(ii) In southeast Pacific surface waters the end of the Antarctic Cold Reversal (ACR; WDC Project Members, 2013) was found precisely coeval with the onset of the Younger

Dryas cold spell (Küssner et al., 2020 subm.), a finding important to further constrain the details of 'bipolar see-saw' (Stocker and Johnsen, 2003).

(iii) Signals of deep-water formation in the subpolar North Pacific can now be separated from signals originating in the North Atlantic (Rae et al. 2014; Sarnthein et al., 2013). In this way we now can specify and tie major short-lasting reversals in Atlantic and Pacific MOC on a global scale.

(iv) Signals of deglacial meltwater advection can now be distinguished from short-term interstadial warmings in the northern subtropical Atlantic, which helps to locate meltwater outbreaks far beyond the well-known Heinrich belt of ice-rafted debris (Balmer and Sarnthein, 2018).

(v) As outlined above, the timing of marine ^{14}C plateaus can now be compared in detail with that of deglacial events of climate and the atmospheric CO_2 rise independently dated by means of ice core-based stratigraphy (Table 2; Fig. 6). These linkages offer a tool to explore details of deglacial changes in deep-ocean MOC once the suite of ^{14}C plateaus has been properly tuned at any particular ocean site.

(vi) The refined scale of age tie points also reveals unexpected details for changes in the sea ice cover of high latitudes as reflected by anomalously high ^{14}C reservoir ages (e.g. north of Iceland and near to the Azores Islands) and for the evolution of Asian summer monsoon in the northern and southern hemisphere as reflected by periods of reduced sea surface salinity (e.g., Sarnthein et al., 2015; Balmer et al., 2018).

Finally, the plateau-based high-resolution chronology has led to the detection of numerous millennial-scale hiatuses (e.g., Sarnthein et al., 2015; Balmer et al., 2016; Küssner et al., 2020 subm.) overlooked by conventional, e.g., *AnalySerie*-based methods (Paillard et al. 1996) of stratigraphic correlation (Fig. S2). In turn, the hiatuses give intriguing new insights into past changes of bottom current dynamics linked to different millennial-scale geometries of overturning circulation and climate change such as in the South China Sea (Sarnthein et al., 2013 and 2015), in the South Atlantic (Balmer et al. 2016) and southern South Pacific (Ronge et al., 2019).

Clearly, the new atmospheric ^{14}C 'rung ladder' of closely-spaced chronostratigraphic tie points has evolved to a valuable tool to uncover functional chains in paleoceanography, that actually have controlled events of climate change over glacial-to-deglacial times.

3.2 Observed vs. model-based ^{14}C reservoir ages acting as tracer of past changes in surface ocean dynamics and as incentive for model refinements (Fig. 8)

The atmospheric ^{14}C plateaus of Suigetsu provide a suite of up to 18 reference plateaus over the time span 10 – 29 cal. ka (Fig. 1). Tuning ^{14}C plateau boundaries in ^{14}C-dated marine sediment sections to the Suigetsu ^{14}C record allows us to establish a suite of highly resolved and robust age tie points on short and long time scales, wherever cores with high hemipelagic sedimentation rates are sampled in the global ocean (Fig. 7). In addition, and likewise intriguing, the difference between the average ^{14}C age of an atmospheric ^{14}C plateau and that of a coeval ^{14}C plateau yields a suite of changing ^{14}C reservoir ages over time, a prime tracer of past oceanography of local surface waters and data set crucial to deduce past apparent deep-water ventilation ages (e.g., Muglia et al., 2018; Cook and Keigwin, 2015; Balmer and Sarnthein, 2018).

To better constrain the water depth of past reservoir ages we dated monospecific planktic foraminifera (Sarnthein et al., 2007); in low-to-mid latitudes on *G. bulloides*, *G. ruber,* or *G. sacculifer* with habitat depths of 0–80/120 m (Jonkers and Kucera, 2017) and in high latitudes, mostly on *N. pachyderma* (s) living at 0–200 m depth (Simstich et al., 2003). Averaging of ^{14}C ages within a ^{14}C plateau helps to bypass the analytical noise in ^{14}C records such as short-term apparent ^{14}C age reversals and to deduce the regional evolution of planktic ^{14}C reservoir ages with semi-millennial-scale resolution. Nine plateaus are located in the LGM, 18–27 cal. ka (Fig. 1). Here, plankton-based reservoir ages show analytical uncertainties of >200 to >300 yr each. By comparison, short-term temporal variations in reservoir age reach 200–400 yr, occasionally up to 600 yr, in particular, close to the end of the LGM (Table 3).

To better decode the informative value of our ^{14}C reservoir ages for late LGM we compared average ages of ^{14}C Plateaus 4-5 with estimates generated by a global ocean model (Muglia et al., 2018; 0–50 m w.d.; Fig. 8c-d; Table 3), an approach similar to that of Toggweiler et al. (2019) applied to modern reservoir ages of the global ocean. In an earlier paper (Balmer et al., 2016) we compared our empiric reservoir ages for the LGM with GCM-based estimates of Franke et al. (2008) and Butzin et al. (2012). Franke et al. (2008) underestimated our mid-latitude values by up to ~2000 ^{14}C yr, while LGM reservoir age estimates of Butzin et al. (2012) were more consistent with ours. Their GCM considered more realistic boundary conditions such as the LGM freshwater balance in the Southern Ocean and, in particular, LGM SST and wind fields plus the gas transfer velocity for the exchange of ^{14}C of CO_2 (Sweeney et al., 2007). Initially we also planned a continuation of these intercomparison tests with our present data set, but were advised by Butzin (pers. com. 2019, Butzin et al., 2020) to wait for results from a revised GCM capable to resolve more properly the details of continental margins and adjacent seas, that frequently form the origin of our sediment-based data sets. We thus focus on a comparison of our empiric values with model estimates of Muglia et al. only.

Their model includes ocean surface reservoir age and ocean radiocarbon fields that have been validated through a comparison to LGM radiocarbon data compilation made by Skinner et al. 2017. It conforms two plausible, recent model estimates of surface reservoir ages that can be compared to our results (Table 3).

Low LGM values (300–750 yr) supposedly document an intensive exchange of surface waters with atmospheric CO_2, most common in model- and foraminifera-based estimates of the low- and mid-latitude Atlantic. Low empiric values also mark LGM waters in mid to high latitudes off Norway and off middle Chile, that is, close to sites of potential deep and/or intermediate water formation. Off Norway and in the northeastern Atlantic, model-based reservoir ages of Muglia et al. (2018) largely match the empiric range. However, the uncertainty envelopes for data shown in Fig. 8c (±560 yr; $r = 0.59$) generally exceed by far the spatial differences calculated for the empiric data. Conversely, model-based reservoir ages reproduce only poorly the low plankton-based estimates off Central Chile and values in the Western Pacific and Southern Ocean.

In part, the differences may be linked to problems like insufficient spatial resolution along continental margins, ignoring east-west differences within ocean basins, and/or the estimates of a correct location and extent of seasonal sea ice cover used as LGM boundary condition such as east off Greenland, in the subpolar northwest Pacific, and off Southern Chile, where sea ice hindered the exchange of atmospheric carbon (per analogy to that of temperature exchange, as recorded by Sessford et al, 2019). Also, yearly mean model estimates are compared to ^{14}C signals of planktic foraminifera that mostly formed during summer only, when large parts of the Nordic Seas were found icefree (Sarnthein et al., 2003). Hence, models may need to better constrain local and seasonal sealing effects of LGM sea ice cover.

In general, however, the foraminifera-based reservoir age estimates for our sites that represent various hydrographic key regions in the high-latitude ocean appear much higher than model-derived values. These deviations reach up to 1400 yr, in particular in the Southern Ocean. In part, they may result from the fact that present models may not yet be suited to capture small-scale ocean structures such as the interference of ocean currents with local bathymetry and local upwelling cells. Here, model-based reservoir ages appear far too low in LGM regions influenced by regional upwelling such as the South China Sea then governed by an estuarine overturning system (Wang et al., 2005; Fig. 9), by coastal upwelling off N.W. Australia (Xu et al., 2010; Sarnthein et al., 2011), or by a melt water lid such as off eastern New Zealand (Bostock et al., 2013; Küssner et al., 2020 subm.). Local oceanic features are likely to be missed in a coarse-resolution model such as Muglia et al. (2018). Our more narrow-spaced empiric data could help to test and refine the skill of models to capture past ^{14}C reservoir ages.

Various differences amongst plankton- and model-based reservoir ages may also result from differential seasonal habitats of the different planktic species analyzed that, in turn, may trace different surface and subsurface water currents. Pertinent details are largely unknown for the modern scenario because of the 'bomb effect', likewise no pertinent data exist yet for the LGM. However, distinct interspecies differences were found in Baja California that record differential, upwelling-controlled habitat conditions (Lindsay et al, 2015). In the northern Norwegian Sea interspecies differences amount up to 600 yr for the time span of the Preboreal ^{14}C plateau, 9.6–10.2 cal. ka (Sarnthein and Werner, 2018). Here ^{14}C records of Arctic *Turborotalita quinqueloba*, dominantly grown close to the sea surface during peak summer, differ from the paired record of *Neogloboquadrina pachyderma*, formed in subsurface waters, and that of subpolar species *N. incompta*, mainly advected from the south by Norwegian Current waters well mixed with the atmosphere during peak winter. This makes closer specification of model results as product of different seasonal extremes a further target.

3.3 Plankton-based ^{14}C reservoir ages – A prime database to estimate past changes in the ^{14}C ventilation age of deep waters, ocean MOC, and DIC of the ocean of the past

'Raw' apparent benthic ventilation ages (in ^{14}C yr; 'raw' *sensu* Balmer et al., 2018) express the difference between the (coeval) atmospheric and benthic ^{14}C levels measured at any site and time of foraminifer deposition. These ages are the sum of (1) the planktic reservoir age of the ^{14}C plateau that covers a group of paired benthic and planktic ^{14}C ages and (2) the (positive or negative) ^{14}C age difference between any benthic ^{14}C age and the average ^{14}C age of the paired planktic ^{14}C plateau. The benthic ventilation ages necessarily rely on the high quality of ^{14}C plateau-based chronology, since the atmospheric ^{14}C level has been subject to substantial short-term changes over glacial-to-deglacial times. Necessarily, the ventilation ages include a mixing of different water masses that might originate from different ocean regions and may contribute differential ^{14}C ventilation ages, an unknown justifying the modifier 'apparent'.

In a further step, the $\Delta\Delta^{14}C$ equivalent of our 'raw' benthic ventilation age may be adjusted to changes in atmospheric ^{14}C that occurred over the (short) time span between deep-water formation and benthic sediment deposition (e.g., Balmer and

Sarnthein, 2018; Cook and Keigwin, 2015). In most cases, however, this second step is omitted since its application usually does not imply any major modification of the ventilation age estimates (Fig. S2a; Skinner et al., 2017; Sarnthein et al., 2013).

On the basis of ^{14}C plateau tuning we now can rely on 18 accurately dated records of apparent benthic ^{14}C ventilation ages (Fig. S2a-d) to reconstruct the global geometry of LGM and HS-1 deep and intermediate water circulation as summarized in ocean transects and maps (Figs. 9–11) and discussed below. The individual matching of our 20 planktic ^{14}C plateau sequences with that of the Suigetsu atmospheric ^{14}C record is displayed in Sarnthein et al. (2015), Balmer et al., (2016), Küssner et al. (2020, subm.), and Ausin et al. (2019, unpubl.). In addition, robust estimates of past reservoir ages are obtained for 4 planktic and benthic ^{14}C records from paired atmospheric ^{14}C ages of wood chunks (Rafter et al., 2018; Zhao and Keigwin, 2018; Broecker et al., 2004).

3.3.1 — Major features of ocean meridional overturning circulation during LGM (Fig. 10)

Off Norway and near the Azores Islands very low benthic ^{14}C ventilation ages of <100–750 yr suggest ongoing deep-water formation in the LGM northern North Atlantic reaching down to more than 3000–3500 m water depth, with a flow strength possibly similar to today (and a coeval deep countercurrent of old waters from the Southern Ocean flowing along the East Atlantic continental margin off Portugal). This pattern clearly corroborates the assembled benthic $\delta^{13}C$ record showing plenty of elevated $\delta^{13}C$ values for the northwestern, eastern and central North Atlantic (Sarnthein et al., 1994; Millo et al., 2006; Keigwin and Swift, 2017). Irrespective of unspecified potential zonal variations in deep-water ventilation age at mid latitudes and different from a number of published models (e.g., Ferrari et al., 2014; Butzin et al., 2017) this ‘anti-estuarine’ pattern has been confirmed by MIROC model simulations (Gebbie, 2014; Sherriff-Tadano et al., 2017, Yamamoto et al., 2019) and, independently, by ε_{Nd} records (Howe et al., 2016; Lippold et al., 2016). The latter suggest an overturning of AMOC possibly even stronger than today, in particular due to a ‘thermal threshold’ (Abé-Ouchi, pers. comm.) overlooked in other model simulations.

In contrast to the northern North Atlantic, deep waters in the southern North Atlantic and Circumpolar (CP) deep waters in the subpolar South Atlantic show an LGM ^{14}C ventilation age of ~3640 yr, finally rising up to 3800 yr (Figs. 10, 11, S2b). These waters were upwelled and admixed from below to surface waters near to the sub-Antarctic Front during terminal LGM (Fig. S2b; Skinner et al., 2010; Balmer and Sarnthein, 2016; model of Butzin et al., 2012).

In the southwestern South Pacific abyssal, in part possibly Antarctic-sourced waters (Rae and Broecker, 2018) likewise show high apparent ^{14}C ventilation ages that rise from 3900 to 4800 yr over the LGM, in particular close to its end (Figs. 10 top and S2c) (^{14}C dates of Ronge et al., 2016, modified by planktic ^{14}C reservoir ages of Küssner et al., 2020 subm.). A vertical transect of benthic $\delta^{13}C$ (McCave et al., 2008) suggests that the abyssal waters were overlain by CP waters, separated by pronounced stratification near ~3500–4000 m water depth. In part, the CP waters stemmed from North Atlantic Deep Water. Probably, their apparent ventilation age came close to 3900–4500 yr, similar to the values found in the southern South Atlantic. East of New Zealand the CP waters entered the deep western Pacific and spread up to the subpolar North Pacific, where LGM ^{14}C ventilation ages reached ~3700 yr, possibly occasionally 5000 yr (Fig. S2d).

Similar to today, the MOC of the LGM Pacific was shaped by estuarine geometry, probably more weakened than today (Du et al., 2018) and more distinct in the far northwest than in the far northeast. This geometry resulted in an upwelling of old deep waters in the subarctic Northwest Pacific, here leading to a ^{14}C reservoir age of ~1700 yr for surface waters at terminal LGM. On top of the Lower Pacific Deep Waters we may surmise Upper Pacific Deep Waters that moved toward south (Figs. 10 top and 11).

The Pacific deep waters were overlain by Antarctic / Pacific Intermediate Waters (IW) with LGM ^{14}C ventilation ages as low as 1400–1600 yr, except for a shelf ice-covered site at the southern tip of Chile with IW ages of 2460–3760 yr, possibly a result of local upwelling of CP waters. In general, however, the low values of Pacific IW are similar to those estimated for South Atlantic IW and likewise reflect a vivid exchange with atmospheric CO_2 in their source regions in the Southern Ocean (Skinner et al., 2015).

When entering and crossing the entrance sill to the marginal South China Sea the 'young' IW were mixed with 'old' CP waters entrained from below, here leading to ^{14}C ventilation ages of 2600–3450 yr (Figs. 9 and S2d). The LGM South China Sea was shaped by an estuarine-style overturning system marked by major upwelling near to its distal end in the far southwest (Wang L. et al., 1999). This upwelling led to planktic ^{14}C reservoir ages as high as 1200–1800 yr, values rarely found elsewhere in surface waters of low latitudes.

Our wide-spaced distribution pattern of 18 open-ocean ^{14}C ventilation ages (plus 4 values based on paired wood chunks) in Figs. 10 and 11 agrees only in part with the circulation patterns suggested by the much larger datasets of ^{14}C ventilation ages compiled by Skinner et al. (2017) and Zhao et al. (2018). Several features in Figs. 10 and 11 directly deviate, e.g., the ages we derive for the North Atlantic and mid-depth Pacific. These deviations may be linked to both the different derivation of our ^{14}C ventilation age estimates and the details of our calendar-year chronology now based on the narrow-standing suite of ^{14}C plateau-boundary ages. The quality of our ^{14}C reservoir ages of surface waters also controls the 'apparent' ventilation age of deep-waters, as it results from direct addition of the short-term average ^{14}C age of a planktic ^{14}C plateau to a paired, that is coeval benthic ^{14}C age (formed during the time of benthic foraminiferal growth, somewhat after the actual time of deep-water formation).

3.3.2 — Major features of meridional overturning circulation during early HS-1 (Fig. 10)

Near the onset of deglacial Heinrich Stadial 1 (HS-1; ~18–14.7 cal. ka) major shifts in ^{14}C ventilation age suggest some short-lasting but fundamental changes in the circulation geometry of the deep ocean, a central theme of marine paleoclimate research (lower panel of Figs. 10, 11 and S2a and b). Deep waters in the eastern Nordic Seas, west of the Azores Islands, and off northern Brazil show a rapid rise to high ^{14}C ventilation ages of ~2000–2500 yr and up to 4000 yr off Brazil, values that give first proof for a brief switch from 'anti-estuarine' to 'estuarine' circulation that governed the central North Atlantic and Norwegian Sea during early HS-1. This geometry continued – except for a brief but marked and widespread event of recurring NADW formation near 15.2 ka – until the very end of HS-1 near 14.5 ka (Fig. S2a; Muschitiello et al., 2019). The MOC switch from LGM to HS-1 is in line with changes depicted in paired benthic $\delta^{13}C$ data (Sarnthein et al., 1994), but not confirmed by the coeval ε_{Nd} record that suggests a constant source of 'mid-depth waters', with the $\delta^{13}C$ drop being simply linked to a higher age (Howe et al., 2018).

Conversely, benthic ^{14}C ventilation ages in the northeastern North Pacific (Site MD02-2489) show a coeval and distinct but brief minimum of 1050-1450 yr near 3640 m w.d. during early HS-1 (~18.1–16.8 ka; Figs. 10, 11, and S2d). This minimum was produced by extremely small benthic-planktic age differences of 350–650 yr and provides robust evidence for a millennial-scale event of deep-water formation, that has flushed the northeastern North Pacific down to more than 3640 m w.d. (Gebhardt et al., 2008; Sarnthein et al., 2013; Rae et al., 2014). Similar circulation geometries were reported for the Pliocene (Burls et al., 2017). 'Young' Upper North Pacific Deep Waters (North Pacific Intermediate Waters *sensu* Gong et al., 2019) then penetrated as 'western boundary current' far south, up to the northern continental margin of the South China Sea (Figs. 9b, 11, and S2d). The short-lasting North Pacific regime of anti-estuarine overturning was similar to that we find in the modern and LGM Atlantic and, most interesting, simultaneous with the Atlantic's estuarine episode.

Recent data on benthic-planktic ^{14}C age differences (Du et al., 2018) precisely recover our results in a core at ~680 m w.d. off southern Alaska. However, they do not depict the 'young' deep waters at their Site U1418 at ~3680 m w.d., as corroborated by a paired autigenic ε_{Nd} maximum suggesting a high local bottom water age nearby. We assume that the amazing difference in local deep-water ventilation ages is due to small-scale differences in the effect of Coriolis forcing at high latitudes between a site located directly at the base of the Alaskan continental margin (U1418; Fig. 10b) and that on the distal Murray Sea Mount in the 'open' Pacific (MD02-2489; Figs. 7 and 11), which probably has been been washed by a plume of newly formed North Pacific deep waters probably stemming from the Bering and/or Ochotsk Seas. In contrast, the incursion of almost 3000 yr old deep waters from the Southern Ocean has continued along the continental margin all over HS-1. In summary we may conclude that the geometry of ocean MOC was briefly reversed in the 'open' North Pacific over almost 1500 years during HS-1, far deeper than suggested by previous authors (e.g., Okazaki et al., 2012; Gong, S., et al. 2019), but similar to changes in geometry first proposed by Broecker et al. (1985) then, however, for an LGM ocean.

3.3.3 — Deep-Ocean DIC inventory

Apart from the changing geometries in ocean MOC during LGM and HS-1, the global set of ^{14}C plateau-based, hence refined estimates of apparent ^{14}C ventilation ages (Fig. 10) has ultimately also revealed new insights into glacial-to-deglacial changes in deep-ocean DIC inventories (Sarnthein et al., 2013; Skinner et al., 2019). On the basis of GLODAP data (Key et al., 2004) any drop in ^{14}C concentration (i.e., any rise in average ^{14}C ventilation age) of modern deep waters is tied linearly to a rise of carbon (DIC) dissolved in deep ocean waters below ~2000 m, making for 1.22 micromole C / -1 ‰ ^{14}C. By and large, GCM and box model simulations of Chikamoto and Abé-Ouchi (2012) and Wallmann et al. (2016) suggest that this ratio may also apply to LGM deep-water circulation, when apparent ^{14}C ventilation ages in the Southern Ocean increased significantly (from 2400 up to ~5000 yr) and accordingly, thermohaline circulation was more sluggish and transit times of deep waters extended. Accordingly, a 'back-of-the-envelope' calculation of LGM ventilation age averages in the global deep ocean suggests an additional carbon absorption of 730–980 Gt (Sarnthein et al., 2013). This estimate can easily accommodate the glacial transfer of ~200 Gt C from the atmosphere and biosphere, moreover, may also explain 200–450 Gt C then most probably removed from glacial Atlantic and Pacific intermediate waters. These estimates offer an independent evaluation of ice core-based data, other proxies, and model-based data on past changes in the global carbon cycle (e.g., Menviel et al., 2018).

4. SOME CONCLUSIONS AND PERSPECTIVES

– Despite some analytical scatter, ^{14}C ages for the top and base of Lake Suigetsu-based atmospheric ^{14}C plateaus and coeval planktic ^{14}C plateaus do not present statistical 'outliers' but real age estimates that are reproduced by tree ring-based ^{14}C ages over the interval 10–13 cal. ka and further back.

– Hulu U/Th model-based ages of ^{14}C plateau boundaries of the Suigetsu atmospheric ^{14}C record appear superior to those derived from microscopy-based varve counts only, since U/Th model-based ages match far more closely the age deduced from XRF-based varve counts for the test case of lower plateau boundary 2b in the early deglacial, and the age assigned to the Laschamp event prior to the LGM.

– During deglacial times, several ^{14}C plateaus paralleled a rise in air-sea gas exchange, and, in turn, distinct changes in ocean MOC. By contrast, changes in cosmogenic ^{14}C production rarely provide a complete explanation for the plateaus identified in the Suigetsu ^{14}C data under discussion.

– In total, ^{14}C plateau boundaries in the range 29–10 cal. ka provide a suite of ~30 age tie points to establish – like chronological ladder rungs – a robust global age control for deep-sea sediment sections and global stratigraphic correlations of last glacial to deglacial climate events, 29–10 cal. ka. U/Th model ages confine the cal. age uncertainty of Suigetsu plateau boundaries assigned halfway between two ^{14}C ages nearby inside and outside a plateau's scatter band to less than ±50 to ±70 yr.

– The difference in ^{14}C age between coeval atmospheric and planktic ^{14}C plateaus presents a robust tracer of planktic ^{14}C reservoir ages and shows their temporal and spatial variability, for the LGM and HS-1 now established for 18/20 sediment sites.

– Paired reservoir ages obtained from different planktic species document the local distribution patterns of different surface water masses and prevailing foraminiferal habitats at different seasons.

– New, more robust deep-water ^{14}C ventilation ages can be derived on the basis of our robust planktic ^{14}C reservoir ages. These ventilation ages reveal geometries of LGM overturning circulation similar to those of today. In contrast, ^{14}C ventilation ages of early HS-1 suggest an almost 1500 yr long event of widely reversed circulation patterns marked by deep-water formation and brief flushing of the northern North Pacific and estuarine circulation geometry in the northern North Atlantic.

– Increased glacial ^{14}C ventilation ages and carbon (DIC) inventories of ocean deep waters suggest an LGM drawdown of about 850 Gt C into the deep ocean. Starting with HS-1 a drop of ventilation age suggests carbon released to the atmosphere (Sarnthein et al., 2013).

– Comparison of planktic and model-based reservoir age estimates reveals some major discrepancies, in particular at sites in middle to high latitudes, and highlights the need for further model refinements to make the models better reflect the real complex patterns of ocean circulation, including seasonality.

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Author contribution

All authors contributed data and valuable suggestions to write up this synthesis. MS and PG designed the outline of this manuscript. KK, BA, TE and MS provided new marine ^{14}C records in addition to records previously published. GS displayed the details of Suigetsu varve counts. RM provided a ^{10}Be-based ^{14}C record and plots of raw ^{14}C data sets of Suigetsu und Hulu Cave. Discussions amongst PG, RM, GS and MS served to select U/Th-based model ages as best-possible time scale. JM streamlined the sections on data-model intercomparison.

Data availability

Primary radiocarbon data of most sites are available at PANGAEA de, except for the ^{14}C data of 5 marine cores still under publication by Küssner et al. (2020 subm.) and Ausin et al. (unpubl.; also see caption of Fig. S2).

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TABLE CAPTIONS

~~V~~ **Table 1 a and b.** Summary of varve- and U/Th model-based age estimates (Schlolaut et al., 2018; Bronk Ramsey et al., 2012) for ~30 plateau (pl.) boundaries in the atmospheric ^{14}C record identified in Lake Suigetsu Core $SG06_{2012}$ by means of visual inspection over the interval 10.5–27 cal. ka (Sarnthein et al., 2015, suppl. and modified). At the right hand side, three columns give the average (Ø) and uncertainty range of ^{14}C ages for each ^{14}C plateau.

SUIGETSU SG06_2012 Plateau no.	Plateau Top Varve-based age (yr BP)	***U/Th-based*** *age (yr BP)*	Depth (cm c.d.)	Plateau Base Varve-based age (yr BP)	***U/Th-based*** *age (yr BP)*	Depth (cm c.d.)	Ø 14C Age of 14C Plateau (14C yr)	±Uncertainty (14C yr)	14C age BP min/max. (1.6 σ range)
'Preboreal'	10525	***10560***	1325	11100	***11108***	1383	**9525**	–170/+110	9356/9635
'Top YD'	11290	***11281***	1402	11760	***11755***	1453	**10060**	–100/+35	9963/10095
'YD'	11950	***11895***	1467	12490	***12475***	1525	**10380**	–170/ 124	10211 10504
1a	13580	***13656***	1626	13980	***14042***	1657	**12006**	100	11857 12050
1	14095	***14160***	1666	15095	***15100***	1740	**12471**	185	12315 12683
2a	15310	***15420***	1754	16140	***16520***	1802	**13406**	245	13174 13665
2b	16075	***16520***	1802	16400	***16930***	1820	**13850**	40	13808 13885
3	16835	***17500***	1847	17500	***18220***	1888	**14671**	105	14582 14792
4	17880	***18650***	1913	18830	***19590***	1971	**15851**	190	15661 16044
5a	18960	***19720***	1978	19305	***20240***	2003	**16670**	90	16570

									16750
5b	19305	***20240***	2003	20000	***20900***	2032	**17007**	190	16830 17247
6a	20190	***21000***	2050	20920	***21890***	2105	**17667**	262	17435 17960
6b	20920	***21890***	2105	21275	***22300***	2132	**18075**	140	17960 18240
7	21375	***22400***	2140	21790	***22870***	2171	**18843**	117	18741 18975
8	21835	***22940***	2175	22730	***24250***	2257	**19715**	–290 325	19425 20041
9	22730	***24250***	2257	23395	***25150***	2312	**20465**	–227 263	20238 20728
10a	23935	***25880***	2358	25080	***27000***	2400	**22328**	–380 270	21946 22600
10b	25080	***27000***	2400	25800	***27600***	2426	**22708**	–475 440	22233 23147
11	26110	***27770***	2443	27265	***28730***	2525	**24088**	–360 505	23727 24595

Table 2. Temporal match of various ^{14}C plateaus with deglacial periods of major atmospheric CO_2 rise and ocean warmings (AA = Antarctic; GIS = Greenland Interstadial).

pCO_2 RISE (~12 ppm) AGE based on annual layers AA ice core (Marcott et al. 2014)	Plateau no.	Plateau boundaries AGE range (cal. ka) based on **U/Th model ages** (Bronk Ramsey et al., 2012)
11.7 – 11.5	# 'Top YD'	**11.83 – 11.3**
14.8 – 14.53	# 1	**15.1 – 14.2**
16.4 – 16.15	# 2a	**16.52 – 15.5**
17.4 – ~17.1	(data gap)	**17.3 – 17.1**
FURTHER POTENTIAL CORRELATIVES:		
Progressive N. Atlantic warming during the YD at 12.39 – 12.03 ka *	# 'YD'	**12.46 – 11.98**
Onset of Antarctic ** warming at 18.3–17.6 ka (ice-based time scale)	#3	**18.22 – 17.5**
Onset of North Atlantic *** warming at 19.3–18.6 ka (U/Th-based time scale)	# 4	**19.6 – 18.65**
Top H2: GIS 2 N. Atlantic warming at 23.4 – 23.3 ka ****	#8	**24.25 – 22.95**

AGE CONTROL based on

* Naughton et al. (2019), ** Kawamura et al. (2007),

*** Balmer and Sarnthein (2018), **** Grootes and Stuiver (1997)

~~V~~ **Table 3** a-c. ^{14}C reservoir / ventilation ages of surface (top 50-100 m) and bottom waters vs. U/Th-based model age at 19/22 core sites in the ocean. (a) Spatial and temporal changes over early and late LGM (24–21 and 21–18.7 cal. ka), (b) HS-1, and the B/A. Late LGM estimates (average res. age of Plateau 4-5) are compared to model-based estimates of Muglia et al. (2018). (c) Data sources. For core locations see Fig. 7.

(a)

Sediment Core	Latitude	Longitude	Water depth	LGM pla. res. age				LGM model res. age	
U/Th-based model age				24–21 ka (early LGM)		21–18.7 ka (late LGM)		strong AMOC	weak
Plateau (Pl.) no.			(m)	Pl. 8 - 7 - 6	Error (yr)	Pl. 5 - 4	Error (yr)	(yr)	(yr)
ATLANTIC O.									
PS2644	67°52.02'N	21°45.92'W	777	2100	±390	1920–2200	±325 –±125	1136	1100
GIK 23074	66°66.67'N	4°90'E	1157	620–790	±145–±270	550–1175	±100–±200	1054	1059
MD08-3180	38°N	31°13.45'W	3064	–		320–605	±125–±405	827	887
SHAK06-5K	37°34'N	10°09'W	2646	700–930		330–650		872	855
(= MD99-2334)	(37°48'N	10°10'W	3146						
ODP 1002	10°42.37'N	65°10.18'W	893	700–210	±230–±310	25 – -205	±205–±215	751	738
GeoB 3910-1	4°15'S	36°21'W	2361	–		–		779	796
GeoB 1711-4	23°17'S	12°23'W	1976	1080	±290	730–840	±240–±190	711	721
KNR 159-5-36GGC	27°31'S	46°48'W	1268	540	±140	870	±120	757	777
MD07-3076	44°4'S	4°12'W	3770	–		2300	±200	928	989
INDIAN O./TIMOR SEA									
MD01-2378	13°08.25'S	121°78.8'E	1783	–		2000–1700	±300–±320	885	890
PACIFIC O.									
MD02-2489	54°39.07'N	148°92.13'W	3640	–		1560–1110	±310–±335	972	965
MD01-2416	51°26.8'N	167°72.5'E	2317	–		1710	±440	1227	1202
ODP 893A	34°17.25'N	120°02.33'W	588	–		1065	±280	839	846
MD02-2503	34°16.6'N	120°01.6'W	580	–		–		839	846
GIK 17940	20°07.0'N	117°23.0'E	1727	1820–1260	±320–±230	hiatus		836	838
(= SO50-37)	18°55'N	115°55'E	2655	1820–1260				836	840
PS75/104-1	44°46'S	174°31'E,	835	1650–1280		1500		881	895
(= SO213-84)	45°7.5'S	174°34,9'E	972	1650–1280		1500		881	895
MD07-3088	46°S	75°W	1536	380		200-350		917	–
SO213-76-2	46°13'S	178°1.7´W	4339	–		1600–1560		915	842
PS97/137-1	52°39.5'S	75°33.9'E	1027	2290–2110		2400–1800		1505	1419

(b)

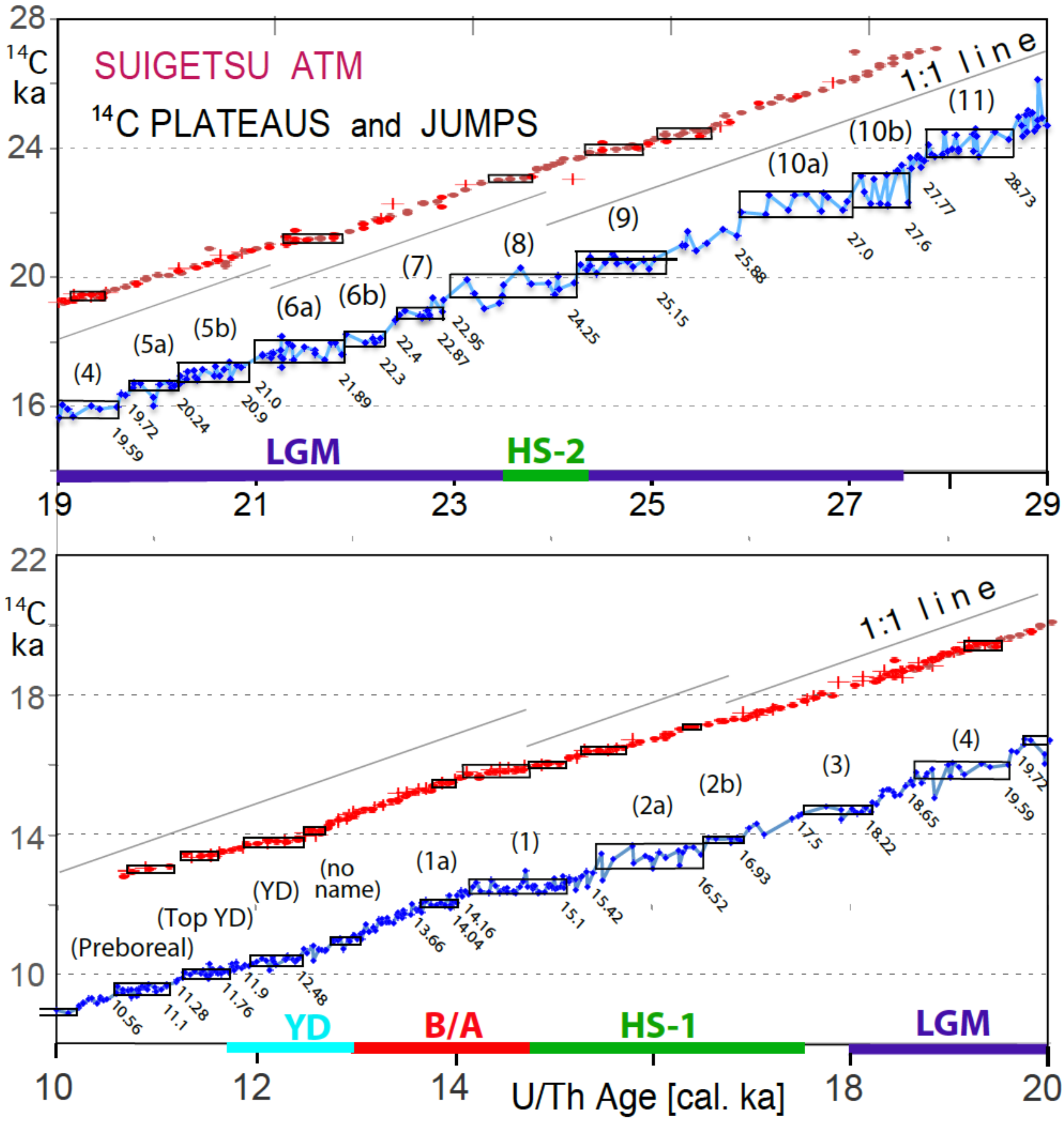
Sediment Core	HS-1 pla. res. age				B/A pla. res. age		LGM be. vent age		LGM b.w. model age	
U/Th-based model	18 –16.5 ka		16.5–15.5 ka		14.7 –13.6 ka		(yr)		strong AMOC	weak
Plateau (Pl.) no.	Pl. 3 - 2b (yr)	Error (yr)	Pl. 2a (yr)	Error (yr)	Pl. 1 - 1a	Error (yr)	early	late	(yr)	(yr)
ATLANTIC O.										
PS2644	1775–1660	±105–±160	1900	±355	–		345	2400	948	918
GIK 23074	1730–2000	±125–±160	670	±310	140–310	±250–±100	375	375	960	931
MD08-3180	1420–1610	±310–±160	1460	±390	630–360	±310	600	600	1031	1004
SHAK06-5K	350–420		550		800–1200		—		—	—
(= MD99-2334)							2200–2700	1900	—	—
ODP 1002	–100 – 20	±140	90	±345	355	±200	—		1247	1175
GeoB 3910-1	630–560	±160–±180	175	±475	210–230	±220–±110	2150	2150	—	—
GeoB 1711-4	660–690	±195–±45	420	±320	880	±255	1500	1500	1387	1714
KNR 159-5-36GGC	460–340	±380–±300	170	±700	180–230	±370–±310	1470	1470	1354	1563
MD07-3076	1650	±180	–		920	±230	3640	3640	1653	2060
INDIAN O./TIMOR SEA										
MD01-2378	740	±125	–		200–185	±345–±135	2720	—	1679	1881
PACIFIC O.										
MD02-2489	800–550	±155–±120	550	±305	440	±285		2625	2332	2595
MD01-2416	1480–1140	±135–±195	–		720–570	±285–±140		3700/510	2400	2683
ODP 893A	1065–1490	±280–±125	1400	±370	520	±185		1430	1677	1705
MD02-2503	965–1365	±160–±165	1215	±325	395–535	±240–±130	—	—	—	—
GIK 17940	1210–1370	±200–±470	1045	±320	870–970	325–±100	3300–1800		1807	1897
(= SO50-37)							3225	3225	2373	2667
PS75/104-1	1050		1100		800–250		—	—	—	—
(= SO213-84)							1500	2400	1101	1146
MD07-3088	800–1090		1010		730–940		1600	1600	1808	1701
SO213-76-2	200		–		–		4685	4685	1712	2001
PS97/137-1	1500–670		435		–		3300	2100	1631	1871

(c)

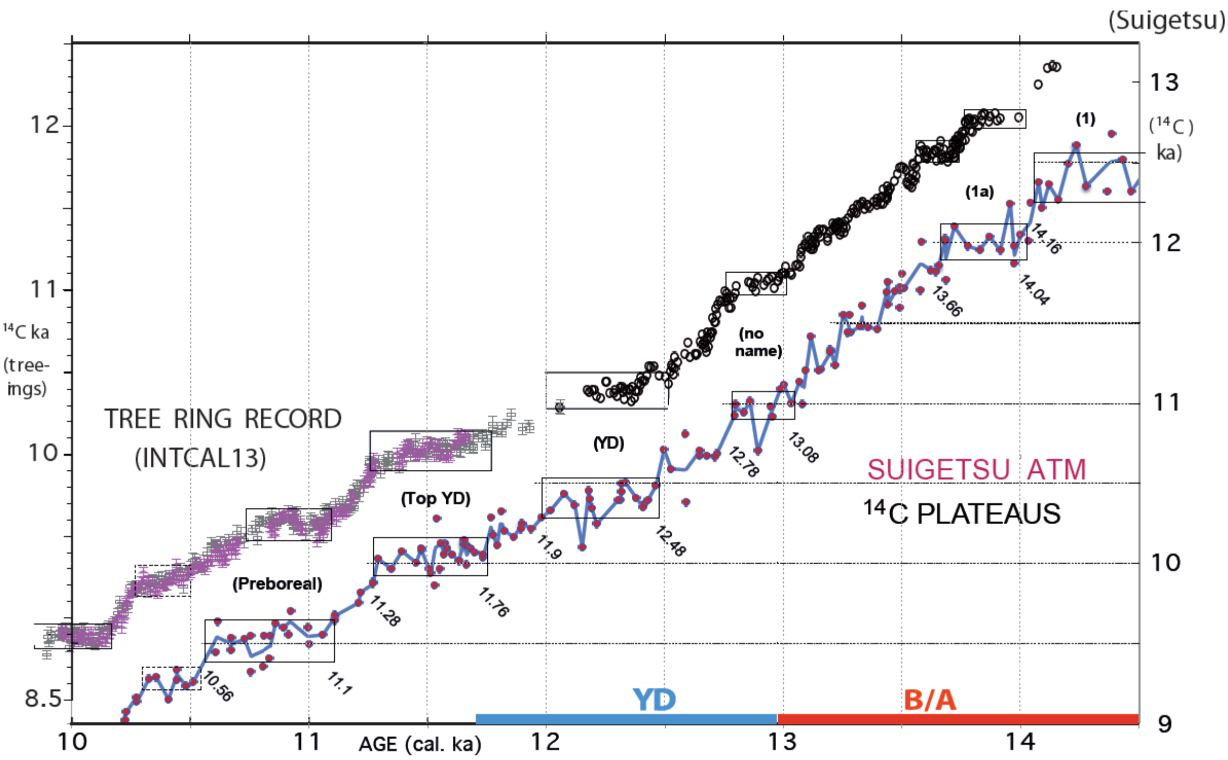
Sediment Core	DATA Source	
ATLANTIC O.		
PS2644	Samthein et al. 2015	Be.data suppl.
GIK 23074	Samthein et al. 2015	
MD08-3180	Balmer et al. 2018	
SHAK06-5K	Ausin et al., 2019	
(= MD99-2334)	Skinner et al. 2014	
ODP 1002	Samthein et al. 2015	
GeoB 3910-1	Balmer et al. 2016	
GeoB 1711-4	Balmer et al. 2016	
KNR 159-5-36GGC	Balmer et al. 2016	data suppl.
MD07-3076	Balmer et al. 2016	
INDIAN O./TIMOR SEA		
MD01-2378	Samthein et al. 2015	
PACIFIC O.		
MD02-2489	Samthein et al. 2015	
MD01-2416	Samthein et al. 2015	modified
ODP 893A	Samthein et al. 2015	data suppl.
MD02-2503	Samthein et al. 2015	
GIK 17940	Samthein et al. 2015	
(= SO50-37)	Samthein et al. 2015	
PS75/104-1	Küssner et al., 2018	
(= SO213-84)	Ronge et al., 2016	
MD07-3088	Küssner et al., 2019	
SO213-76-2	Küssner et al., 2019	
PS97/137-1	Küssner et al., 2019	

FIGURE CAPTIONS

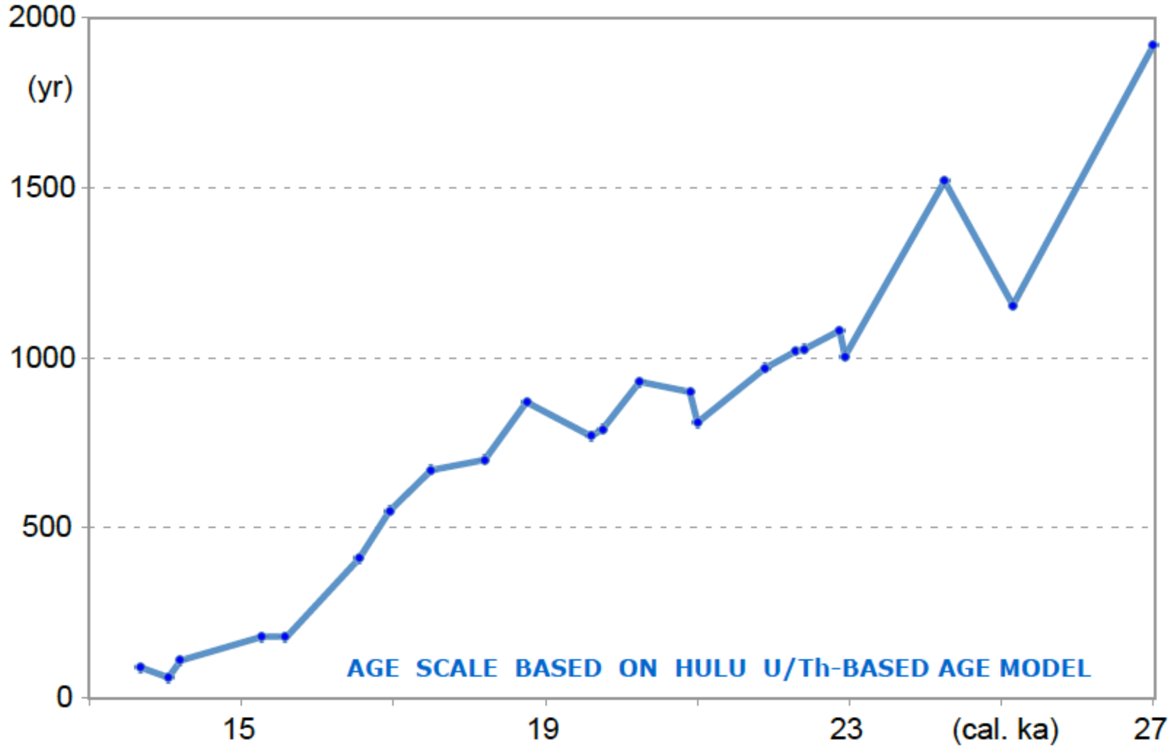
– Fig. 1. Atmospheric ^{14}C ages of Lake Suigetsu plant macrofossils 10–20 cal. ka (bottom panel) and 19–29 cal. ka (top panel) vs. U/Th-based model age (blue dots; Bronk Ramsey et al., 2012). The 1:1 line reflects gradient of one ^{14}C yr / cal. yr. Double and triple ^{14}C measurements are averaged. (In part large) error bars of single ^{14}C ages are given in Suppl. Fig. S1. Suite of labeled horizontal boxes that envelop scatter bands of largely constant ^{14}C ages shows ^{14}C plateaus longer than 250 yr (plateau boundary ages listed in Table 1). Red and brown dots (powder samples from trench and wall) and + signs (off-axis samples) depict raw ^{14}C ages of Hulu stalagmites H82 and MSD (Cheng et al., 2018; Southon et al., 2012; plot offset by +3000 ^{14}C yr). Suite of short ^{14}C plateaus (black boxes) tentatively assigned to Hulu-based record occupies age ranges slightly different from those deduced for Suigetsu-based plateaus. The difference possibly results from short-term changes in the Old / Dead Carbon Fraction (ocf / dcf) that in turn may reflect major short-term changes in LGM and deglacial monsoon climate (Wang et al., 2001; Kong et al., 2005).


SUIGETSU ATM
14C PLATEAUS and JUMPS
14C ka
1:1 line
(4)
(5a)
(5b)
(6a)
(6b)
(7)
(8)
(9)
(10a)
(10b)
(11)
LGM
HS-2
(Preboreal)
(Top YD)
(YD)
(no name)
(1a)
(1)
(2a)
(2b)
(3)
YD
B/A
HS-1
U/Th Age [cal. ka]

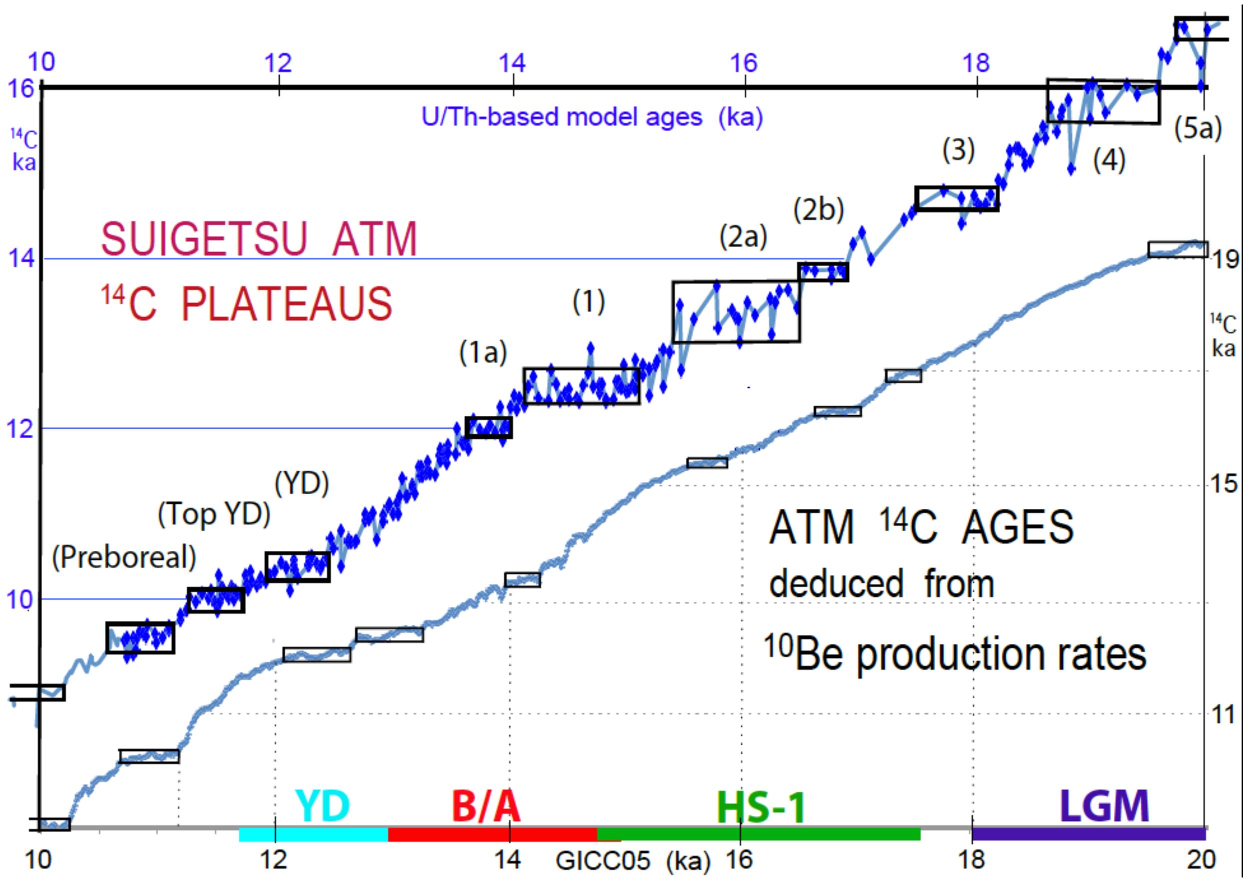
~~V~~ Fig. 2. High-resolution record of atmospheric ^{14}C jumps and plateaus (= suite of labeled horizontal boxes that envelop scatter bands of largely constant ^{14}C ages extending over >300 cal. yr) in a sediment section of Lake Suigetsu vs. tree ring-based ^{14}C jumps and plateaus 10–14.5 cal. ka (Reimer et al., 2013). Blue line averages paired double and triple ^{14}C ages of Suigetsu plant macrofossils. Age control points (cal. ka) follow varve counts (Schlolaut et al., 2018) and U/Th model-based ages of Bronk Ramsey et al. (2012). YD = Younger Dryas, B/A = Bølling-Allerød.

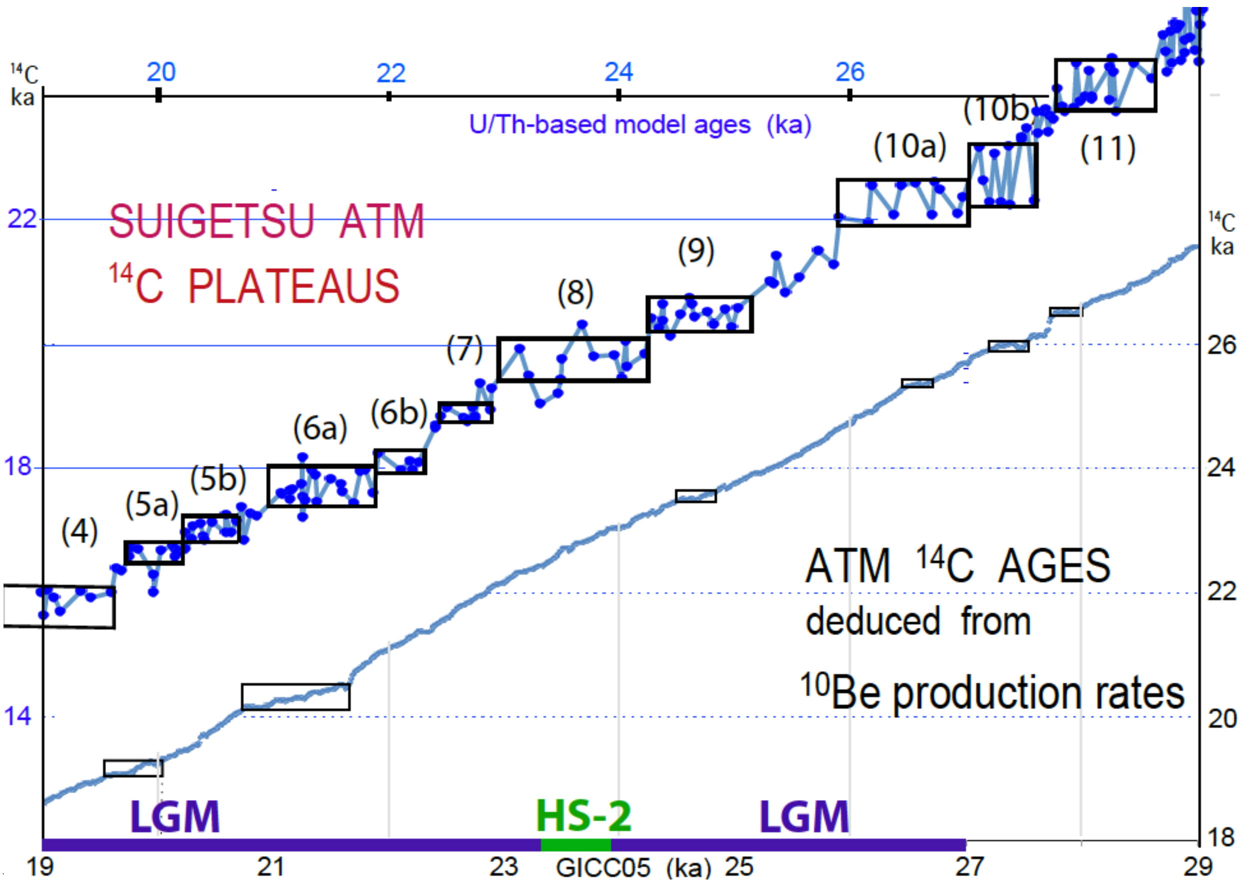


~~V~~ Fig. 3. Difference between Hulu Cave U/Th-based model ages (Southon et al., 2012; Bronk Ramsey et al., 2012; Cheng et al., 2018) and varve count-based cal. ages for atmospheric ^{14}C plateau boundaries in Lake Suigetsu sediment record (Schlolaut et al., 2018) (Sarnthein et al., 2015, suppl. and revised), displayed on the U/Th-based time scale 13–27 cal. ka.



~~V~~ Fig. 4 a and b. Atmospheric ^{14}C ages and plateaus (horizontal boxes) deduced from ^{10}Be production rates vs. GICC05 age scale (Adolphi et al., 2018) compared to the Suigetsu record of atmospheric ^{14}C plateaus vs. Hulu U/Th-based model ages (Southon et al., 2012; Cheng et al., 2018) for the intervals a) 10-20 and b) 19-29 cal ka BP.




SUIGETSU ATM
14C PLATEAUS
ATM 14C AGES
deduced from
10Be production rates
U/Th-based model ages (ka)
14C ka
GICC05 (ka)
LGM
HS-2
LGM
(4)
(5a)
(5b)
(6a)
(6b)
(7)
(8)
(9)
(10a)
(10b)
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~~V~~ Fig. 5. Sediment facies and microfacies zones in Lake Suigetsu Core SG06, ~13–32 m depth (simplified and suppl. from Schlolaut et al., 2018). Microscopy-based frequency of siderite layers with quality level 1–3 (= running average of layer counts per 20 cm thick sediment section) serves as measure of seasonal lamination quality and shows gradual transitions between varved and poorly varved sediment sections. Rounded varve ages are microscopy based and constrain age of major facies and microfacies boundaries. ANI I to ANI III mark core sections with ultrafine lamination due to sedimentation rate minima, AT marks tephra layer named AT, ‘Event layers’ label major thin mud slides probably earth quake-induced.s

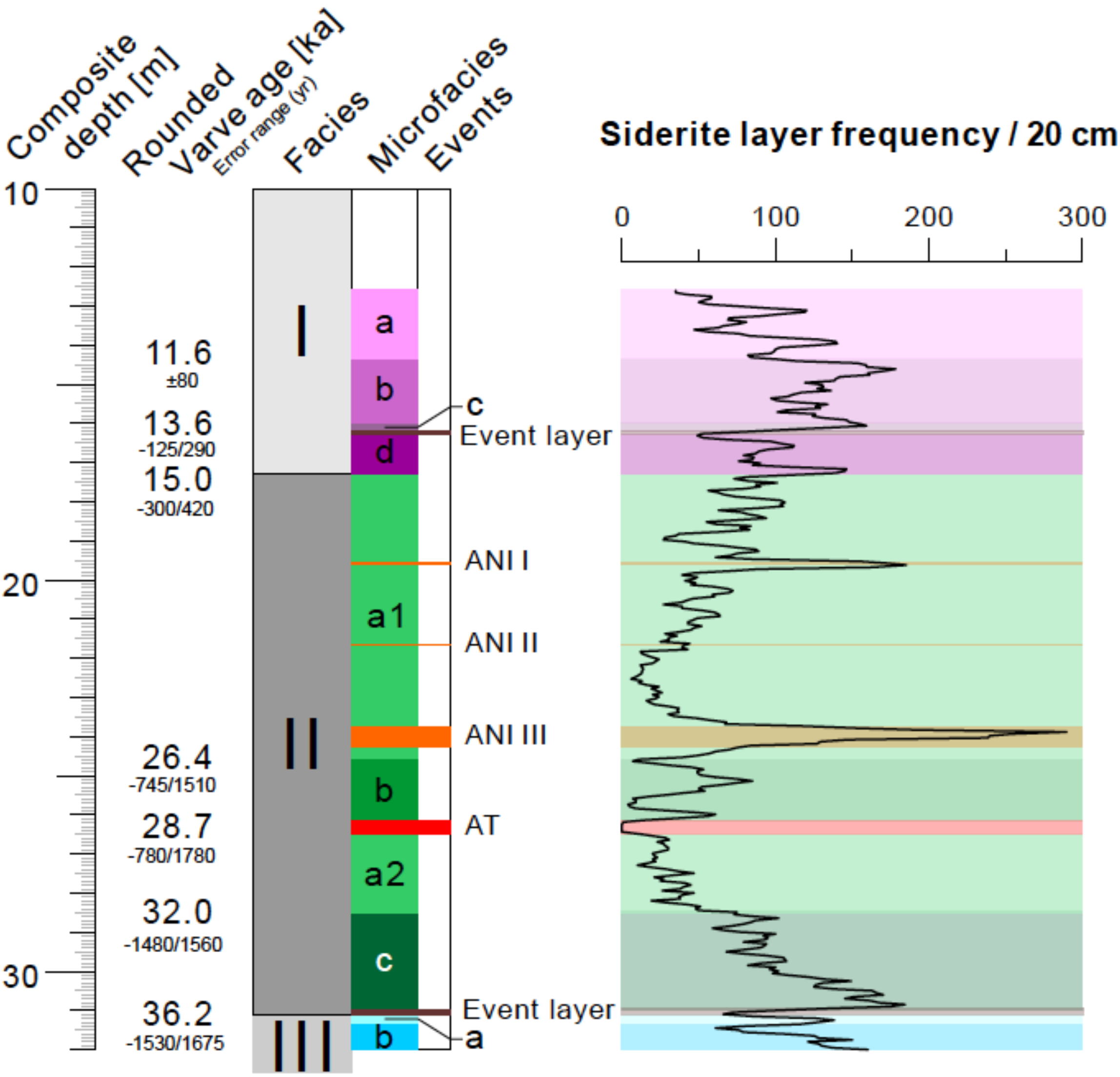


Fig. 6 (a). Four sudden steps (pink bars) in the deglacial atmospheric CO_2 rise at West Antarctic Ice Sheet Divide ice core (WDC) reflect events of fast ocean degassing, that may have contributed to the origin of deglacial ^{14}C plateaus. Age control based on ice cores (Marcott et al., 2014). (b) The steps are compared to suite of atmospheric ^{14}C plateaus dated by Hulu U/Th-based model ages (Bronk Ramsey et al., 2012). Hol = Holocene; YD = Younger Dryas; B/A = Bølling-Allerød; HS = Heinrich stadials 1 and 2; LGM = Last Glacial Maximum, GIS-2 = Greenland interstadial 2.

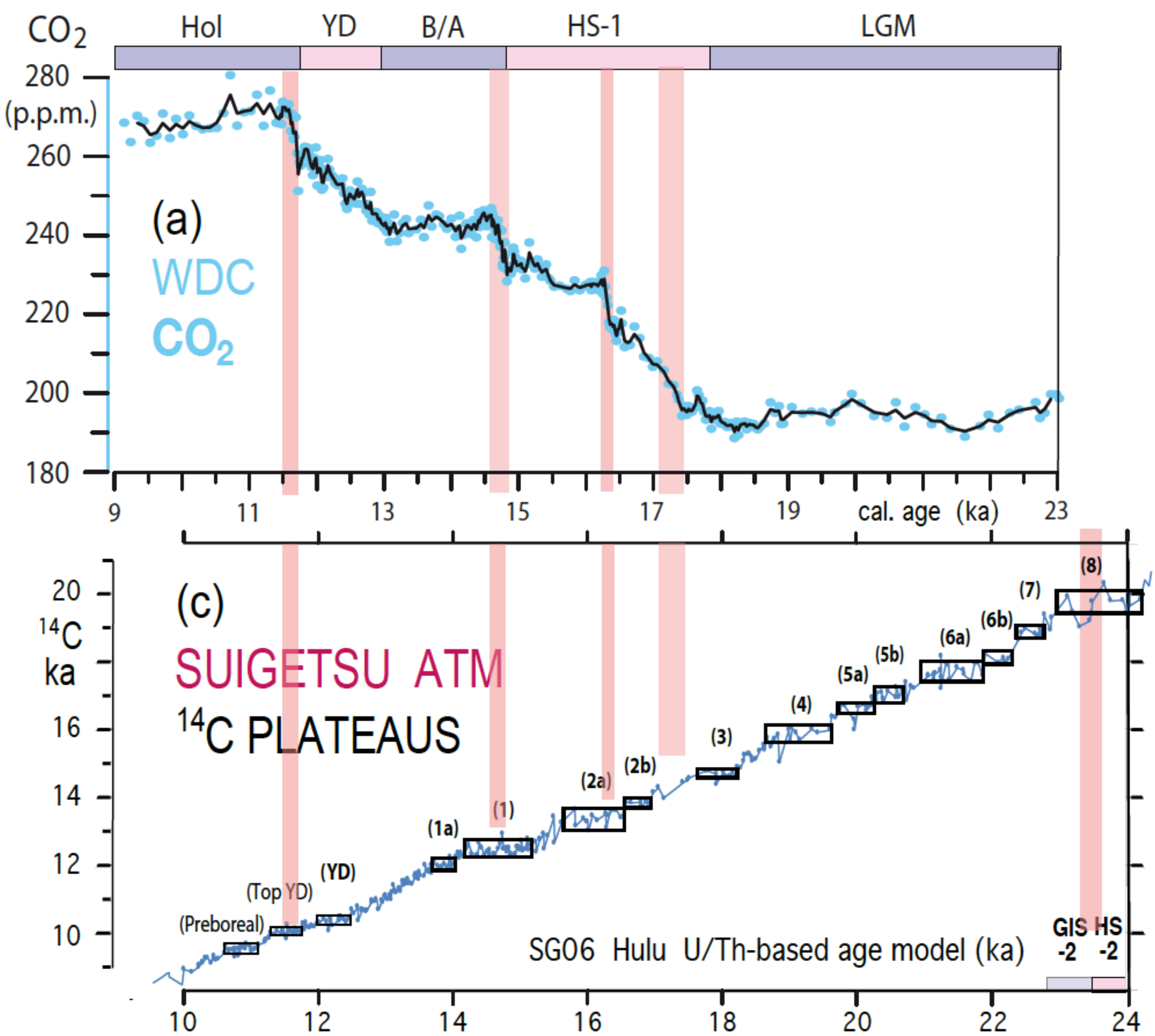
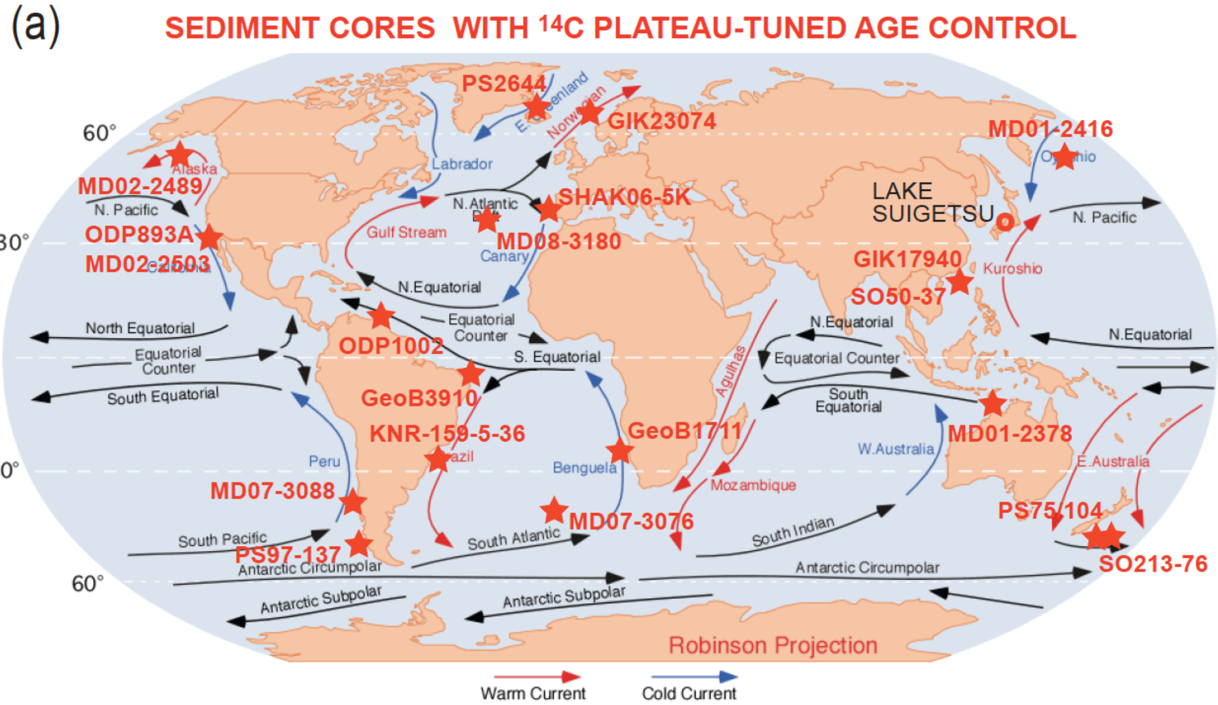
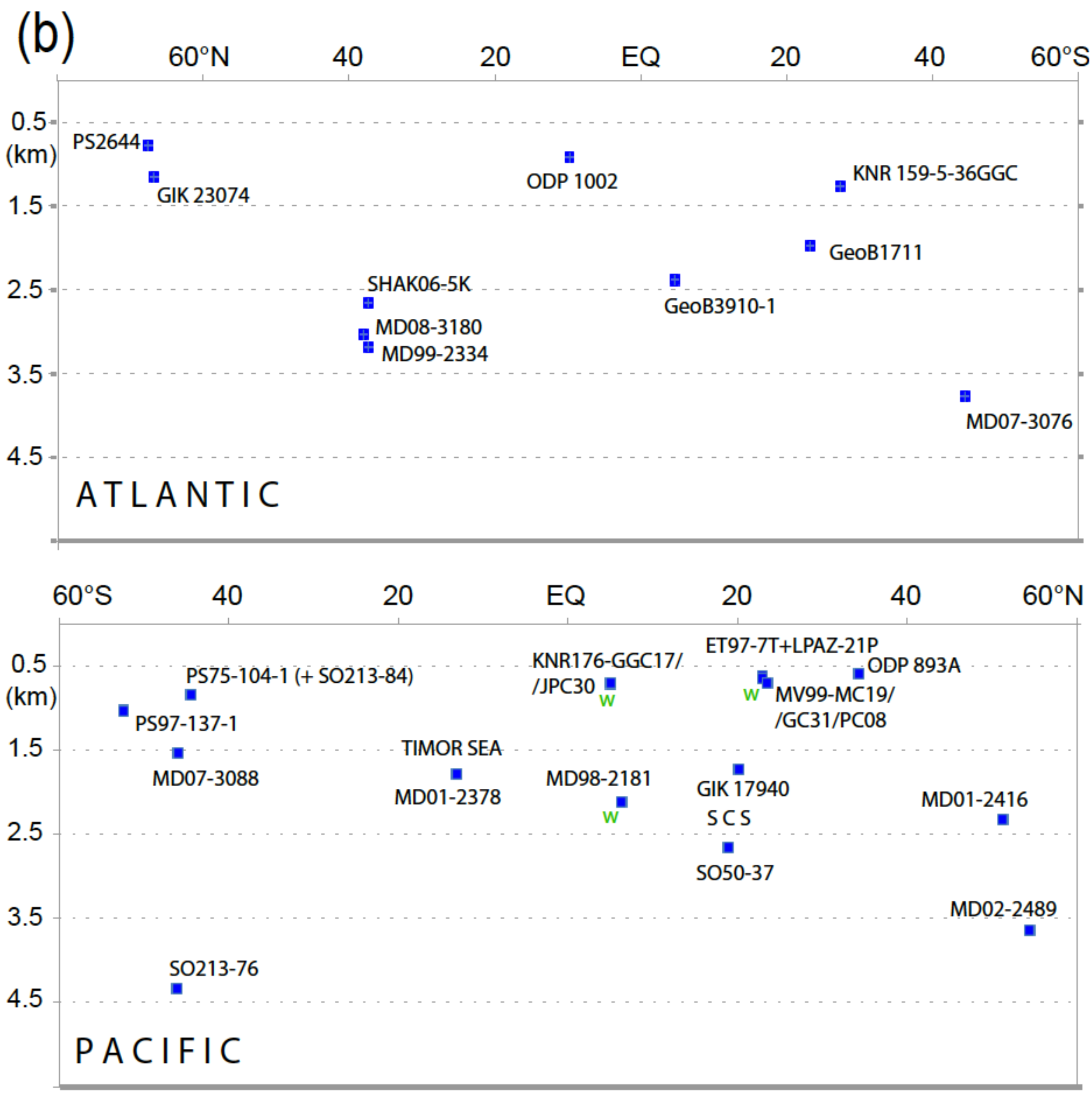


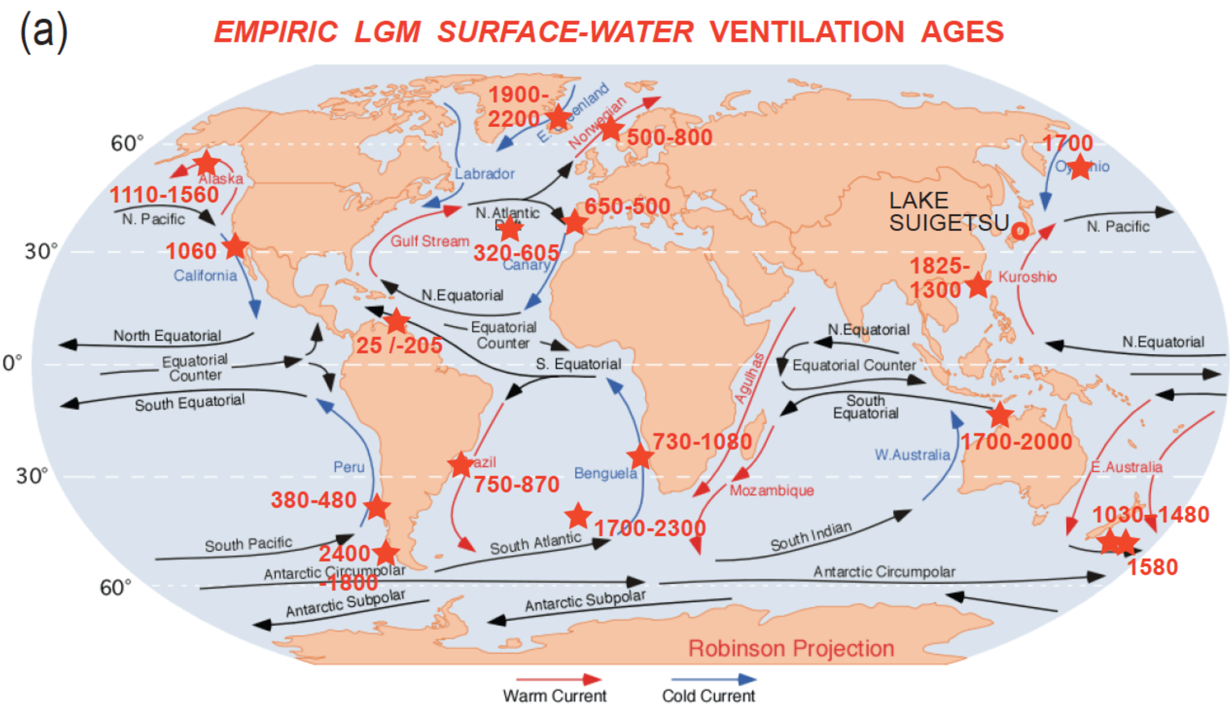
Fig. 7. Location (a) and water depth (km) (b) of sediment cores with age control based on ^{14}C plateau tuning. ^{14}C reservoir ages of cores labeled with ‘w’ are derived from samples with paired wood chunks and planktic foraminifers.

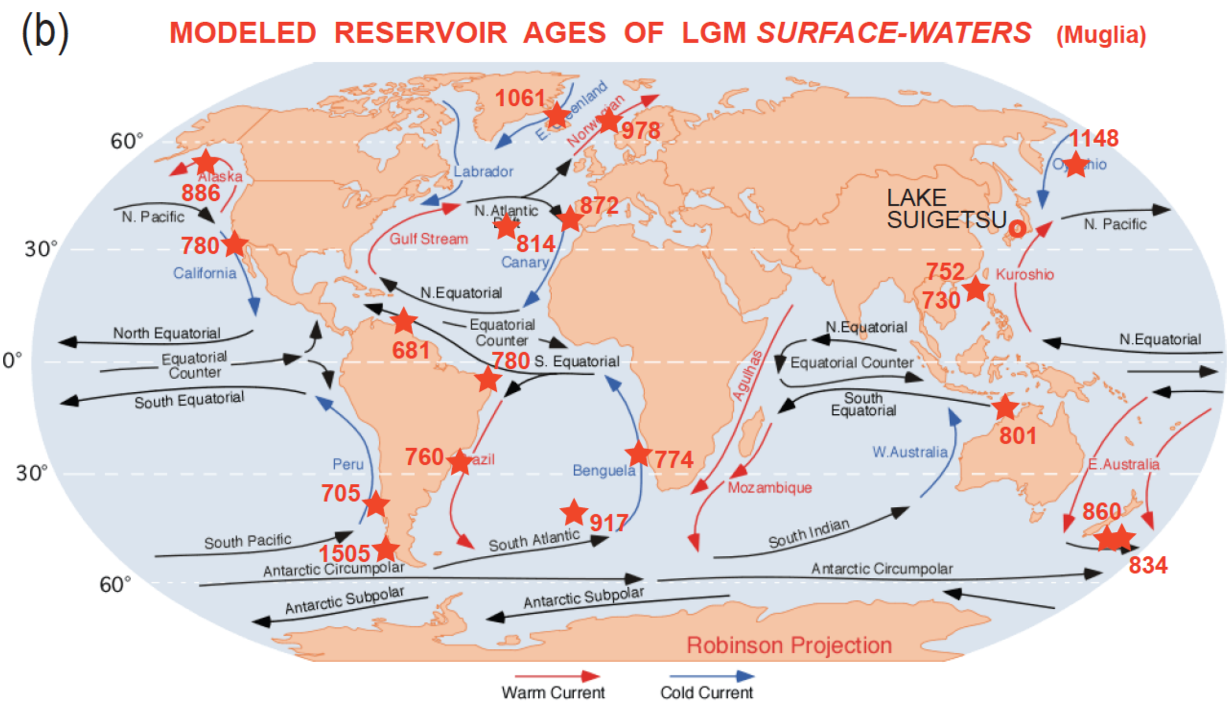
(a)

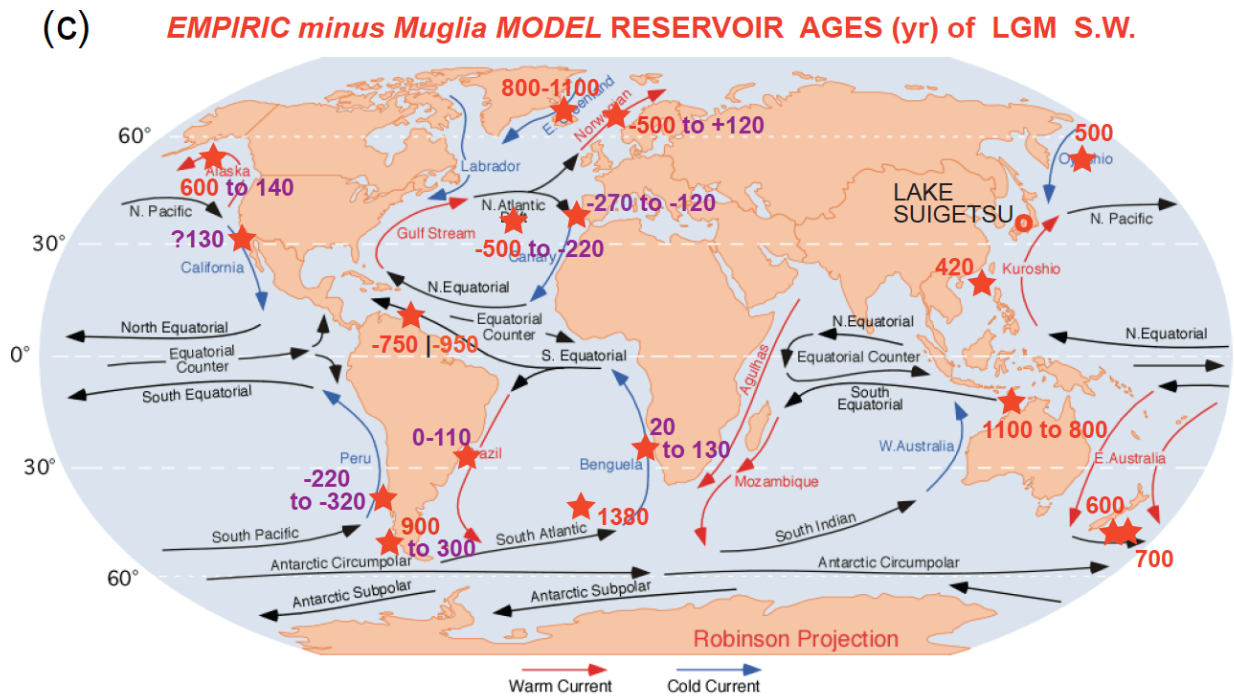


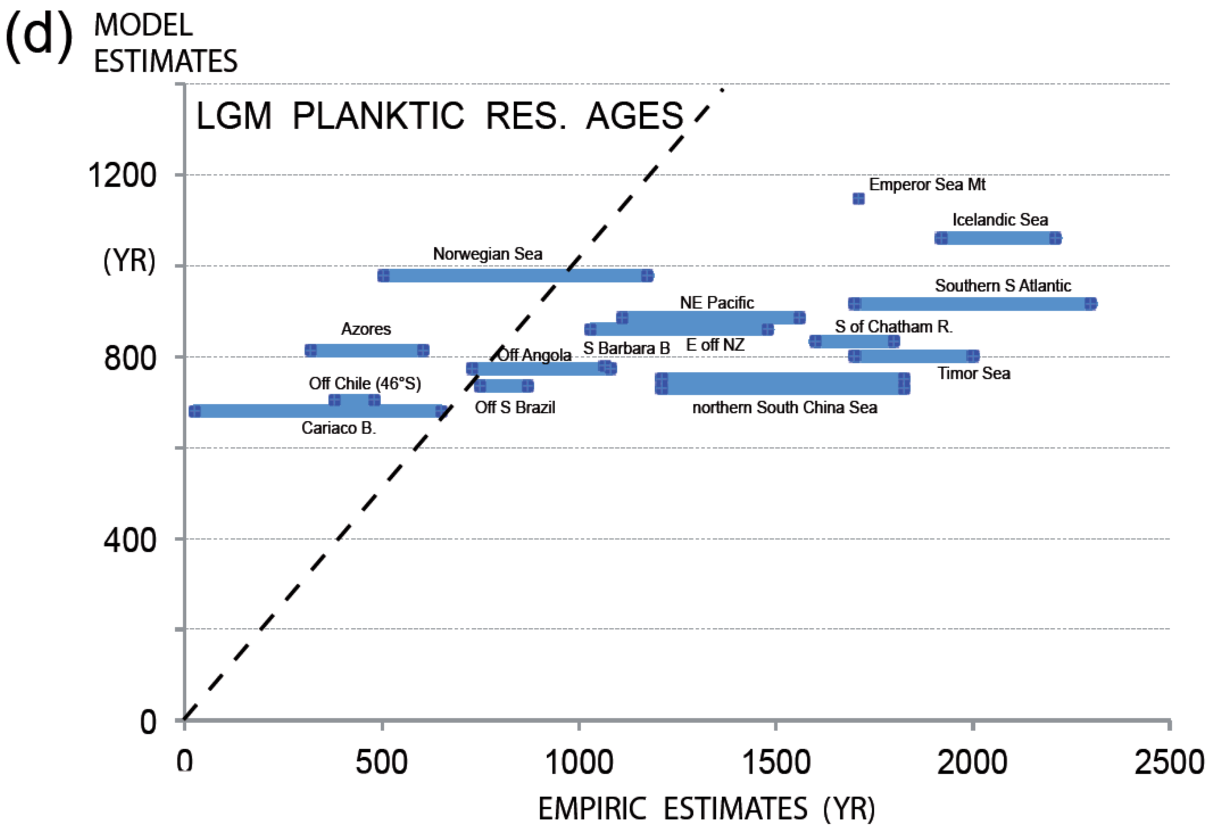


~~V~~ Fig. 8. Global distribution of ^{14}C reservoir ages of Late LGM surface waters estimated (a) by means of ^{14}C plateau tuning of planktic 14C records. (b) Model-based estimates (GCM of Muglia et al., 2018, assuming an AMOC strength of 13 Sv) for sites with plankton-based age values. X-Y graph (c) and map (d) show (rounded) differences between observed and modeled values and their intra-LGM trends. Minor differences are displayed in magenta, larger differences of >400 yr in red. Planktic habitat depths and model estimates are largely confined to 0–100 m water depth. Arrows of surface currents delineate different sea regions important to assess potential limits of spatial extrapolation of reservoir ages. Distribution of core numbers and references for ^{14}C records are given in Table 3a-c and Fig. 7a.

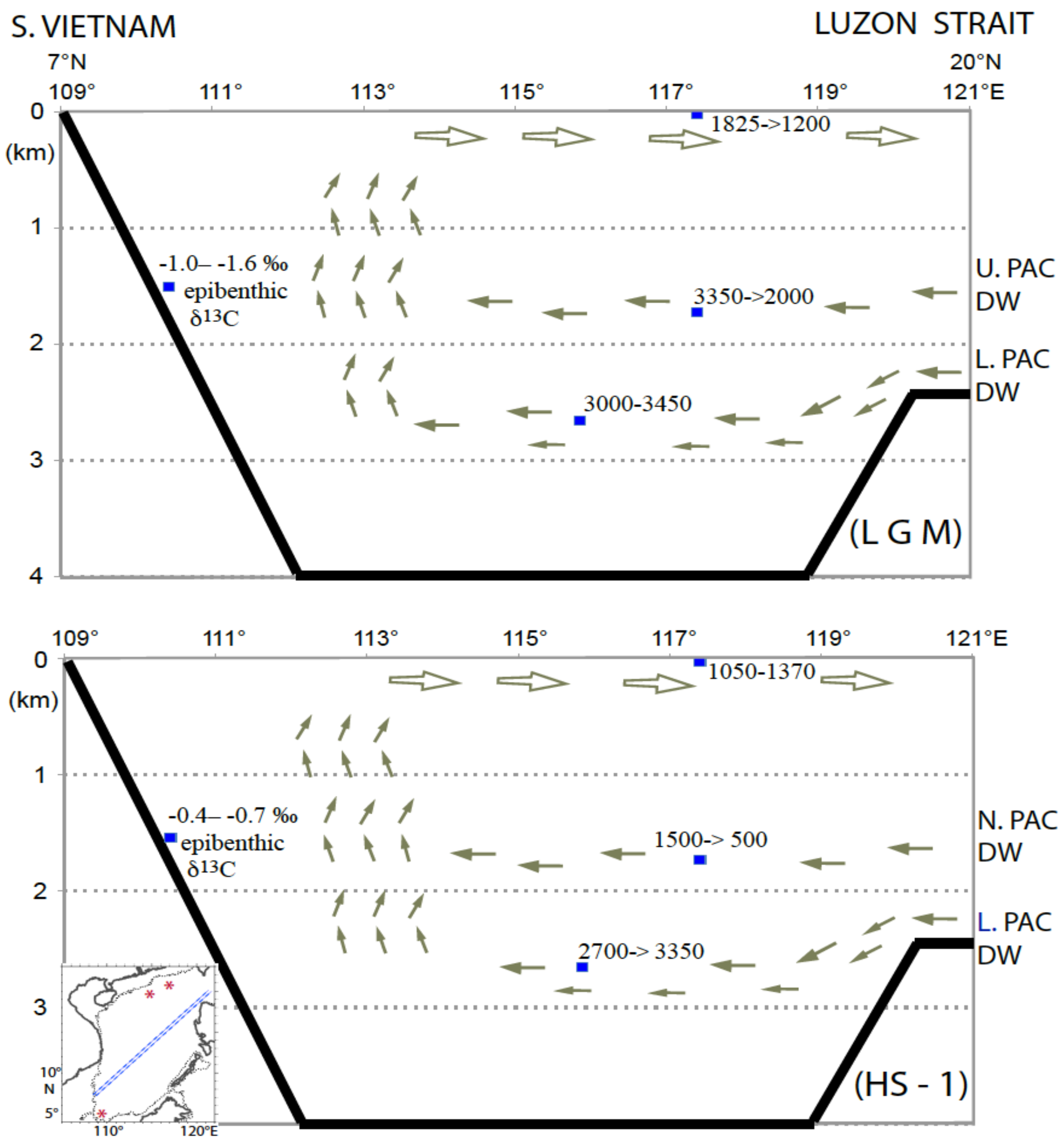




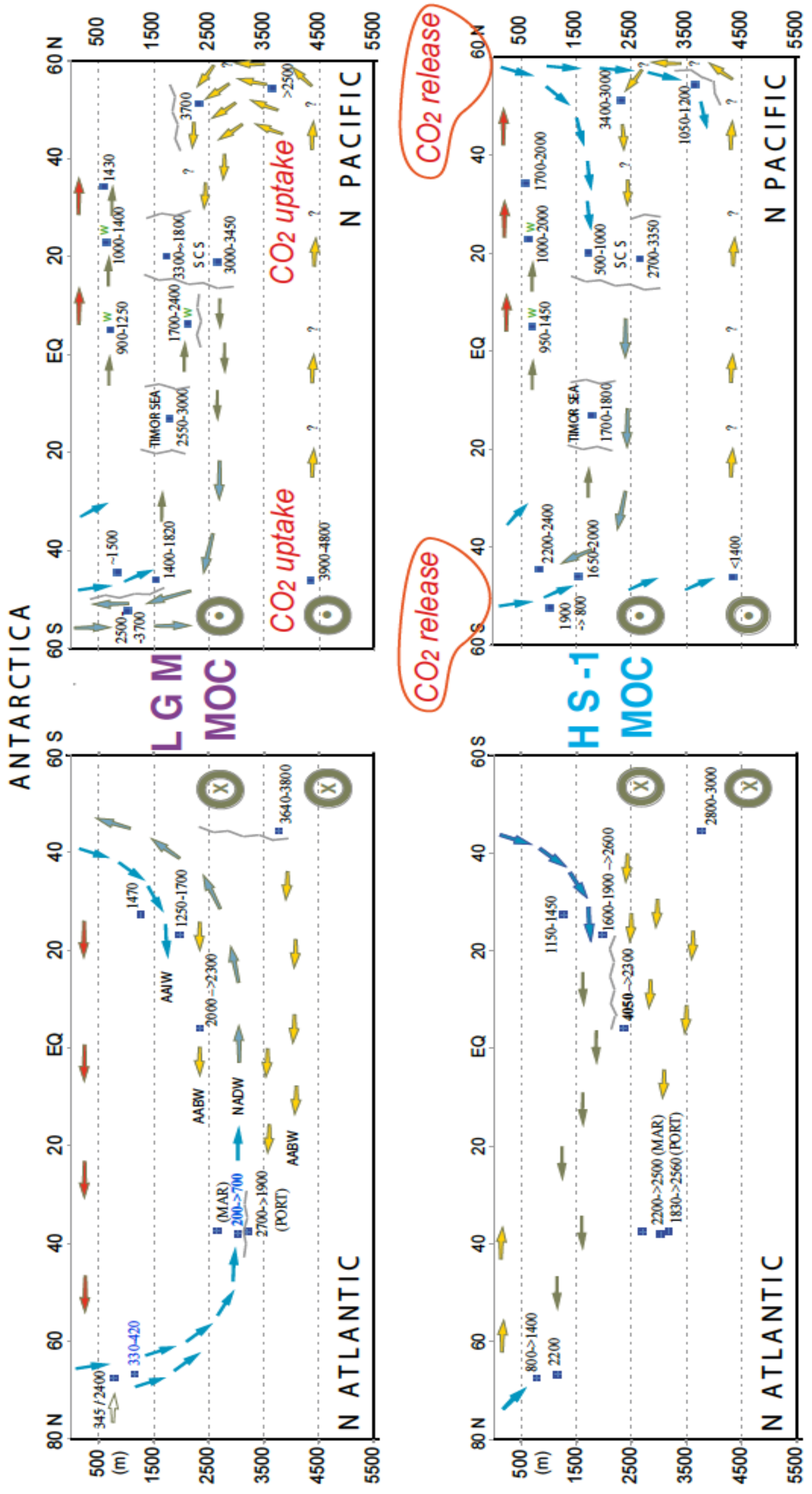




√ Fig. 9. SW–NE transect of ^{14}C reservoir age and changes in ventilation age across sites GIK17940 and SO50-37 in the South China Sea during late LGM (^{14}C Plateaus 5 and 4; upper panel) and HS-1 (lower panel). Insert map shows location of transect and core locations. Core locations are given in Fig. 7. An extreme epibenthic $\delta^{13}C$ minimum in far southwest (Core GIK17964; Sarnthein et al., 1999) reflects an LGM incursion of Lower/Upper Pacific Deep Waters (L./ U. PAC DW) with extremely high ^{14}C ventilation age and DIC enrichment in contrast to a low ventilation age of North Pacific Deep Water (N. PAC DW). Arrows show direction of potential deep and intermediate-water currents.

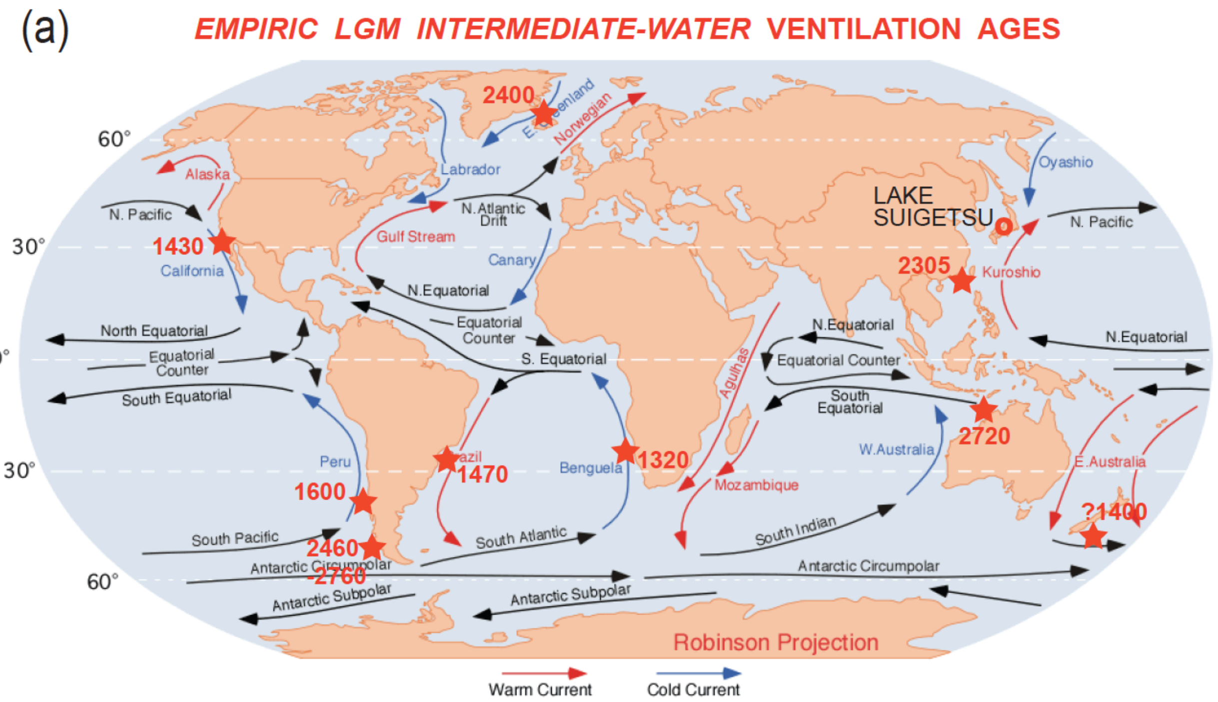


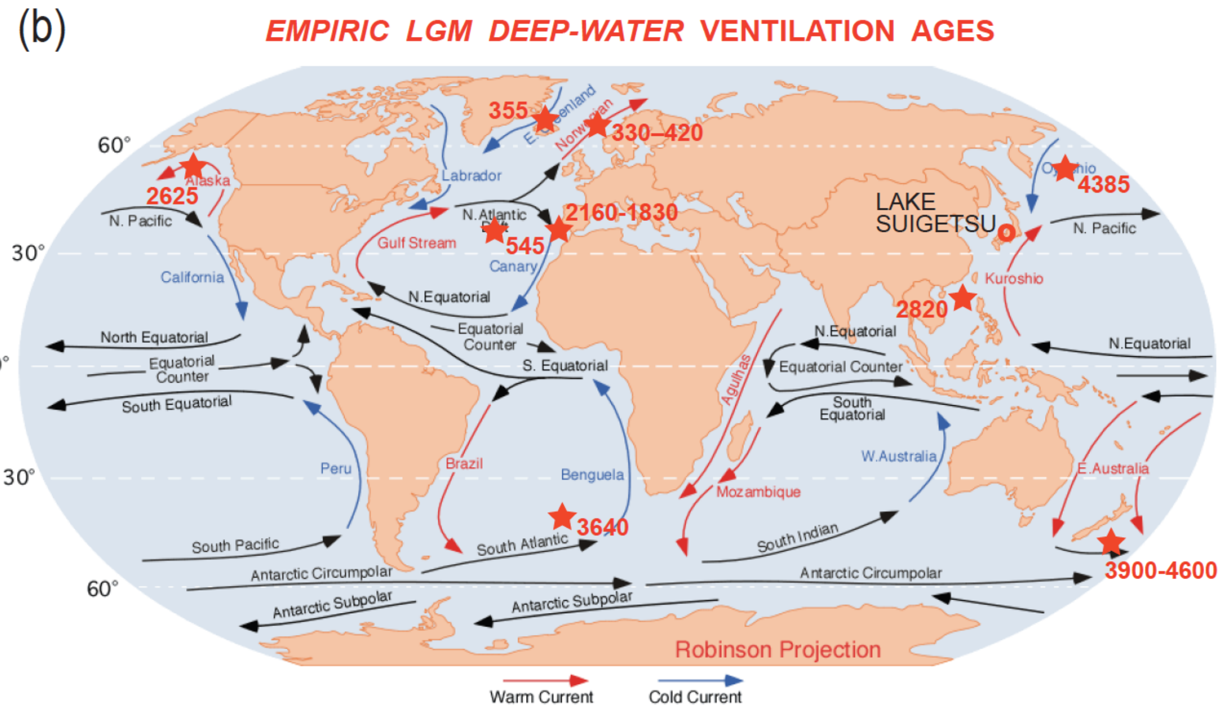
~~V~~ Fig. 10. 2D transects of the geometries of global ocean MOC. Arrows (blue = high, yellow = poor ventilation) suggest average deep and intermediate-water currents that follow the gradient from low to high benthic ventilation ages based on paired planktic ^{14}C reservoir ages derived by means of ^{14}C plateau tuning technique (Sarnthein et al., 2013, Balmer et al., 2018, Küssner et al., 2020 subm.). Reservoir ages at some Pacific sites are based on paired ^{14}C ages of planktic foraminifera and wood chunks (marked by green 'w'; Sarnthein et al., 2015; Zhao and Keigwin, 2018, Rafter et al., 2018). Red arrows suggest poleward warm surface water currents. Zigzag lines mark location of major frontal systems separating counter rotating ocean currents (e.g., W of Portugal and N of MD07-307; after Skinner et al., 2014). (a) Late LGM circulation geometry, largely similar as today. Note the major east-west gradient of ventilation ages in the central North Atlantic, between Portugal (PORT) and Mid-Atlantic Ridge W of Azores (MAR)). (b) HS-1 benthic ventilation ages reveal a short-lasting MOC reversal leading to Atlantic-style overturning in the subpolar North Pacific and coeval Pacific-style stratific-ation in the northern North Atlantic, with seesaw-style reversals of global MOC at the onset and end of early HS-1 (first proposed by Broecker et al., 1985, however, for LGM times). Increased ventilation ages reflect enhanced uptake of dissolved carbon in the LGM deep ocean (Sarnthein et al., 2013), major drops suggest major degassing of CO_2 from both the deep Southern Ocean and North Pacific during early HS-1. – SCS = South China Sea. AABW = Antarctic Bottom Water; AAIW = Antarctic Intermediate Water. NADW = North Atlantic Deep Water. Small arrows within age numbers reflect temporal trends. Many arrows are speculative using circumstantial evidence of benthic $\delta^{13}C$ records and local Coriolis forcing at high-latitude sites per analogy to modern scenarios. Location of sediment cores are given in Fig. 7, short-term variations in planktic and benthic ^{14}C reservoir/ventilation age in Suppl. Fig. S2 and Table 3.


ANTARCTICA
L G M
MOC
H S -1
MOC
N PACIFIC
N ATLANTIC
CO2 uptake
CO2 uptake
CO2 release
CO2 release
AAIW
AABW
NADW
AABW
TIMOR SEA
S C S

s

~~V~~ Fig. 11. Global distribution of ^{14}C reservoir ages obtained (a) for late LGM intermediate waters (100–1800 m w.d.) and (b) for LGM deep waters (>1800 m w.d., including Site GIK 23074 at 1157 m in the Norwegian Sea).





1427 - - - - - - - - - - - - -

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Supplementary Materials

SUPPLEMENTARY TEXT #1. Uncertainties of age control

Rough estimates of uncertainty and aspects of analytical quality were published by Sarnthein et al. (2007, 2015). We now focus on uncertainties tied to the calendar age definition for each ^{14}C plateau boundary both in the Suigetsu atmospheric and the various marine sediment records (Table 1). To recap, an age/sediment section is formally defined as containing a '^{14}C plateau', when ^{14}C ages show almost constant values with an overall gradient of <0.3 to <0.5 ^{14}C yr per cal. yr (based on visual description and/or statistical estimates by means of the 1st derivative of all downcore changes in the ^{14}C age – calendar age relationship; Sarnthein et al., 2015) and a variance of less than ±100 to ±300 ^{14}C yr, and up to 500 ^{14}C yr prior to 25 cal. ka. Here ^{14}C ages form a plateau-shaped scatter band with up to 10% outliers, that extends over more than 300 cal. yr in the Suigetsu record and/or equivalent sections of marine sediment depth (following rules defined by Sarnthein et al., 2007).

On visual inspection a plateau boundary is assigned to the break point between the low to zero or reversed slope of a ^{14}C plateau and the normally high regression slope of the ^{14}C concentration jump that separates two consecutive plateaus (Figs. 1 and S1). More precisely, a boundary marks the point, where the ^{14}C curve exceeds the scatter band of the plateau either crossing the upper or lower envelope line. Thus, the boundary is chosen about halfway between the last ^{14}C age within a plateau band and the next following age outside the scatter band (Figs. 1 and 2). On the U/Th-based model age scale (Bronk Ramsey et al., 2012) most ^{14}C dates of the Lake Suigetsu section are spaced at intervals of <10–60 yr from 10 to 15 cal. ka and 20–140 yr between 15 and 29 cal. ka (Fig. 1). Thus the uncertainty of a plateau boundary age assigned halfway between two ^{14}C ages nearby inside and outside a plateau's scatter band would, on average, amount to ±10–±70 cal. yr.

In principle, the calendar age uncertainties of marine ^{14}C plateau boundaries are treated likewise: After being tuned to those in the Suigetsu ^{14}C record, the uncertainties are deduced for the position of all plateaus of a suite within the uncertainty envelope of the U/Th model-based age calibration. Hence the estimates of total age uncertainty present the propagated error of the calibrated age of a Suigetsu plateau boundary plus that of the pertinent plateau in the marine record, where variable depth spacing of ^{14}C ages is converted into average time spans.

SUPPLEMENTARY FIGURE CAPTIONS

~~V~~ Fig. S1. Individual atmospheric ^{14}C ages and error bars of Lake Suigetsu plant macrofossils vs. U/Th-based model age of 15–21 (bottom) and 21–27 (top) cal. ka (blue dots; Bronk Ramsey et al., 2012). ^{14}C plateaus longer than 250 yr are outlined by a suite of labeled horizontal boxes that envelop scatter bands of largely constant ^{14}C ages. Red dots and black circles in Fig. 1a display ^{14}C ages of Hulu stalagmites. Similar to ^{14}C ages of Suigetsu also those of Hulu Cave reveal a suite of ^{14}C plateaus (red boxes) tentatively assigned in this figure, plateaus that are shorter than Suigetsu-based plateaus and occupy slightly different age ranges. The 1:1 line reflects gradient of one ^{14}C yr / cal. yr.

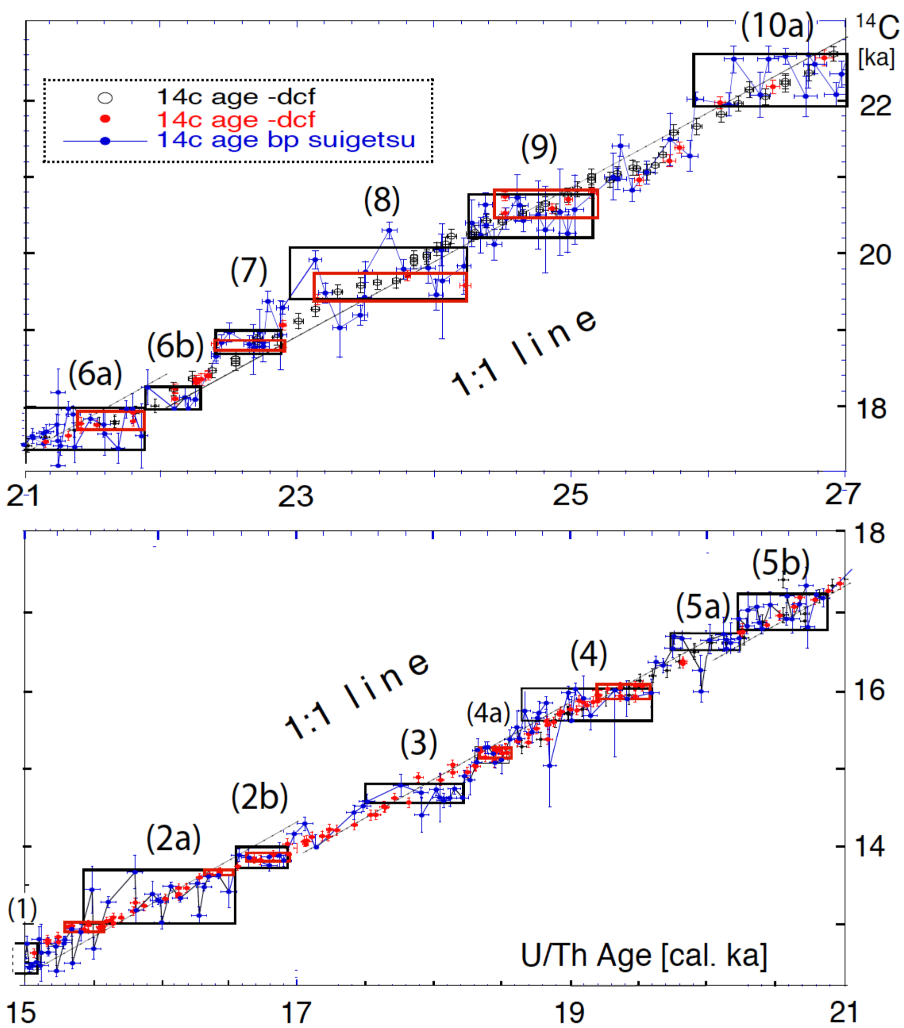


Fig. S2. Centennial-to-millennial-scale temporal and spatial variations in planktic (pla.) reservoir (res.) and (raw = uncorrected) apparent (app.) benthic ^{14}C ventilation (vent.) ages recorded at 18/20 key sites in the Atlantic (S2a, b, e), Pacific (S2c, d), and Indian (S2e). Site locations are given in Fig. 7. Stratigraphic units are marked on top of each diagram: Younger Dryas (YD), Bølling-Allerød (B/A) Heinrich Stadial 1 (HS-1), Last Glacial Maximum (LGM), and Heinrich Stadial 2 (HS-2).

Origin and various features characteristic of ^{14}C records: About 50% of all planktic and ('raw') benthic ^{14}C records were already published in Sarnthein et al. (2015). However, the cal. age of all records originally based on microscopy-based varve counts was now converted into U/Th-based model ages (Bronk-Ramsey et al., 2012). Planktic ^{14}C

reservoir ages of Core GIK23074 are now supplemented by benthic ventilation ages. Planktic ^{14}C reservoir ages of SHAK06-5K are detailed in Ausin et al. (2019, unpubl.). Benthic ventilation ages plotted for SHAK06-5K are matched from neighbor core MD99-2334K (Skinner et al., 2014) the stratigraphy and ^{14}C reservoir ages of which are closely correlated by means of narrow-spaced suites of ^{14}C ages. To show an example, 'raw' benthic ventilation ages in Core MD08-3180 are recalculated into 'actual' ventilation ages (Balmer and Sarnthein, 2018) that incorporate past changes in atmospheric ^{14}C concentration between the time of deep-water formation and the local growth of benthic foraminifers. South Atlantic ^{14}C records GeoB3910, GeoB1711-4, and KNR-159-5-36 (data slightly supplemented) are from Balmer et al. (2016), now however, with cal. ages converted into U/Th based model ages. The same applies to MD07-3076, where the continuous planktic and benthic ^{14}C records are from Skinner et al. (2010), corroborated by three blue bars reflecting the extent of planktic ^{14}C plateaus tuned to atmospheric plateaus no. 1, 2b, and 4. South Pacific ^{14}C records PS75-104, SO213-76, MD07-3088, and PS97-137-1 are from Küssner et al., 2018 and subm.). Planktic and benthic ^{14}C records of neighbor cores GIK17940 and SO50-37, PS75-104 and SO213-84, and ODP893A and MD02-2503 each are plotted on joint graphs, paired records that are obtained from small-scale sea regions with a common level of planktic ^{14}C reservoir age. Benthic ^{14}C ages of SO50-37 and SO213-84 are from Ronge et al. (2016), those of MD07-3088 from Siani et al. (2013).

Fig. S2a. NORTH ATLANTIC AND NORDIC SEA SITES

WEST and CENTER — *— EAST*

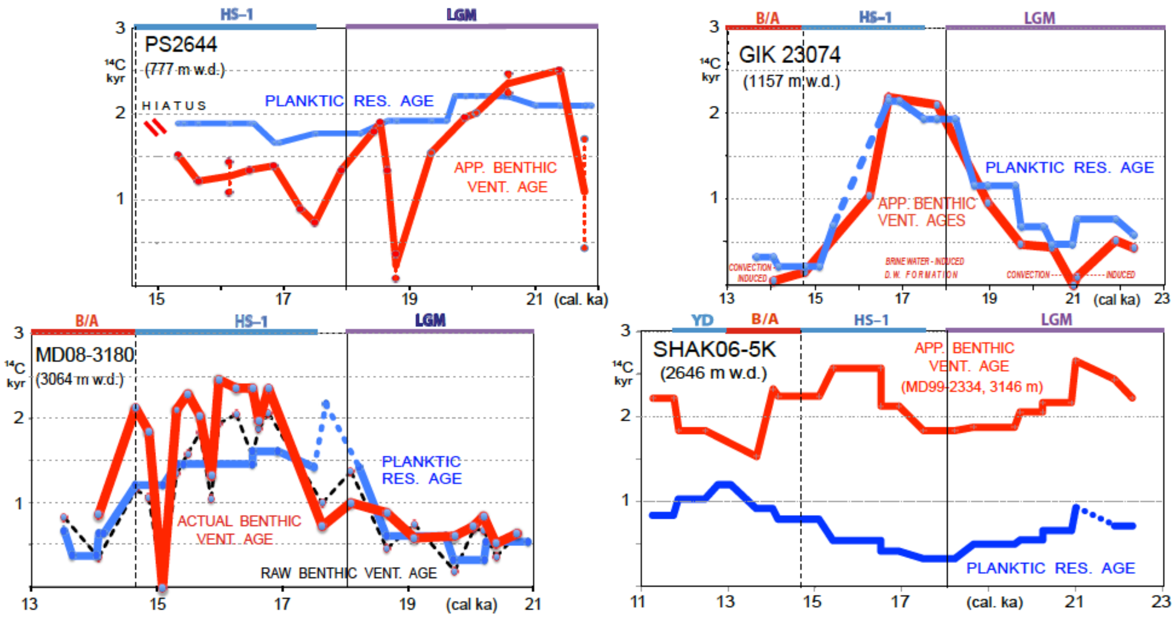


Fig. S2b. SOUTH ATLANTIC SITES

WEST — *— CENTER and EAST*

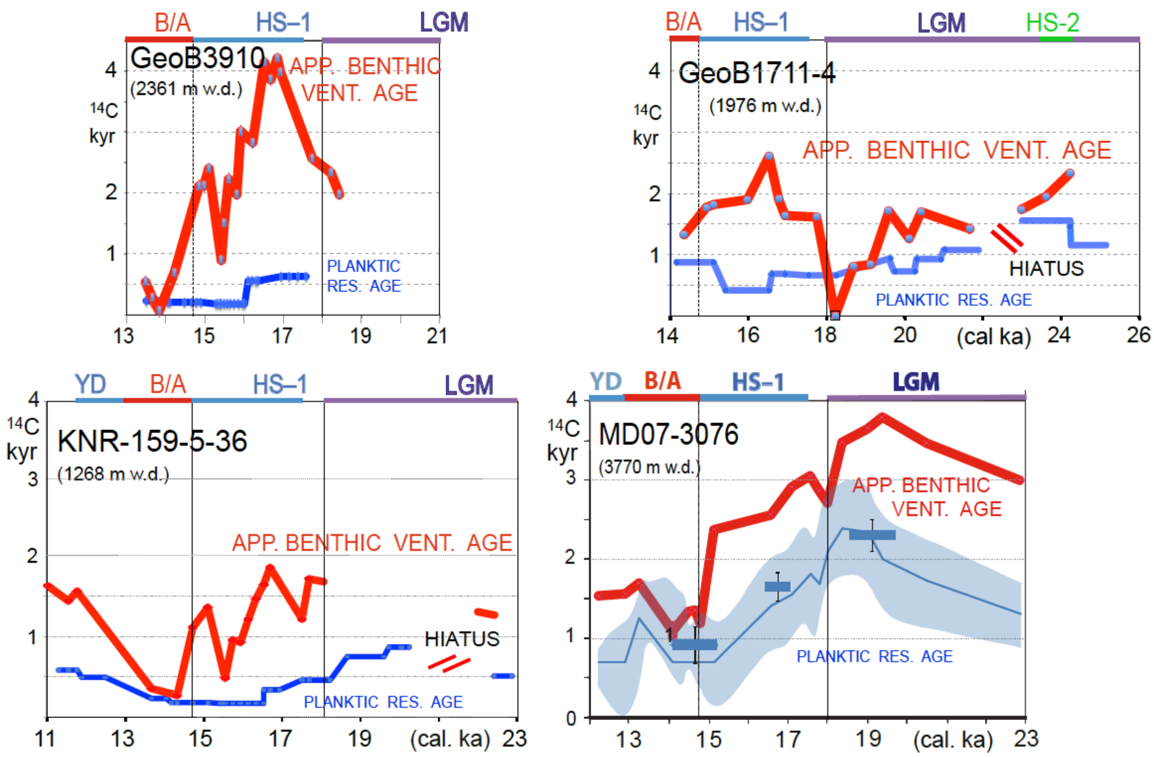


Fig. S2c. SOUTH PACIFIC SITES

WEST — — EAST

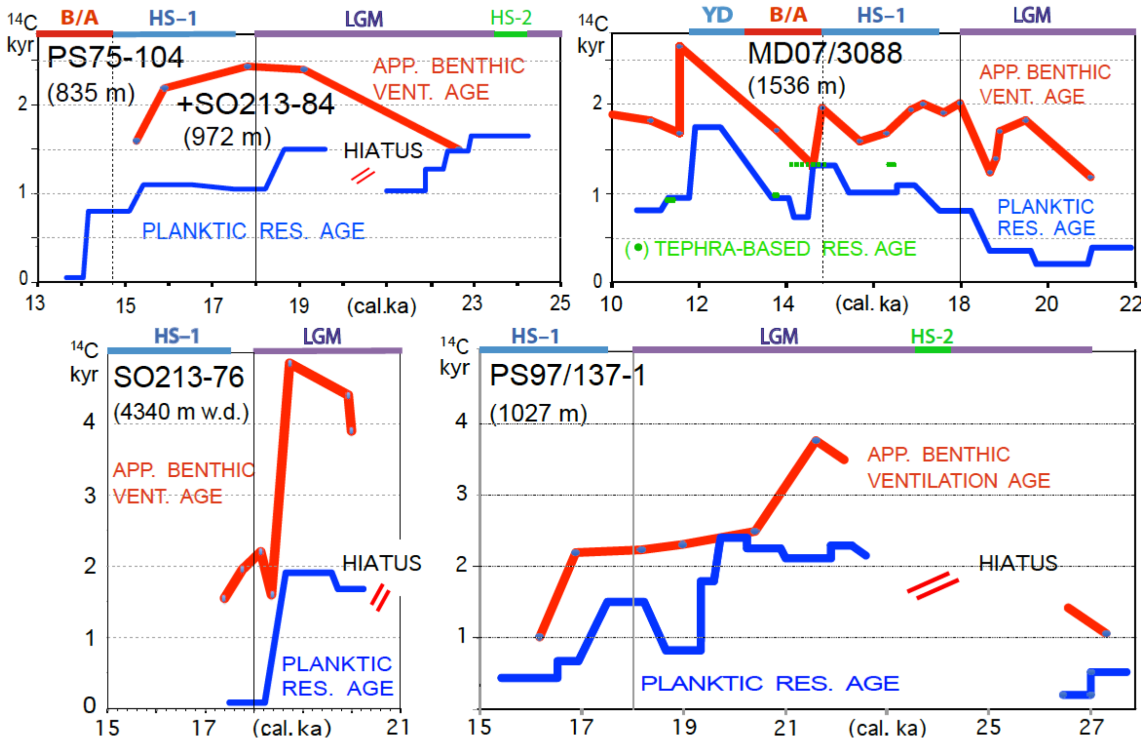


Fig. S2d. NORTH PACIFIC SITES

WEST and SOUTH CHINA SEA — — EAST

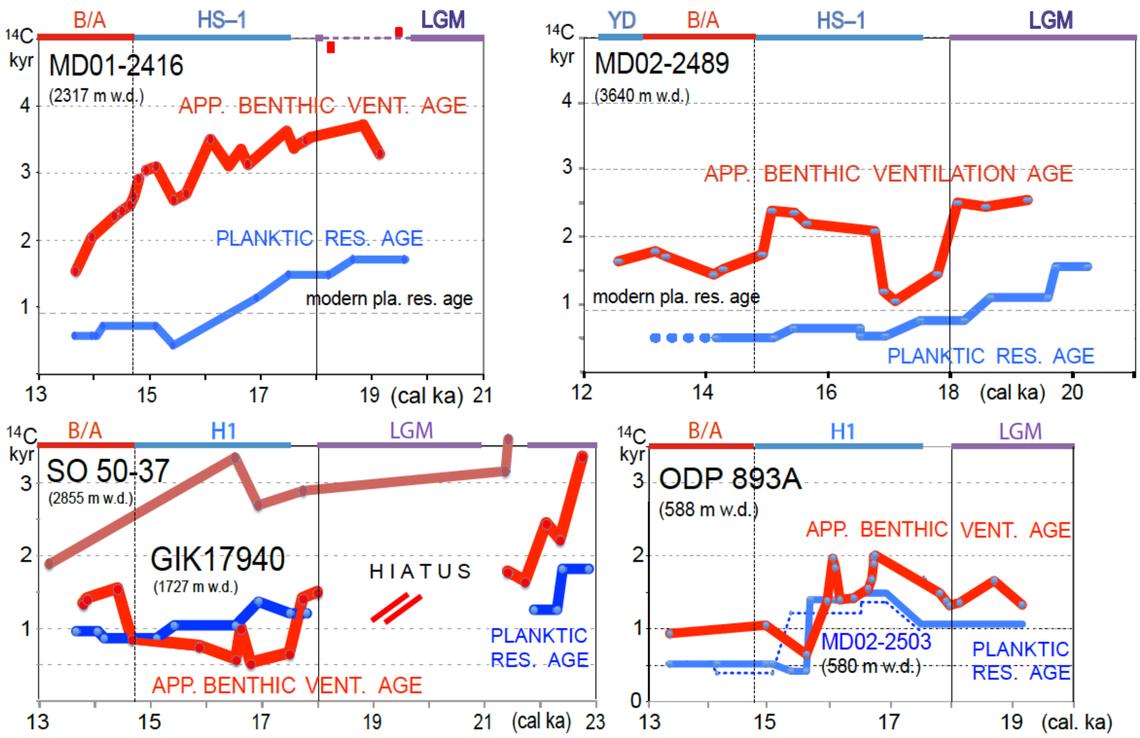
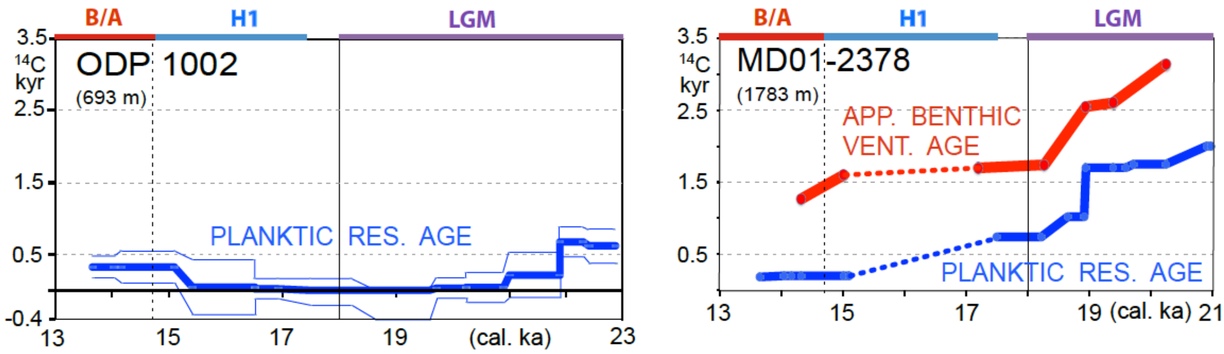


Fig. S2e. SITES in the EQUATORIAL OCEAN

CARIACO BASIN — — *SOUTHERN TIMOR SEA*



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