nature portfolio

Peer Review File

The Peruvian oxygen minimum zone was similar in extent but weaker during the Last Glacial Maximum than Late Holocene

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality

14th Sep 22

Dear Dr Glock,

Your manuscript titled "Foraminiferal pore densities reveal similar but weaker Peruvian oxygen minimum zone during Last Glacial Maximum" has now been seen by 3 reviewers, and I include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

Specifically, for publication in Communications Earth & Environment to be appropriate, we will need you to:

1) Place your findings firmly in the context of other relevant work on the evolution of the deglacial oxygen minimum zone on the Pacific margin

2) Ensure your approach is clearly justified and explained so that your results are fully reproducible (please note that we allow unlimited room for methods).

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter) and the completed checklist:
[link redacted]
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

Please do not hesitate to contact me if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Alienor Lavergne, PhD
Associate Editor
Communications Earth & Environment

EDITORIAL POLICIES AND FORMATTING

We ask that you ensure your manuscript complies with our editorial policies. Please ensure that the following formatting requirements are met, and any checklist relevant to your research is completed and uploaded as a Related Manuscript file type with the revised article.

Editorial Policy: Policy requirements (Download the link to your computer as a PDF.)

Furthermore, please align your manuscript with our format requirements, which are summarized on the following checklist:
Communications Earth & Environment formatting checklist

and also in our style and formatting guide Communications Earth & Environment formatting guide .

*** DATA: Communications Earth & Environment endorses the principles of the Enabling FAIR data project (http://www.copdess.org/enabling-fair-data-project/). We ask authors to make the data that support their conclusions available in permanent, publically accessible data repositories. (Please contact the editor if you are unable to make your data available).

All Communications Earth & Environment manuscripts must include a section titled "Data Availability" at the end of the Methods section or main text (if no Methods). More information on this policy, is available at http://www.nature.com/authors/policies/data/data-availability-statements-data-citations.pdf.

In particular, the Data availability statement should include:
- Unique identifiers (such as DOIs and hyperlinks for datasets in public repositories)
- Accession codes where appropriate
- If applicable, a statement regarding data available with restrictions

- If a dataset has a Digital Object Identifier (DOI) as its unique identifier, we strongly encourage including this in the Reference list and citing the dataset in the Data Availability Statement.

DATA SOURCES: All new data associated with the paper should be placed in a persistent repository where they can be freely and enduringly accessed. We recommend submitting the data to discipline-specific, community-recognized repositories, where possible and a list of recommended repositories is provided at http://www.nature.com/sdata/policies/repositories.

If a community resource is unavailable, data can be submitted to generalist repositories such as figshare or Dryad Digital Repository. Please provide a unique identifier for the data (for example a DOI or a permanent URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The manuscript by Glock et al., aims to reconstruct shallow-intermediate water (~500 m) oxygenation in the Peruvian OMZ during time slices from the LGM and Late Holocene (LH). They first present several new calibrations of the pore density oxygen proxy for the foraminifer limbata from the Peruvian margin. These are compared and then applied to reconstruct oxygenation in the region. By combining this new data with previously published neighboring records the authors are able to convincingly show a present but weakened OMZ along the Peruvian margin in the LGM as compared to the LH. The manuscript is well-written and well-constructed. I could see the newly presented calibration being used in similar studies and the findings contribute to an important and rapidly evolving discussion of deglacial OMZ evolution on the Pacific margin.

My only major comment is in regards to the difference in inferred shape of the OMZ at present as compared to the LH (just 1-0 kya!). This is seen most clearly in Figure 6 and commented upon on lines 294-296. The difference in oxygenation and slope of the lower oxycline between the recent sedimentary and modern observational records is striking. Could this be elaborated upon? Is this indicative of very recent increases in oxygenation of deep-intermediate waters? Or something else? The difference between LH and modern

oxygenation may also raise some skepticism around how reliable modern [O2]BW measurements may be for calibrating “recent” coretop material, which should be addressed.

Other comments are as below:
15: “a proxy”
27: no “the”
30: no “the”
37: Given the importance of deeper water masses to this story, could intermediate water hydrography be added here as well?
55-57: This requires a reference
60: to -> too
63-64: “had been assumed that”
66-68: “depend” doesn’t seem quite the right word given this is just the observation of individuals at higher O2. Could this be rephrased?
68: Is there any information available on the ecology on limbate for comparison?
69: remove comma
70: as well -> also AND remove comma
71: at -> in
75: remove comma
76: What is the rationale behind developing a local calibration? If the relationship between PD and O2 is highly spatially variable, would this relationship not also be expected to vary through time?
86: “samples contained”
87: “model for core”
86 & 89 & throughout: check for consistency in “planktic” and “planktonic”
224: Is it so destructive that shells could not be used even for geochemical analyses?
229: “elaboration” isn’t quite right. “test of”?
272: “concentration of preformed”
278: “change in”
307-308: Could this be elaborated upon? I am struggling to understand how this observation connects with seasonality. Is the suggestion that limbata are living preferentially in higher O2 seasons? If so, why would this impact only part of the record? Clarification would be helpful.
Figure 5: This figure would be more legible with some of the white space between intervals removed and data expanded horizontally. I’d recommend removing ~4-15 kyr from the x axis and replacing with a clearly visible axis break. Alternately, the two intervals could be shown in adjacent panels with a shared y axis.

Reviewer #2 (Remarks to the Author):

The study investigates the possible use of foraminifera pore density as proxy for bottom water oxygen concentration during LGM and late Holocene in the Peruvian OMZ region. Oxygen past reconstruction is crucial in the current context of global oceanic deoxygenation. The authors compare different methodologies to measure the pore density on the shell of foraminifera specimens using an optic microscope. Then, they calibrate modern bottom water oxygen concentrations with pore density of modern specimens from different locations along an oxygen concentration gradient. Using long sediment records on which age

models were determined, the authors reconstruct the past bottom water oxygen concentrations using pore density of foraminifera shell following the former calibration. Results are coherent with other studies investigating past oxygen concentrations in the bottom water in this region (but at other periods), arguing for a decrease in oxygenation between LGM and late Holocene. Authors then explore the reasons for this decrease, contrasting with other oceanic regions.

I found the manuscript clear, straightforward, and well written. I think that data acquisition and statistical treatment procedures are suited for the purpose of the study, and that the study is a significant advancement in the field of past oxygen concentrations reconstruction. This work will be of interest for the community interested in foraminifera and their use as proxy, but also to all researchers interested in past climate reconstruction. For these reasons, I think this work is worth publishing in Communications Earth & Environment.

I have few comments and suggestions about the study, listed in detail below and also in the pdf file attached. Briefly, I suggest moving the first part of the section line 142 ("Downcore [O2]BW reconstruction using the pore density epifaunal P. limbate") to the method section. I also suggest few ideas, but I let the author choose if it might be interesting or not to discuss it in their manuscript, especially about two things that could impact the proxy used:

- Shell thickness, which is greater in oldest chambers (if I am right?), hampering passive oxygen diffusion through pores. This questions the efficiency of oxygen uptake in the oldest chambers compared to the newest ones, and the benefit to include these chambers in the calculus of PD (for proxy purpose). Exclusion of the youngest chambers (done in method #4 if total area was higher than 700 000 µm2) that are usually the biggest ones and showing the highest porosity. Since they seem should play a major role in oxygen uptake, building a proxy ignoring them is questionable. On the other hand, I understand why the authors proceed this way: significant ontogenetic effect might be problematic in the calibration and further use of such proxy.
- The idea that foraminifera PD (and by extension porosity) tracks the lowest oxygen concentrations in the bottom water allowing individuals to survive instead of an "averaged" [O2]BW. This would argue in favour of the fact that bottom water oxygen concentrations at the Peruvian shelf have continued to decrease until today. However, this process might only be accurate if youngest chambers (the ones that theoretically represent the compromise between improving oxygen uptake by increasing porosity and assuring mechanic integrity of the shell by limiting porosity increase) are considered in the proxy calibration.

I would like to inform the editor that I am not comfortable with the age model determination since it is out of my field of expertise. For this reason, I cannot fully assess the quality of this part in the manuscript.

I recommend minor revisions for this manuscript since my suggestions and comments are not going against the interpretations of results and the conclusions of the study.

Because it is not double anonymised, I require my name to be attached to this review.

Julien Richirt

Comments and suggestions

Abstract

Line 16: "mbss" or "mbs" later in the manuscript on line 144, 250, 253, 254, 256, and Figure 1 caption line 550 & 646. Please if you mean something different precise it or homogenise the spelling.

Introduction

Lines 54-55: “species-specific” or “species specific”. Homogenise in the manuscript if needed. I think you mean that the responses of foraminifera to different environmental factors are species-specific. I am not sure you can say that environmental factors are species-specific. Reformulate please.
Lines 57-58: Please be more specific about what pore characteristic B. spissa adapt to nitrate concentrations.
Line 69: Please change “porosity” for “pore density” on line 69. If I understood correctly you test for pore density (PD, pore number per unit of surface) in your study, and not porosity (area covered occupied by pores in %) since you state line 181-183: “This is a good option for high resolution SEM images but our study is based on light micrographs that do not have a resolution allowing to accurately determine the pore area. Thus, we focused on the PD instead”. Please change accordingly through the manuscript, since depending on the species, pore density and porosity might be negatively correlated.
Methods
Lines 336-338: Is there a specific reason why you used this mesh size to sieve? How did you check that the specimens you used for the modern calibration (only the top layer of the small cores) were alive when you picked them and not dead or transported from elsewhere?
Lines 364-366: “Due to the low number of specimens in the depths 5.5 cm, 7 cm and 9 cm, we decided to pool the specimens to one datapoint in fig. 5.” What calibrated age did you choose for these specimens, an average of the 3 samples? Please specify in the text.
Results
I consider that lines 143-166 are rather method description than results. Consequently, this part should be moved to the Methods section.
Lines 138-141: You state “In addition, the variability of the PD after method #1 was very high at station M77/1-459/MUC-25, which had the highest [O2]BW and the uncertainties of the regressions are also relatively high (Fig. 4C).” For station M77/1-459/MUC-25, you measured 2 specimens only, which is too few to describe variability or uncertainty for a regression in my opinion. I suggest removing this statement since the highest correlation (coupled with its significance) for method #4 using all specimens from all stations is convincing enough that this is the method to use in your case.

Lines 145-147: You state “Since method #4 showed the best correlation between PD and [O2]BW, we mainly used this method for the downcore reconstructions.” Later in the manuscript you state on lines 379-380 “All four methods have been applied to the core top samples and only method #4 was used for the downcore PD analyses in M77/1 416-GC4 and M77/1 406-MUC6.” Please precise if you mainly or only used the method #4 for downcore reconstructions.

Line 168: If this is equivalent to a Welch’s T test, then change “heteroscedastic Student’s T-test” by “Welch’s T-test”.

Discussion
Line 236: Change “porosity” by “pore density” please.

Lines 268-270: I have difficulties to understand this sentence. Is it the lower Fe burial that is due to a decrease in sediment deposition and increased erosion? Please rephrase more clearly.

Lines 266-267: unclear: is oxygen concentrations higher in intermediate water masses?
Lines 271-272: “pre-formed” or “preformed”, homogenise spelling.
Lines 307-308: “This might be related to seasonality in the life cycle of P. limbata.” In what way? Could it be also related to a possible different respiration pathway in this species? Below a certain oxygen concentration, the species might shift to alternative electron acceptor (nitrate for example?). Additionally, could oxygen uptake though pseudopods occur when they are extruded? Could this represent an active and easy way for foraminifera to finely adjust their ability to uptake oxygen.

Lines 308-310: “Another explanation for this phenomenon could be an observation that bottom waters at the Peruvian shelf became more oxygenated over the last ~100 yr.”
Alternatively:
- If we assume that PD is related to oxygen content with a negative correlation.
- Increasing PD is assumed to be an adaptation to better cope with low oxygen concentration. This means that foraminifera adapt their PD regarding the lowest oxygen concentrations they have to cope with (why would they increase PD further if not needed?).
- This implies that PD might be correlated with the lowest oxygen concentrations specimens are exposed to, instead of an average oxygen concentration value (kind of threshold effect, below this value of oxygen concentration the foraminifera cannot cope, above -during pulses- it can survive).
- The modern lowest oxygen concentrations recorded are about 1 µmol/kg in the region. This value is below the oxygen concentration values indicated by the proxy using foraminiferal PD. This would argue for a continuous decrease of the lowest oxygen concentrations occurring in the region during LH.
References
Line 445: correct ref. 28
Figures & Tables
Line 574, 583 and 623: I was confused by the use of SEM acronym for 2 different things (Standard Error of the Mean and Scanning Electron Microscope lines 181, 345 and 347). I suggest changing one of the 2 acronyms to avoid confusion for the reader.

Figure 1: I suspect the black square in the top right panel to be a little shifted north compared to the biggest map panel

Figure 5: in the caption you state “Since only two specimens were found in one sample each individual reconstructed [O2]BW instead of mean values were plotted as grey crosses.” It is unclear, which sample?
On the figure itself: I suggest making a discontinuous x axis by removing the period between 4 and 14 kyr BP. It would make the data easier to read and avoid a figure where 70% is blank. Alternatively, I understand that the authors made the choice to keep continuous x axis to keep time scale coherent for the reader.

Reviewer #3 (Remarks to the Author):

Glock et al evaluate and expand upon the foraminiferal pore-density oxygenation proxy and apply it back in time to a core collected from the Peruvian margin. It can often be difficult to unravel the effects of productivity and oxygenation on our traditional oxygenation proxies, yet records of oxygenation can give us key insight on past changes in deep-ocean respired carbon storage and shallow-ocean OMZ expansion. However, we tend to have few studies that actually take the time to evaluate and improve upon our methods in a clear and practical way as was done in this study. This study is a great introduction to the pore-density proxy that will be of immense value to others who would like to apply this proxy to their own research areas.

I have no major issues with the methods or results in this study, but I think it could use some revision for clarity and some expanded discussion. As I was reading, it felt like I sometimes had to go back and forth to different sections in the paper because parts of one idea were split across sections resulting in things being repeated in some spots and left out of others. It would help to bring these ideas together in one place. Specifically, I noticed this when it came to an explanation of the different pore density methods. The methods are described in the results, the discussion, and again in the methods section. It would clarify things if you bring these different pieces together in one section focused on describing in detail the four different methods. I think this portion of the paper is extremely valuable, and if we want to get more people to try out these methods and apply this proxy then you want to make it as easy to follow as possible.

Here's my suggestion for reorganizing the PD methods (take it or leave it). Before the section you have comparing the four different methods add a section describing the four pore density methods in detail (include figure 3), the pros and cons of each method, how to do the method, the practicalities etc. Move the methodological recommendations you have later in the paper up to this section. You could also add an additional summary chart of the pros and cons of each method, that would be a great way to reinforce the info quickly and clearly. I also think your current description of methodological recommendations can probably be edited down a bit, it starts to get a bit verbose in some spots. This might be a great section to take advantage of things like bullet points or numbering or charts to show the information more clearly.

I really enjoyed reading your core stratigraphy section. You were working with very challenging core material but did a great job breaking down each of the challenges you faced and explaining how you tackled those challenges and the caveats that come with dealing with imperfect core material. One small thought about your stratigraphic methods- Could you use the reservoir ages from the peru-chile transect of Martínez-Fontaine et al. (2019) rather than Bova et al? Or are they perhaps less suitable? Either way this is nothing that would affect your results, I was just curious why you chose the reservoir ages that you chose. I found this section to be very well researched and explained.

The downcore O2 reconstruction section seems to be a mix of methods and results, it might be worth splitting these up a bit.

The section on deoxygenation reads a bit like a results section with some added literature review, but I would have liked to see more discussion in this section. The other sections have

proven your expertise, so when I got to this section I was eager to hear more about why these results are interesting and important. Expand upon the big-picture implications of a well oxygenated glacial eastern tropical Pacific.

Methods: How many forams do you use for each sample? What is a good representative number?

Table 1: It was a bit hard to tell which names were italicized. Maybe draw a line between the coretops and long cores?

Tables 2-4 could maybe be shifted to supplemental information.

Figure 1: Add the location of the bova core to the inset map

Figure 2: It might be worth expanding the x-axis on the top figure to match the bottom figure. The error initially looks a bit alarming compared to the lower figure, but it's just a function of the axes.

Figure 4: Add the species to the legend in A. Add labels to the photographs in B to indicate the high and low PD specimens. Shouldn't oxygen go on the x-axis because it's the independent variable? Also, why is the error on the >12 umol/kg method 1 PD so high?

The study investigates the possible use of foraminifera pore density as proxy for bottom water oxygen concentration during LGM and late Holocene in the Peruvian OMZ region. Oxygen past reconstruction is crucial in the current context of global oceanic deoxygenation.

The authors compare different methodologies to measure the pore density on the shell of foraminifera specimens using an optic microscope. Then, they calibrate modern bottom water oxygen concentrations with pore density of modern specimens from different locations along an oxygen concentration gradient. Using long sediment records on which age models were determined, the authors reconstruct the past bottom water oxygen concentrations using pore density of foraminifera shell following the former calibration. Results are coherent with other studies investigating past oxygen concentrations in the bottom water in this region (but at other periods), arguing for a decrease in oxygenation between LGM and late Holocene. Authors then explore the reasons for this decrease, contrasting with other oceanic regions.

I found the manuscript clear, straightforward, and well written. I think that data acquisition and statistical treatment procedures are suited for the purpose of the study, and that the study is a significant advancement in the field of past oxygen concentrations reconstruction. This work will be of interest for the community interested in foraminifera and their use as proxy, but also to all researchers interested in past climate reconstruction. For these reasons, I think this work is worth publishing in Communications Earth & Environment.

I have few comments and suggestions about the study, listed in detail below and also in the pdf file attached. Briefly, I suggest moving the first part of the section line 142 ("Downcore $[O2]_{BW}$ reconstruction using the pore density epifaunal *P. limbate"*) to the method section. I also suggest few ideas, but I let the author choose if it might be interesting or not to discuss it in their manuscript, especially about two things that could impact the proxy used:

- Shell thickness, which is greater in oldest chambers (if I am right?), hampering passive oxygen diffusion through pores. This questions the efficiency of oxygen uptake in the oldest chambers compared to the newest ones, and the benefit to include these chambers in the calculus of PD (for proxy purpose). Exclusion of the youngest chambers (done in method #4 if total area was higher than 700 000 μm^2) that are usually the biggest ones and showing the highest porosity. Since they seem should play a major role in oxygen uptake, building a proxy ignoring them is questionable. On the other hand, I understand why the authors proceed this way: significant ontogenetic effect might be problematic in the calibration and further use of such proxy.
- The idea that foraminifera PD (and by extension porosity) tracks the lowest oxygen concentrations in the bottom water allowing individuals to survive instead of an "averaged" $[O2]_{BW}$. This would argue in favour of the fact that bottom water oxygen concentrations at the Peruvian shelf have continued to decrease until today. However, this process might only be accurate if youngest chambers (the ones that theoretically represent the compromise between improving oxygen uptake by increasing porosity and assuring mechanic integrity of the shell by limiting porosity increase) are considered in the proxy calibration.

I would like to inform the editor that I am not comfortable with the age model determination since it is out of my field of expertise. For this reason, I cannot fully assess the quality of this part in the manuscript.

I recommend minor revisions for this manuscript since my suggestions and comments are not going against the interpretations of results and the conclusions of the study.

Because it is not double anonymised, I require my name to be attached to this review.

Julien Richirt

Comments and suggestions

Abstract

Line 16: “mbss” or “mbs” later in the manuscript on line 144, 250, 253, 254, 256, and Figure 1 caption line 550 & 646. Please if you mean something different precise it or homogenise the spelling.

Introduction

Lines 54-55: “species-specific” or “species specific”. Homogenise in the manuscript if needed. I think you mean that the responses of foraminifera to different environmental factors are species-specific. I am not sure you can say that environmental factors are species-specific. Reformulate please.

Lines 57-58: Please be more specific about what pore characteristic *B. spissa* adapt to nitrate concentrations.

Line 69: Please change “porosity” for “pore density” on line 69. If I understood correctly you test for pore density (PD, pore number per unit of surface) in your study, and not porosity (area covered occupied by pores in %) since you state line 181-183: “*This is a good option for high resolution SEM images but our study is based on light micrographs that do not have a resolution allowing to accurately determine the pore area. Thus, we focused on the PD instead*”. Please change accordingly through the manuscript, since depending on the species, pore density and porosity might be negatively correlated.

Methods

Lines 336-338: Is there a specific reason why you used this mesh size to sieve? How did you check that the specimens you used for the modern calibration (only the top layer of the small cores) were alive when you picked them and not dead or transported from elsewhere?

Lines 364-366: *“Due to the low number of specimens in the depths 5.5 cm, 7 cm and 9 cm, we decided to pool the specimens to one datapoint in fig. 5.”* What calibrated age did you choose for these specimens, an average of the 3 samples? Please specify in the text.

Results

I consider that lines 143-166 are rather method description than results. Consequently, this part should be moved to the Methods section.

Lines 138-141: You state “*In addition, the variability of the PD after method #1 was very high at station M77/1-459/MUC-25, which had the highest [O2]BW and the uncertainties of the regressions are also relatively high (Fig. 4C).*” For station M77/1-459/MUC-25, you measured 2 specimens only, which is too few to describe variability or uncertainty for a regression in my opinion. I suggest removing this statement since the highest correlation (coupled with its significance) for method #4 using all specimens from all stations is convincing enough that this is the method to use in your case.

Lines 145-147: You state “*Since method #4 showed the best correlation between PD and [O2]BW, we mainly used this method for the downcore reconstructions.”* Later in the manuscript you state on lines 379-380 “*All four methods have been applied to the core top samples and only method #4 was used for the downcore PD analyses in M77/1 416-GC4 and M77/1 406-MUC6.”* Please precise if you mainly or only used the method #4 for downcore reconstructions.

Line 168: If this is equivalent to a Welch’s T test, then change “*heteroscedastic Student’s T-test*” by “Welch’s T-test”.

Discussion

Line 236: Change “porosity” by “pore density” please.

Lines 268-270: I have difficulties to understand this sentence. Is it the lower Fe burial that is due to a decrease in sediment deposition and increased erosion? Please rephrase more clearly.

Lines 266-267: unclear: is oxygen concentrations higher in intermediate water masses?

Lines 271-272: “*pre-formed*” or “*preformed*”, homogenise spelling.

Lines 307-308: “*This might be related to seasonality in the life cycle of P. limbata.”* In what way? Could it be also related to a possible different respiration pathway in this species? Below a certain oxygen concentration, the species might shift to alternative electron acceptor (nitrate for example?). Additionally, could oxygen uptake though pseudopods occur when they are extruded? Could this represent an active and easy way for foraminifera to finely adjust their ability to uptake oxygen.

Lines 308-310: *“Another explanation for this phenomenon could be an observation that bottom waters at the Peruvian shelf became more oxygenated over the last ~100 yr.”*
Alternatively:
- If we assume that PD is related to oxygen content with a negative correlation.
- Increasing PD is assumed to be an adaptation to better cope with low oxygen concentration.
This means that foraminifera adapt their PD regarding the lowest oxygen concentrations they have to cope with (why would they increase PD further if not needed?).
- This implies that PD might be correlated with the lowest oxygen concentrations specimens are exposed to, instead of an average oxygen concentration value (kind of threshold effect, below this value of oxygen concentration the foraminifera cannot cope, above -during pulses- it can survive).
- The modern lowest oxygen concentrations recorded are about 1 µmol/kg in the region. This value is below the oxygen concentration values indicated by the proxy using foraminiferal PD.
This would argue for a continuous decrease of the lowest oxygen concentrations occurring in the region during LH.

References

Line 445: correct ref. 28

Figures & Tables

Line 574, 583 and 623: I was confused by the use of SEM acronym for 2 different things (Standard Error of the Mean and Scanning Electron Microscope lines 181, 345 and 347). I suggest changing one of the 2 acronyms to avoid confusion for the reader.

Figure 1: I suspect the black square in the top right panel to be a little shifted north compared to the biggest map panel

Figure 5: in the caption you state “*Since only two specimens were found in one sample each individual reconstructed [O2]BW instead of mean values were plotted as grey crosses.*” It is unclear, which sample?
On the figure itself: I suggest making a discontinuous x axis by removing the period between 4 and 14 kyr BP. It would make the data easier to read and avoid a figure where 70% is blank. Alternatively, I understand that the authors made the choice to keep continuous x axis to keep time scale coherent for the reader.

Foraminiferal pore densities reveal similar but weaker Peruvian oxygen minimum zone during Last Glacial Maximum

Nicolaas Glock[1,*], Zeynep Erdem[2], Joachim Schönfeld[3]

[1]: Institute for Geology, University of Hamburg, Bundesstraße 55, 20146 Hamburg, Germany
[2]: NIOZ Royal Netherlands Institute for Sea Research and Utrecht University, Landsdiep 4, 1797 SZ 't Horntje (Texel), The Netherlands
[3]: GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstrasse 1-3, 24148 Kiel, Germany
*: Correspondence to N. Glock (nicolaas.glock@uni-hamburg.de)

Abstract

Ongoing ocean deoxygenation is a severe problem, mainly caused by decreased oxygen (O_2) solubility due to climate warming and eutrophication in coastal environments. Quantitative reconstructions to understand past O_2 variability are thus highly desirable. In this study, we calibrated the pore density (PD) of the epibenthic foraminifer *Planulina limbata* from the Peruvian OMZ as proxy for bottom water O_2 concentrations ($[O_2]_{BW}$). This calibration was used to reconstruct $[O_2]_{BW}$ at 17.5°S ~500 mbss during the Last Glacial Maximum (LGM) and the Late Holocene (LH). We found a deoxygenation of ~40% from ~11.1 (LGM) to 6.7 µmol/kg (LH). A comparison with other $[O_2]$ reconstructions at the Peruvian OMZ reveals a shallow OMZ during the LGM that was similar but weaker than during the LH. Increased glacial $[O_2]$ are likely related to lower temperatures (higher O_2 solubility), decreased nutrient and increased oxygen supply by source waters, and a decrease in coastal upwelling.

Introduction

Ongoing ocean deoxygenation and the expansion of tropical oxygen minimum zones (OMZs) due to a combination of climate warming and anthropogenic fertilization became a challenging task for contemporary earth science[1,2]. The Peruvian OMZ in the Eastern Tropical South Pacific is one of the most distinctive regions of oxygen (O_2) depletion in the world's oceans and biogeochemical cycling within this region influences the global biogeochemistry. In particular, OMZs are major regions of reactive nitrogen loss by denitrification or anammox[3] and have a strong impact on global carbon cycling, since photosynthetic organisms bind atmospheric CO_2 near the water surface and the fixed carbon is transported into the deep via the downward flux of organic matter[4]. Vice versa dissolved CO_2 from deeper water masses is released to the atmosphere via upwelling[4]. The cold, upwelled deeper water masses warm up when they are transported to the water surface, which reduces the solubility of CO_2. Bioproductivity in these regions therefore has a substantial influence on the CO_2 concentrations in the atmosphere. The hydrography at the Peruvian margin is dominated by the O_2 rich, equatorward Peru-Chile Current (flowing in depths between 0-100 m) and the O_2 deficient, nutrient-rich, poleward Peru-Chile undercurrent (flowing between ~100-350 m)[5–10]. Coastal upwelling off Peru is perennial and wind-driven[8,11].

A quantitative assessment of pre-anthropogenic Peruvian OMZ extension and OMZ fluctuations between cold (glacial) and warm (interglacial) periods is still missing. There are only a few approaches of quantitative deglacial O_2 paleo reconstructions at the Peruvian OMZ so far, which are based on the variation of benthic foraminifera assemblages and redox sensitive elements in the sediments[12,13]. These studies indicated a decrease in bottom water O_2 concentrations of ~30 µmol/kg in intermediate depths (~1000 - 1250 m) of the northern OMZ

boundary[12] and a loss of 5-10 µmol/kg O_2 at 240 m in the OMZ centre at 11°S[13] between the Last Glacial Maximum (LGM) and the Late Holocene (LH). This is equal to a loss of about 50% O_2 in intermediate water depths. The results are supported by other semi-quantitative redox proxies, such as the ratio of redox sensitive elements in the sediments (i.e. Mo/Re) and the variability of stable nitrogen (N) isotopes in sedimentary organic matter ($\delta^{15}N_{org}$), both indicating O_2 depletion over the last deglaciation[14].

The porosity of epibenthic *Cibicides spp.* is an emerging foraminifera based quantitative O_2 proxy that has recently been calibrated[15]. Some deep dwelling planktic foraminifera also adapt their porosity to O_2 variability[16]. Pore size and shape are conservative morphological features in evolution and species-specific[17–19]. In addition, the factors that influence the porosity of benthic foraminifera appear to be also species specific. While epifaunal *Cibicides spp.* likely require O_2 for aerobic respiration they increase their porosity under O_2 depletion to optimize the uptake of O_2. Some denitrifying foraminifera such as *Bolivina spissa* adapt their pore characteristics to the availability of nitrate (NO_3^-) instead of O_2 and can be used as quantitative proxy for bottom water NO_3^- concentration ($[NO_3^-]_{BW}$)[20,21]. Several species of benthic foraminifera are able to denitrify when O_2 is to depleted for respiration[22–26]. *B. spissa* belongs to a group of denitrifying species that prefer NO_3^- over O_2 as an electron acceptor[27]. It is possible that some *Cibicides spp.* can switch to denitrification under O_2 depletion, since they cluster next to the known denitrifying species within the phylogenetic tree[28]. It has been assumed for a while that *Cibicidoides wuellerstoerfi* cannot survive longer O_2 depletion[29]. However, Rathburn et al.[15] observed living *Cibicidoides* spp. in environments of < 2 µmol/kg [O_2]. In addition, fossil specimens have been found in paleorecords during periods of severe O_2 depletion[30]. Though, *Cibicidoides* spp. usually depend on O_2, since living specimens can be found in [O_2] of up to 275 µmol/kg[15], even if some might be able to denitrify during periods of O_2 depletion.

In this study we test, if the porosity of the epibenthic foraminifer *Planulina limbata* from the Peruvian OMZ might as well be used as a quantitative O_2 proxy. We show, that the pore density (PD = number of pores/area) of *P. limbata* from core tops of five short sediment cores at the Peruvian OMZ is significantly correlated to $[O_2]_{BW}$. In addition, we test if the correlation between pore density and $[O_2]_{BW}$ is better on the spiral or the umbilical side of the foraminiferal test. Furthermore, we compare the results of our calibration with the results for *Cibicides spp.* from Rathburn et al.[15]. This should evaluate, if this correlation can be used for other epifaunal species as well and a stacked global calibration is possible. Finally, we use our new local calibration to quantify the $[O_2]_{BW}$ change between the LGM and the LH using sediment cores from the southern boundary of the Peruvian OMZ (17.5°S) and compile our record with other quantitative records from this region to assess the change in OMZ extension and strength between the LGM and the LH.

Results

Core stratigraphy

The age models of cores M77/1 416-GC4 and M77/1 406-MUC6 (locations see fig. 1 and tab. 1) are mainly based on radiocarbon dating. In addition, the $\delta^{18}O$ record has been used to exclude some samples from M77/1 406-MUC6 that were obviously located below a hiatus. None of the samples did contain a sufficient number of planktonic foraminifera for radiocarbon dating. Thus, the age model core M77/1 416-GC4 is completely based on radiocarbon ages of epibenthic *P. limbata* (Tab.2). There is an offset in radiocarbon ages between benthic and planktic foraminifera, based on the ventilation age of the near-bottom water and the marine

reservoir age (MRA) of the surface water, in which planktic foraminifera are dwelling (see review by Skinner and Bard[31]). To minimize this age uncertainty, we used the benthic-planktic radiocarbon age offset of the closest sediment core in literature that provided this data for our time slice of interest, which is CDH 26 (03°59.160S, 81°18.520W, 1023 m) from Bova et al.[32]. Since the location of CDH 26 is ~500 m deeper than M77/1 416-GC4, we assume that the ventilation age was likely a bit higher at CDH 26 resulting in a slight overestimation of our benthic-planktic offset. After the correction for the benthic-planktic radiocarbon age offset we did an additional MRA correction, using the MRA values for 18.75°S 75°W for the different time slices from the model output by Butzin et al.[33,34] (Suppl. Fig. 1). The radiocarbon ages of core M77/1 406-MUC6 that were measured on sedimentary organic matter were only MRA corrected using the model output by Butzin et al.[33,34] (Suppl. Fig. 1). The corrected radiocarbon dates were calibrated using Intcal20[35]. Age-depth models (Fig. 2) and sedimentation rates (Suppl. Fig. 2) for both cores were calculated, using the Bchron software package[36]. One outlier in core M77/1 416-GC4 that showed an age reversal at 290 cm depth was excluded for construction of the age depth model. The calibrated ages, as well as all the correction steps are summarized in table 2.

Both cores showed a distinct hiatus. The longer core M77/1 416-GC4 only covered the LGM from 17.5 to 24.1 cal. kyr BP. The Deglaciation and Holocene are missing. Benthic $\delta^{18}O$ were relatively uniform along M77/1 416-GC4 and showed an offset of around ~1‰ compared to the top centimeters of M77/1 406-MUC6. One ‰ is a common offset between LGM and LH (see Suppl. Fig. 3). In core M77/1 406-MUC6 benthic $\delta^{18}O$ shows an abrupt step to glacial values below 10 cm sediment depth and, in addition, there is a jump in the radiocarbon age in this part of the core (Tab. 2). Since these depths were obviously located below a hiatus, we ignored the PD data from this part of the core, since these foraminifera were not from the LH. We also excluded the elevated radiocarbon age of sedimentary organic matter at ~14 cm depth for the construction of our age-depth model. So, only the first 10 cm of M77/1 406-MUC6 were used for our paleo reconstructions, since they were from the LH. The sedimentation rates were much lower during the LH in comparison to the LGM (Suppl. Fig. 2). Both the hiatus and the low sedimentation rates during the LH are a typical phenomenon for this region in similar water depths. A widespread hiatus evolved in this region over the last deglaciation, likely erosion through high energetic non-linear internal waves[37]. Under modern conditions low sedimentation rates are common in water depths around 500 m at the Peruvian Margin because the internal waves hit the seafloor in these depths within a critical angle, which facilitates erosion[38].

Comparison of four different methods to determine foraminiferal pore density

Four different methods have been compared to determine the PD of *P. limbata* in the core top samples (locations see fig. 1 and tab. 1; results see tab.3 for averages and suppl. tab. 1 for all individual PDs). A visual discription of the methods is shown in fig. 3. The core top PDs of *P. limbata* that have been determined with method #1 were compared with the PDs of *Cibicides spp.* by Rathburn et al.[15] (Fig. 4A). Our new data complemented the dataset by Rathburn et al.[15] since it mainly added datapoints within the lower $[O_2]_{BW}$ range. Logarithmic regression through the compiled datasets showed a highly significant relationship between the pore density of epibenthic foraminifera with $[O_2]_{BW}$ ($R^2 = 0.80$; $F = 572$; $P < 0.0001$) over a wide range from saturated O_2 to nearly anoxic conditions ($[O_2] < 2$ µmol/kg). The pore density is higher at locations with lower $[O_2]$ (for visual example see Fig. 4B).

All of the four PD determination methods that we tested showed a significant relationship between the mean core top PD of *P. limbata* and $[O_2]_{BW}$ at the five locations that were used for our local calibration (Fig. 4 C-F). Method #1 showed the worst correlation (R^2 = 0.92; F = 33; P = 0.01) while the correlation was best using method #4 (R^2 = 0.97; F = 86; P = 0.0026). In addition, the variability of the PD after method #1 was very high at station M77/1-459/MUC-25, which had the highest $[O_2]_{BW}$ and the uncertainties of the regressions are also relatively high (Fig. 4C). We therefor decided to use method #4 for our downcore $[O_2]_{BW}$ reconstruction.

Downcore $[O_2]_{BW}$ reconstruction using the pore density epifaunal *P. limbata*

The $[O_2]_{BW}$ for two time slices (LGM ~20-17 kyr BP and LH ~1-0 kyr BP) were reconstructed at the southern boundary of the Peruvian OMZ (~17.5°S; ~500 mbs) using the PD of epifaunal *P. limbata* (Fig. 5, Tab. 4, Suppl. Tab. 2 for all individual PDs). Since method #4 showed the best correlation between PD and $[O_2]_{BW}$, we mainly used this method for the downcore reconstructions. $[O_2]_{BW}$ was therefore calculated according to Eq. 1:

Eq. 1: $$[O_2]_{BW} = -6027(\pm652)\cdot PD + 22.0(\pm1.7)$$

A progression of uncertainty was used to calculate the errors for the reconstructed $[O_2]_{BW}$. Both the uncertainty of the mean PD within each sample and the uncertainties of the calibration function were included. The propagation of uncertainty has been applied to Eq. 1, resulting in

Eq. 2: $$\sigma_{[O_2]_{BW}} = \sqrt{\left(\frac{\delta[O_2]_{BW}}{\delta a}.\sigma_a\right)^2 + \left(\frac{\delta[O_2]_{BW}}{\delta PD}.\sigma_{PD}\right)^2 + \left(\frac{\delta[O_2]_{BW}}{\delta b}.\sigma_b\right)^2}$$

, where σ_x is the uncertainty (1sd) of the corresponding parameter x (in this case $[O_2]_{BW}$, a, b and PD), a is the slope in eq.1 (in this case -6027) and b is the X-axis intercept (in this case 22.0). Application of Eq.2 on Eq.1 results in Eq.3 for the calculation of $\sigma_{[O_2]_{BW}}$.

Eq.3: $$\sigma_{[O_2]_{BW}} = \sqrt{(652\cdot PD)^2 + (-6027\cdot\sigma_{PD})^2 + (1.7)^2}$$

The standard error of the mean (SEM) was then calculated according to Eq.4:

Eq.4 $$SEM_{[O_2]_{BW}} = \frac{\sigma_{[O_2]_{BW}}}{\sqrt{n}}$$

, where n is the # of specimens analyzed in each sample.

The short core M77/1-406/MUC-6 was used for the LH slice, while the longer M77/1-416/GC-4 was used for the LGM slice. As mentioned above, only the data above 10 cm depth was used for core M77/1-406/MUC-6 due to the hiatus below 10 cm depth. The specimens at a depth of 3.5 cm were very small and out of the range for the size normalization in method #4. For 3.5 cm depth we used the calibration of method #3 to calculate $[O_2]_{BW}$. Due to the low number of specimens in the depths 5.5 cm, 7 cm and 9 cm, we decided to pool the specimens to one datapoint in fig. 5.

The PD was significantly higher for the LH in comparison to the LGM ($P < 0.001$; N = 114; two-sided heteroscedastic Student´s T-test), indicating distinct deoxygenation at the southern boundary of the Peruvian OMZ after the LGM. The mean $[O_2]_{BW}$ was 11.1 µmol/kg during the LGM and 6.7 µmol/kg during the LH indicating a loss of ~40% O_2 at this location between these two time slices. The $[O_2]_{BW}$ was relatively constant during the LGM and, with one exception, always higher than during the LH. Only at ~18.7 kyr BP, a sudden drop of $[O_2]_{BW}$ to the concentration range of the LH was recognized.

Discussion

Modern pore density calibration for epibenthic foraminifera and methodological recommendations

Our new data for the correlation of the PD of the epibenthic foraminiferal species *P. limbata* to $[O_2]_{BW}$ very well match the dataset for *Cibicides spp.* of Rathburn et al.[15] (Fig. 4A). Both datasets shown in fig. 4A used method #1 for the PD determination. Rathburn et al.[15] suggested to use the porosity instead of the PD for $[O_2]$ reconstruction, since they found a better correlation with the porosity instead of PD. This is a good option for high resolution SEM images but our study is based on light micrographs that do not have a resolution allowing to accurately determine the pore area. Thus, we focused on the PD instead. This has the advantage that paleoreconstructions can solely be based on optical images that only need a stereo microscope or a macro objective with a good magnification coupled to a digital (optical) camera, which is less expensive and time consuming than electron microscopy.

Our data for *P. limbata* from the Peruvian OMZ is in very good agreement with the data for *Cibicides wuellerstorfi*, *Cibicides lobatulus* and *Planulina sp.* from the global dataset by Rathburn et al.[15]. This indicates that all these species adapt their PD in a similar way to O_2 availability and it is likely that the correlation can be adapted to other epibenthic species from a wide range of habitats as well. It has to be emphasized that this is different for denitrifying foraminifera such as *B. spissa*, which adapts its PD to nitrate availability[20,21].

In literature there are different methods suggested for the determination of pore characteristics of benthic foraminifera. The most common method is to focus on a small window within a smooth surface in the middle of the ultimate or penultimate chamber[15,17,18,39–41] (Method #1 in this study). This has several advantages. This type of analysis is relatively fast, it minimizes artifacts related to the curvature of the specimens, normalizes regarding the ontogenetic stage of the specimen and ignores problems with overgrown pores. Nevertheless, the dataset for each individual foraminifer is limited, due to the small window size that is usually used for this method and there might be another factor that influences the pore characteristics in the ultimate and penultimate chambers: the stability of the test. Porosity and PD usually increases from the oldest to the youngest chamber related to the decreasing surface to volume ratio with increasing size of the specimen[20]. Our results also showed that the PD determined after method #1 was generally higher in comparison to the other methods (Fig. 4C-F). Other recent studies described that the stability of the foraminiferal test is decreasing with increasing porosity[41]. Richirt et al.[41] also found that different *Ammonia* phylotypes increase their porosity by building less but larger pores in their ultimate or penultimate chamber since the walls have more stability this way instead of simply building more pores. This might not be the case in older, less porous parts of the test where the porosity is not high enough to restrict the stability of the test walls. Finally, Method #1 ignores the pore free area between and on the outside corners of the test walls. These areas increase with increasing $[O_2]_{BW}$ (Fig. 4B).

Another method that has been used in other studies to determine the PD is to focus on a larger size normalized part of the older chambers of the foraminifer[20,21] (Method #4 in this study). This method has the advantages that the ontogenetic effects are also minimized by size normalization, the larger area provides a larger dataset for each individual and the stability of the test walls is less restricting, since the older parts of the test are usually less porous. The main disadvantages of this method is the higher effort that is necessary to acquire the data, the problem that pores in older chambers might be overgrown and artifacts by the curvature of the tests.

An additional method that recently came up is the automated image analysis to determine the porosity on shards of benthic foraminifera after crushing using optical microscopy[42]. From all the methods so far this appears to be the least time consuming and it is possible to generate huge datasets with relatively low effort. Though, this method is destructive and it is neither possible to archive the specimens nor to use the specimens for other analyses. Finally, a method has been suggested for automated morphometric analysis on benthic foraminifera using atomic force microscopy[43]. This approach most likely generates the most metadata, since it is even possible to measure the depth and 3D shape of the pores but it is also the most effortful of the methods discussed above.

Our methodological comparison also included the elaboration if it is better to use the umbilical (Method #2) or the spiral side (Method #3&4) of the foraminifer for the PD analysis (Fig. 4D-F). The correlation between the PD of *P. limbata* and $[O_2]_{BW}$ was better using the spiral side. The average umbilical PD is much higher than the average spiral PD. The closely related *Planulina ariminensis* was found on stalked substrates well above the sediment surface in that spiral and umbilical sides were exposed in the same way to the bottom-near water[44]. Therefore, the worse correlation on the umbilical side might be related to stability restrictions of the test wall due to the elevated porosity[41]. In addition, due to the higher PD, the determination on the umbilical side is usually more effortful. We thus suggest to always focus on the spiral side of the specimens for the application of PD or porosity as a paleo proxy. Since we found the best correlation between PD and $[O_2]_{BW}$ using method #4 for our local calibration, we also used this method for our paleo $[O_2]_{BW}$ reconstructions in this region. This does not mean that this is the best approach for other regions and foraminiferal species. The dataset using method #1 is now relatively large including the global data by Rathburn et al.[15] and our new data for *P. limbata* for the Peruvian OMZ. For $[O_2]$ reconstructions in regions of larger $[O_2]$ variability where no local calibration is available, we would therefor recommend to use method #1 and the correlation shown in fig. 4A. Though, our dataset includes only specimens from O_2 depleted locations. If $[O_2]$ should be reconstructed at locations with higher O_2 levels it might be good to focus on the calibration by Rathburn et al.[15] only and to use the porosity instead of the PD if high resolution electron micrographs are available.

Deoxygenation off Peru between the Last Glacial Maximum and the Late Holocene

Our $[O_2]_{BW}$ paleo reconstruction at 17.5°S off Peru (~500 mbs) indicates a deoxygenation from ~11.1 to 6.7 µmol/kg, which is equal to an O_2 loss of ~40% (~5 µmol/kg). This is in good agreement with other quantitative $[O_2]$ reconstructions in this region. Scholz et al.[13] found an $[O_2]$ drop of 5 – 10 µmol/kg at 11°S (240 mbs) and Erdem et al.[12] an $[O_2]_{BW}$ decrease of ~50% in intermediate water depths (~1000 - 1250 mbs) below the Peruvian OMZ between the LGM and the LH. The modern O_2 in the Peruvian OMZ is located in water depths between 300 and 400 mbs[14]. With ~500 m water depth sites M77/1 406-MUC6 and M77/1-416/GC-4 are located at the lower OMZ boundary. During the LGM, the sea level was ~120 m lower[45]. Thus, sites M77/1 406-MUC6 and M77/1-416/GC-4 would be shifted into water depths of today's core OMZ. This indicates that $[O_2]_{BW}$ during the LGM was higher even within the core OMZ than compared to the lower OMZ boundary during the LH.

The elevated $[O_2]_{BW}$ during the LGM is in good agreement with trends for the Pacific Ocean in the data compilations by Jaccard et al.[46] and Moffit et al.[47]. The simultaneous increase of $[O_2]$ during the LGM in all parts of the Peruvian OMZ is likely caused by interactions between decreased temperatures, higher $[O_2]$ to the subsurface water masses, the supply of preformed

nutrients to the subtropics and decreased coastal upwelling off Peru. The low sea surface temperatures during the LGM resulted in an increase of O_2 solubility and a generally higher $[O_2]$ in and increased formation of intermediate water masses, that supply O_2 to subsurface water masses off Peru[13,14,48]. In addition, there was likely an increase in Fe supply to higher latitudes during the LGM, related to the lower sea level, the lower Fe burial, due to the decrease in shelf sediments and increased erosion[49,50]. This Fe fertilization at high latitudes stimulated primary productivity at the Southern Ocean which resulted in an increased burial of pre-formed nutrients to the deep Southern Ocean[21,50]. This reduced the concentration preformed nutrients in Subantarctic Mode Water, which supplied nutrients to the subtropics, and affected limitation of primary productivity at lower latitudes[21,50]. Less O_2 was consumed by remineralization below the photic zone due to this decrease in primary productivity. This is supported by a quantitative NO_3^- record at the Northern part of the Peruvian OMZ[21]. Finally, the intertropical convergence zone (ITCZ) experienced a southward shift during the LGM at the Eastern Tropical Pacific, implying a general decrease in coastal upwelling in this region[14,51]. A study on the change nutrient utilization at the Peruvian OMZ during the last deglaciation based on stable Si isotope fractionation also infers a decrease in upwelling during the LGM at 15°S close to our study site[52]. Though, due to the distinct hiatus at our location there is only a slight overlap in this record and our data at the end of the LGM.

The common observation that $[O_2]$ at the Peruvian OMZ was higher during the LGM in shallow depths ~240 m[13], intermediate depths ~500 m (this study) and "deep"-intermediate depths ~1,000 – 1,250 m[12] indicates that the LGM conditions at the Eastern Tropical South Pacific were decoupled from the Eastern Equatorial Pacific[30,53]. Actually, the OMZ at the Eastern Tropical Pacific was expanded during the LGM, likely due to a decrease in ventilation and an increase in the respired deep carbon storage in intermediate to deep water depths during the LGM[30]. In addition, a recent study showed that there was no shallow OMZ at the Eastern Equatorial Pacific during the LGM but a massive suboxycline connecting the old O_2 depleted deep to intermediate water masses[53]. The shallow OMZ at the Eastern Equatorial Pacific only established during the Holocene[53]. The results from the regionally adjacent Peruvian margin indicate that there was a shallow OMZ at the Eastern Tropical South Pacific which was similar but less O_2 depleted than during the LH (Fig. 6). A comparison of the available quantitative $[O_2]$ paleo data with modern conditions indicates that the oxycline below the OMZ is steeper today than during the LGM or the LH.

During the LGM time slice there are no obvious trends in $[O_2]_{BW}$ at site M77/1-416/GC-4 indicating that the conditions were relatively stable during this time interval. The LH time slice at site M77/1 406-MUC6 starts ~1 kyr BP. Within this time interval there is a distinct trend in decreasing $[O_2]_{BW}$ over time. A record of sea surface temperatures ~17°S, close to our location documented a strong cooling trend during this time interval[54] and another record at 14°S showed an increase in sedimentary fish scales and the redox sensitive Mo/Re ratio[14]. Thus, the decreasing bottom water $[O_2]_{BW}$ over the past 1 kyr are likely related to an increase in upwelling and primary productivity in this region. Mean modern $[O_2]_{BW}$ close to our study site is highly variable (range from ~1-25 µmol/kg[55–58]). All the $[O_2]_{BW}$ in our palaeorecord are within this range of modern $[O_2]_{BW}$ variability (See fig. 5). Though, there seem to be $[O_2]$ pulses ~17.5°S at ~500 m that exceed our averaged values from the palaeorecord. This might be related to seasonality in the life cycle of *P. limbata*. Another explanation for this phenomenon could be an observation that bottom waters at the Peruvian shelf became more oxygenated over the last ~100 yr[59].

In conclusion, our quantitative $[O_2]_{BW}$ is in good agreement with other palaeorecords from the Peruvian OMZ and the combined datasets of these studies indicate a similar but weaker OMZ during the LGM. We found a deoxygenation of ~40% in intermediate water at 17.5°S off Peru between the LGM and the LH which is likely related to higher temperatures (lower O_2 solubility), increased nutrient and decreased oxygen supply by source waters and an increase in coastal upwelling. This is a contrasting situation to the adjacent Eastern Equatorial Pacific, which had an expansion of O_2 depleted waters to deeper depth but better ventilated shallow waters during the LGM[30,53].

Methods

Sampling procedure

Six short sediment cores from the Peruvian OMZ were extracted during R.V. *Meteor* cruise M77/1 in October 2008 using a video guided multicorer (Fig. 1; tab. 1). Within a couple of minutes after the multicorer came on deck, one tube was chosen from the array, and brought to a laboratory with a constant room temperature of 4°C. Supernatant water of the core was carefully removed. Then the core was gently pushed out of the multicorer tube and cut into 12 slices (10-mm-thick) for benthic foraminiferal analysis. The samples were transferred to Whirl-Pak™ plastic bags and transported at a temperature of 4°C. One additional long sediment core (3.88 m) was extracted using a gravity corer (M77/1 416-GC4; tab. 1). This core was immediately cut into one meter sections and each section was sliced into two halves (work and archive half). These were stored and transported back at a temperature of 4°C. The samples of these seven cores were used to collect the specimens for the PD analyses, radiocarbon dating and benthic foraminiferal $\delta^{18}O$ measurements.

Foraminiferal studies

The sediment samples were washed over a 63-µm mesh sieve and dried at 50°C. They were further subdivided into the grain-size fractions of 63–125, 125–250, 250–315, 315–355, 355–400, and > 400 µm. Specimens of the epifaunal species *P. limbata* were picked from the >400 µm fraction. Specimens of *Uvigerina striata and Uvigerina peregrina* were picked from the 355-400 µm fraction.

Images of *P. limbata* were taken using a MiniPixie MPX2051UC CCD camera (AOS Technologies™), mounted on a macro objective (1-6233 and 1-6010 by Navitar™). The programs AxioVision, Zen and ImageJ were used for the image analyses. In total 185 specimens were used for the image analyses.

Two additional specimens from M77/1-487/MUC-39 ($[O_2]_{BW}$ = 3.70 µmol/kg; see tab.1) and M77/1-565/MUC-60 ($[O_2]_{BW}$ = 8.17 µmol/kg; see tab.1) were imaged with scanning electron microscopy (SEM) for visual documentation of the influence of $[O_2]_{BW}$ on the porosity of *P. limbata* (see fig. 4B). These two specimens were mounted on aluminum stubs, sputter-coated with gold, and imaged using a CamScan-CS-44 SEM at the Christian-Albrecht-University in Kiel.

Additional specimens of *P. limbata* from 12 sediment depths were used for the radiocarbon dating on core M77/1 416-GC4. The radiocarbon dating for three sediment depths on core M77/1 406-MUC6 has been done on sedimentary organic matter. All radiocarbon analyses were performed at Beta Analytic, Inc., Florida, USA.

Three to six individuals of *U. peregrina* and *U. striata* were used for the stable isotope measurements ($\delta^{18}O$ and $\delta^{13}C$). The tests of the foraminiferal specimens were gently crushed between two glass slides and the fragments were mixed. The measurements were performed at GEOMAR, Kiel, using a Thermo Scientific MAT253 mass spectrometer equipped with an automated CARBO Kiel IV carbonate preparation device. The isotope values were reported in permil (‰) relative to the Vienna Pee Dee Belemnite (VPDB) scale and calibrated vs. NBS 19 (National Bureau of Standards) as well as to an in-house standard (Solnhofen limestone). Long-term analytical accuracy (1-sigma) for $\delta^{18}O$ and $\delta^{13}C$ was <0.06‰ and <0.03‰, respectively.

Foraminiferal pore densities

Four different methods have been applied and tested to determine the PD of *P. limbata* in order to compare the data with the global porosity calibration on *Cibicides spp.* from Rathburn et al.[15] and to achieve the best possible local calibration of PD vs. $[O_2]_{BW}$ (see also Fig. 3).

#1.: According to Rathburn et al.[15] and Petersen et al.[40] PDs from the core top samples were determined in the middle of the chamber within a rectangular window with a size of ~5000 μm^2. This method has the advantage that a very smooth and flat surface can be chosen and artifacts by the curvature of the sample were avoided. Rathburn et al.[15] chose the ultimate and penultimate chambers for this analyses. We always chose the best preserved chamber without cracks or overgrowths that was closest to the ultimate chamber. This was in most cases either the ultimate or penultimate chamber (Fig. 3A).

#2.: PDs were determined on the umbilical side of the specimen. Pores were counted manual on the whole specimen and the PD is the average of the whole specimen[60] (Fig. 3B).

#3.: Same as method 2 but the spiral side was used instead of the umbilical side[60] (Fig. 3C).

#4.: Same as method 3 but the samples were size normalized to minimize ontogenetic effects[60]. Specimens that had a smaller surface area than 400000 μm^2 were excluded from the dataset and for specimens larger than 700000 μm^2 the last number of chambers were excluded until the total analysed area was <700000 μm^2 (Fig. 3D).

All four methods have been applied to the core top samples and only method #4 was used for the downcore PD analyses in M77/1 416-GC4 and M77/1 406-MUC6.

References

1. Stramma, L., Johnson, G. C., Sprintall, J. & Mohrholz, V. Expanding Oxygen-Minimum Zones in the Tropical Oceans. *Science (80-.).* **320**, 655 LP – 658 (2008).
2. Schmidtko, S., Stramma, L. & Visbeck, M. Decline in global oceanic oxygen content during the past five decades. *Nature* **542**, 335–339 (2017).
3. Lam, P. *et al.* Revising the nitrogen cycle in the Peruvian oxygen minimum zone. *Proc. Natl. Acad. Sci.* **106**, 4752–4757 (2009).
4. Berger, W., Smetacek, V. & Wefer, G. Ocean productivity and paleoproductivity - An overview. in *Productivity of the Ocean: Present and Past, Dahlem Workshop Reports* 1–34 (Wiley-Interscience Publ., 1989).
5. Brockmann, C., Fahrbach, E., Huyer, A. & Smith, R. L. The poleward undercurrent along the Peru coast: 5 to 15°S. *Deep Sea Res. A* **27**, 847–856 (1980).
6. Shaffer, G., Salinas, S., Pizarro, O., Vega, A. & Hormazabal, S. Currents in the deep

ocean off Chile (30°S). *Deep Sea Res. Part I Oceanogr. Res. Pap.* **42**, 425–436 (1995).

7. Shaffer, G., Pizarro, O., Djurfeldt, L., Salinas, S. & Rutllant, J. Circulation and Low-Frequency Variability near the Chilean Coast: Remotely Forced Fluctuations during the 1991–92 El Niño. *J. Phys. Oceanogr.* **27**, 217–235 (1997).

8. Böning, P. *et al.* Geochemistry of Peruvian near-surface sediments. *Geochim. Cosmochim. Acta* **68**, 4429–4451 (2004).

9. Mackas, D. L., Strub, P., Thomas, A. & Montecino, V. Eastern ocean boundaries pan-regional overview. *Sea* 21–59 (2006).

10. Díaz-Ochoa, J. A. *et al.* Fish scales in sediments from off Callao, central Peru. *Deep Sea Res. Part II Top. Stud. Oceanogr.* **56**, 1124–1135 (2009).

11. Suess, E., Kulm, L. & Killingly, J. Coastal upwelling and a history of organic-rich mudstone deposition off Peru. in *Geological Society, London, Special Publications* vol. 26 181–197 (1987).

12. Erdem, Z. *et al.* Bottom-water deoxygenation at the Peruvian margin during the last deglaciation recorded by benthic foraminifera. *Biogeosciences* **17**, 3165–3182 (2020).

13. Scholz, F., Mcmanus, J., Mix, A. C., Hensen, C. & Schneider, R. R. The impact of ocean deoxygenation on iron release from continental margin sediments. **7**, 433–437 (2014).

14. Salvatteci, R. *et al.* Fish debris in sediments from the last 25 kyr in the Humboldt Current reveal the role of productivity and oxygen on small pelagic fishes. *Prog. Oceanogr.* **176**, (2019).

15. Rathburn, A. E., Willingham, J., Ziebis, W., Burkett, A. M. & Corliss, B. H. A New biological proxy for deep-sea paleo-oxygen: Pores of epifaunal benthic foraminifera. *Sci. Rep.* **8**, 9456 (2018).

16. Davis, C. V., Wishner, K., Renema, W. & Hull, P. M. Vertical distribution of planktic foraminifera through an oxygen minimum zone: how assemblages and test morphology reflect oxygen concentrations. *Biogeosciences* **18**, 977–992 (2021).

17. Kuhnt, T. *et al.* Relationship between pore density in benthic foraminifera and bottom-water oxygen content. *Deep Sea Res. Part I Oceanogr. Res. Pap.* **76**, 85–95 (2013).

18. Richirt, J. *et al.* Morphological Distinction of Three Ammonia Phylotypes Occurring Along European Coasts. *J. Foraminifer. Res.* **49**, 76–93 (2019).

19. Schönfeld, J., Beccari, V., Schmidt, S. & Spezzaferri, S. Biometry and taxonomy of Adriatic \textit{Ammonia} species from Bellaria--Igea Marina (Italy). *J. Micropalaeontology* **40**, 195–223 (2021).

20. Glock, N. *et al.* Evironmental influences on the pore density of Bolivina spissa (Cushman). *J. Foraminifer. Res.* **41**, 22–32 (2011).

21. Glock, N. *et al.* Coupling of oceanic carbon and nitrogen facilitates spatially resolved quantitative reconstruction of nitrate inventories. *Nat. Commun.* **9**, 1217 (2018).

22. Risgaard-Petersen, N. *et al.* Evidence for complete denitrification in a benthic foraminifer. *Nature* **443**, 93–96 (2006).

23. Piña-Ochoa, E. *et al.* Widespread occurrence of nitrate storage and denitrification

among Foraminifera and Gromiida. *Proc. Natl. Acad. Sci.* **107**, 1148–1153 (2010).

24. Woehle, C. *et al.* A novel eukaryotic denitrification pathway in foraminifera. *Curr. Biol.* **in review**, (2018).

25. Orsi, W. D. *et al.* Anaerobic metabolism of Foraminifera thriving below the seafloor. *ISME J.* **14**, 2580–2594 (2020).

26. Gomaa, F. *et al.* Multiple integrated metabolic strategies allow foraminiferan protists to thrive in anoxic marine sediments. *Sci. Adv.* **7**, eabf1586 (2021).

27. Glock, N. *et al.* Metabolic preference of nitrate over oxygen as an electron acceptor in foraminifera from the Peruvian oxygen minimum zone. *Proc. Natl. Acad. Sci.* **116**, 2860–2865 (2019).

28. Christian, W. *et al.* Denitrification in foraminifera has an ancient origin and is complemented by associated bacteria. *Proc. Natl. Acad. Sci.* **119**, e2200198119 (2022).

29. Mackensen, A., Schmiedl, G., Harloff, J. & Giese, M. Deep-sea foraminifera in the South Atlantic Ocean; ecology and assemblage generation. *Micropaleontology* **41**, 342–358 (1995).

30. Hoogakker, B. A. A. *et al.* Glacial expansion of oxygen-depleted seawater in the eastern tropical Pacific. *Nature* **562**, 410–413 (2018).

31. Skinner, L. C. & Bard, E. Radiocarbon as a Dating Tool and Tracer in Paleoceanography. *Rev. Geophys.* **60**, e2020RG000720 (2022).

32. Bova, S. C., Herbert, T. D. & Altabet, M. A. Ventilation of Northern and Southern Sources of Aged Carbon in the Eastern Equatorial Pacific During the Younger Dryas Rise in Atmospheric CO2. *Paleoceanogr. Paleoclimatology* **33**, 1151–1168 (2018).

33. Butzin, M., Heaton, T. J., Köhler, P. & Lohmann, G. A Short Note on Marine Reservoir Age Simulations Used in IntCal20. *Radiocarbon* **62**, 865–871 (2020).

34. Heaton, T. J. *et al.* Marine20 - the marine radiocarbon age calibration curve (0 - 55,000 cal BP), simulated data for IntCal20. (2020) doi:10.1594/PANGAEA.914500.

35. Reimer, P. J. *et al.* The IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve (0-55 cal kBP). *Radiocarbon* **62**, 725–757 (2020).

36. Haslett, J. & Parnell, A. A simple monotone process with application to radiocarbon-dated depth chronologies. *J. R. Stat. Soc. Ser. C (Applied Stat.* **57**, 399–418 (2008).

37. Erdem, Z. *et al.* Peruvian sediments as recorders of an evolving hiatus for the last 22 thousand years. *Quat. Sci. Rev.* **137**, 1–14 (2016).

38. Mosch, T. *et al.* Factors influencing the distribution of epibenthic megafauna across the Peruvian oxygen minimum zone. *Deep Sea Res. Part I Oceanogr. Res. Pap.* **68**, 123–135 (2012).

39. Kuhnt, T. *et al.* AUTOMATED AND MANUAL ANALYSES OF THE PORE DENSITY-TO-OXYGEN RELATIONSHIP IN GLOBOBULIMINA TURGIDA (BAILEY). *J. Foraminifer. Res.* **44**, 5–16 (2014).

40. Petersen, J. *et al.* Improved methodology for measuring pore patterns in the benthic foraminiferal genus Ammonia. *Mar. Micropaleontol.* **128**, 1–13 (2016).

41. Richirt, J. *et al.* Scaling laws explain foraminiferal pore patterns. *Sci. Rep.* **9**, 9149

(2019).

42. Tetard, M., Beaufort, L. & Licari, L. A new optical method for automated pore analysis on benthic foraminifera. *Mar. Micropaleontol.* **136**, 30–36 (2017).

43. Giordano, L., Ferraro, L., Salvatore, M., Oscurato, S. L. & Maddalena, P. Morphometric analysis on benthic foraminifera through Atomic Force Microscopy. *Mar. Micropaleontol.* **153**, 101775 (2019).

44. Lutze, G. F. & Thiel, H. Epibenthic foraminifera from elevated microhabitats; Cibicidoides wuellerstorfi and Planulina ariminensis. *J. Foraminifer. Res.* **19**, 153–158 (1989).

45. Fairbanks, R. G. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nat. 1989 3426250* **342**, 637–642 (1989).

46. Jaccard, S. L. & Galbraith, E. D. Large climate-driven changes of oceanic oxygen concentrations during the last deglaciation. *Nat. Geosci. 2012 52* **5**, 151–156 (2011).

47. Moffitt, S. E. *et al.* Paleoceanographic Insights on Recent Oxygen Minimum Zone Expansion: Lessons for Modern Oceanography. *PLoS One* **10**, e0115246 (2015).

48. Meissner, K. J., Galbraith, E. D. & Völker, C. Denitrification under glacial and interglacial conditions: A physical approach. *Paleoceanography* **20**, (2005).

49. Albani, S. *et al.* Improved dust representation in the Community Atmosphere Model. *J. Adv. Model. Earth Syst.* **6**, 541–570 (2014).

50. Somes, C. J., Schmittner, A., Muglia, J. & Oschlies, A. A Three-Dimensional Model of the Marine Nitrogen Cycle during the Last Glacial Maximum Constrained by Sedimentary Isotopes. *Front. Mar. Sci.* **4**, 108 (2017).

51. Koutavas, A. & Lynch-Stieglitz, J. Variability of the Marine ITCZ over the Eastern Pacific during the Past 30,000 Years. 347–369 (2004) doi:10.1007/978-1-4020-2944-8_13.

52. Doering, K. *et al.* Changes in diatom productivity and upwelling intensity off Peru since the Last Glacial Maximum: Response to basin-scale atmospheric and oceanic forcing. *Paleoceanography* **31**, 1453–1473 (2016).

53. Davis, C. V. Deglacial restructuring of the Eastern equatorial Pacific oxygen minimum zone. *Commun. Earth Environ.* **3**, 145 (2022).

54. Salvatteci, R., Schneider, R. R., Blanz, T. & Mollier-Vogel, E. Deglacial to Holocene Ocean Temperatures in the Humboldt Current System as Indicated by Alkenone Paleothermometry. *Geophys. Res. Lett.* **46**, 281–292 (2019).

55. Krahmann, G. Physical oceanography during METEOR cruise M77/1. https://doi.pangaea.de/10.1594/PANGAEA.777978 (2012).

56. Krahmann, G. Physical oceanography during METEOR cruise M77/3. *IFM-GEOMAR Leibniz-Institute of Marine Sciences, Kiel University* (2012) doi:10.1594/PANGAEA.777255.

57. Boyer, T. P. *et al.* World ocean database 2018. (2018) doi:http://doi.org/10.7289/V5NZ85MT.

58. Farías, L., Carrasco, C. & Faúndez, J. Nitrous oxide and biogeochemical variables related to Intermediate Waters into Eastern South Pacific Ocean. *Supplement to: Carrasco, Cristina; Karstensen, Johannes; Farías, Laura (2017): On the Nitrous Oxide Accumulation in Intermediate Waters of the Eastern South Pacific Ocean. Frontiers in Marine Science, 4, https://doi.org/10.3389/fmars.2017.00024* (2019) doi:10.1594/PANGAEA.906231.

59. Cardich, J. *et al.* Multidecadal Changes in Marine Subsurface Oxygenation Off Central Peru During the Last ca. 170 Years. *Front. Mar. Sci.* **0**, 270 (2019).

60. Jauch, S. Kalibration der Porendichte von Planulina limbata als potentiellen Proxy für Redoxbedingungen in der Peruvianischen Sauerstoffminimumzone. (Christian-Albrechts-Universität zu Kiel, 2013).

61. Schlitzer, R. Ocean Data View. (2015).

62. Glock, N., Liebetrau, V. & Eisenhauer, A. I/Ca ratios in benthic foraminifera from the Peruvian oxygen minimum zone: Analytical methodology and evaluation as a proxy for redox conditions. *Biogeosciences* **11**, (2014).

Acknowledgements

The scientific party on R/V Meteor cruise M77 is acknowledged for their general support and help with the coring operation and sampling. We thank Sabrina Jauch for her pioneering work on calibrating the pore density of *Planulina limbata* during her bachelor thesis. Tanita Wein provided additional student assistance to compare the methods for the determination of pore densities. Funding was provided by the Deutsche Forschungsgemeinschaft (DFG) through both the SFB 754 "Climate–Biogeochemistry Interactions in the Tropical Ocean" and N. Glock´s Heisenberg grant GL 999/3-1.

Competing interests

The Authors declare no conflict of interests.

Author contributions

All authors planned the sampling strategy and study design. N. G. did onboard sampling, analyzed and interpreted the foraminiferal pore density data and did core-writing of the manuscript. Z. E. sampled the material for the radiocarbon dating and the stable oxygen isotope stratigraphy. All authors contributed writing the manuscript.

Figure captions:

Figure 1: Map with sampling locations together with dissolved oxygen concentration at 300 mbss in the Southeastern Pacific Ocean (inset map). Data is obtained from World Ocean Atlas 2018[57]. Black crosses indicate the locations of MUC samples used for the core top calibration of PD vs $[O_2]_{BW}$. Red diamond shows the location of sediment cores M77/1-406/MUC-6 and M77/1-416/GC-4) used for the paleoreconstruction of $[O_2]_{BW}$. Prepared using Ocean Data View[61].

Figure 2: Age depth models for cores M77/1 406-MUC6 (A) and M77/1 416-GC4 (B). These models are based on ^{14}C dating and have been modeled using the Bchron software package[36]. Error bands show 95% confidence intervals. The probability distributions and highest density

regions are shown for the ^{14}C age of each analyzed sample. Note that sample 416_10 has been excluded from the age model as an outlier (age reversal).

Figure 3: Visual description of the four methods that have been compared to determine the PD of *Planulina limbata*. For a detailed description of these methods see text. A: Method #1; B: Method #2; C: Method #3; D: Method #4.

Figure 4: **A:** Comparison of epifaunal PD vs. $[O_2]_{BW}$ correlation between our study (red dots) and Rathburn et al.[15] (Black dots). PDs of each individual foraminiferal specimen are plotted. All PDs in this plot were determined after method #1. The dashed line is a logarithmic regression through all data points (Equation and statistics are shown in figure). **B:** Scanning electron micrographs of two epifaunal *Planulina limbata* specimens (umbilical side) with different porosity features. Specimen A (higher porosity) is from M77/1-487/MUC-39 ($[O_2]_{BW}$ = 3.70 µmol/kg); Specimen B (Lower porosity) is from M77/1-565/MUC-60 ($[O_2]_{BW}$ = 8.17 µmol/kg). **C-F:** Comparison of the four methods that have been tested to determine the correlation between $[O_2]_{BW}$ and the mean the PD of *Planulina limbata* in each sample. For a detailed description of these methods see text. C: Method #1; D: Method #2; E: Method #3; F: Method #4. Solid lines are linear regressions (Equation and statistics are shown in figure). Error bars are the standard error of the mean (1SEM).

Figure 5: Quantitative palaeorecord of mean $[O_2]_{BW}$ in cores M77/1 406-MUC6 and M77/1 416-GC4 using the PD of *Planulina limbata*. Note that the slice during the Late Holocene (LH) is from M77/1 406-MUC6 and the slice from the Last Glacial Maximum (LGM) from core M77/1 416-GC4. All PDs were determined after method #4, except in the one sample plotted as a grey triangle. In this sample specimens were too small for size normalization and PD and $[O_2]_{BW}$ were determined using method #3. Since only two specimens were found in one sample each individual reconstructed $[O_2]_{BW}$ instead of mean values were plotted as grey crosses. Horizontal errors are the standard deviation (1SD) Vertical error bars are standard error of the mean (1SEM) except for the grey crosses (1SD). Mean modern $[O_2]_{BW}$ in this region is highly variable in this region (range from 1-25 µmol/kg[55–58]). The red dot represents the mean modern $[O_2]_{BW}$ (red dashed line = 1SD). Note that all the reconstructed $[O_2]_{BW}$ are within the range of short time modern variability.

Figure 6: $[O_2]_{BW}$ reconstructed with different approaches for different depths at the Peruvian OMZ during the LGM (red) and the LH (Black). Data at 1000 – 1250 m is from Erdem et al.[12], at ~500 m from this study and ~240 m from Scholz et al.[13]. Modern data is from 11°S M77/1-438/CTD-RO-16[55]. Note that water depths during the LGM have all been corrected by the lower sea level of ~120 m[45]. Datapoints for our data and Erdem et al.[12] are the weighted mean for each time slice and error bars are the standard error for the weighted mean. Scholz et al.[13] indicated a range of 5-10 µmol/kg for the LGM (shown here as 7.5 ± 2.5 µmol/kg). The data for the LH from Scholz et al.[13] was calculated after their figure 1b and indicated always anoxic conditions (here shown as 1 µmol/kg without error bar).

Tab.1

Station list. Station names in *italic* letters indicate that these stations were used for the paleo O_2 reconstruction. The other stations were used for the modern PD calibrations. [a]: $[O_2]_{BW}$ taken from Glock et al.[62]; [b]: $[O_2]_{BW}$ taken from Glock et al.[20]; *: The $[O_2]$ gradient at the lower OMZ boundary was very steep at this location which results in a highly variable modern $[O_2]_{BW}$. Different data sources list values between 1 and 25 µmol/kg[55–58].

Station	Lattitude (°W)	Longitude (°S)	Water depth (m)	$[O_2]_{BW}$ (µmol/kg)
M77/1-553/MUC-54	78°54.70'	10°26.38'	521	3.00[a]
M77/1-487/MUC-39	78°23.17'	11°00.00'	579	3.70[b]
M77/2-723/MUC-47-3	80°31.36'	07°52.01'	626	8.10[a]
M77/1-565/MUC-60	78°21.40'	11°08.00'	640	8.17[b]
M77/1-459/MUC-25	78°25.60'	11°00.02'	698	12.55[b]
M77/1-406/MUC-6	71°52.40'	17°28.00'	492	*
M77/1-416/GC-4	71°52.62'	17°28.14'	505	*

Table 2:

Radiocarbon (^{14}C) dating results for cores M77/1 416-GC4 and M77/1 406-MUC6. ^{14}C ages were determined on epibenthic *Planulina limbata* in M77/1 416-GC4 and on bulk sedimentary organic matter (Bulk C_{org}) for core M77/1 406-MUC6. All ^{14}C ages have been corrected for the marine reservoir ages (MRA) for 18.75°S 75°W for the different time slices modelled by Butzin et al.[33,34] (Suppl. Fig. 1). ^{14}C ages of *P. limbata* were additionally corrected for the benthic-planktic ^{14}C offset measured in CDH 26 by Bova et al.[32]. SDs are the standard deviations. Propagated SDs for M77/1 416-GC4 include the errors from *P. limbata* in this core and the planktic and benthic ^{14}C ages from Bova et al.[32]. The range (2.5% - 97.5%) of the calibrated ages (Cal. age) has been modelled from the corrected atmospheric (atm.) ^{14}C age with Intcal20[35] using the Bchron software package[36]. Data in italic letters has been excluded from the age model, due to age reversals/redeposition (see text for details).

Core name	depth (cm)	type	^{14}C age (^{14}C yr)	SD	Benthic-planktic offset (^{14}C yr)[32]	Benthic SD from Benthic-planktic offset (^{14}C yr)[32]	Planktic SD from Benthic-planktic offset (^{14}C yr)[32]	Benthic-planktic offset corrected ^{14}C age (^{14}C yr)	MRA (^{14}C yr)[34]	Corrected atm. ^{14}C age (^{14}C yr)	Propagated SD	Cal. age min (yr BP)	Cal. age max (yr BP)
M77/1 416-GC4	20	*P. limbata*	15900	60	850	60	65	15050	782	14268	107	17087	17788
M77/1 416-GC4	60	*P. limbata*	16910	70	850	60	65	16060	832	15228	113	18275	18759
M77/1 416-GC4	100	*P. limbata*	17690	80	1000	70	70	16690	904	15786	127	18842	19402
M77/1 416-GC4	110	*P. limbata*	17560	80	1000	70	70	16560	888	15672	127	18747	19283
M77/1 416-GC4	160	*P. limbata*	18080	90	1000	70	70	17080	925	16155	134	19146	19855
M77/1 416-GC4	210	*P. limbata*	18610	80	1250	100	70	17360	978	16382	146	19447	20172
M77/1 416-GC4	230	*P. limbata*	18970	80	1250	100	70	17720	1045	16675	146	19682	20481
M77/1 416-GC4	245	*P. limbata*	19370	90	850	90	110	18520	1094	17426	168	20610	21664
M77/1 416-GC4	250	*P. limbata*	19550	100	850	90	110	18700	1058	17642	174	20905	21919
M77/1 416-GC4	*290*	*P. limbata*	*18930*	*90*	*850*	*90*	*110*	*18080*	*1133*	*16947*	*168*	*20040*	*20853*
M77/1 416-GC4	310	*P. limbata*	21050	130	850	90	110	20200	994	19206	193	22669	23716
M77/1 416-GC4	345	*P. limbata*	22560	120	1400	160	80	21160	964	20196	215	23838	23838
M77/1 406-MUC6	0-2	Bulk C_{org}	800	30					652	148	30	9	275
M77/1 406-MUC6	5-8	Bulk C_{org}	1500	30					652	848	30	690	882
M77/1 406-MUC6	*14-18*	*Bulk C_{org}*	*8070*	*40*					*691*	*7379*	*40*	*8043*	*8320*

Table 3:

Mean pore densities (PD), standard deviations (SD) and standard errors of the mean (SEM) for the core top samples that have been used for the modern calibrations. Data includes all the four different methods that have been tested to determine foraminiferal PDs.

Station	Mean PD after Method #1 ($P/\mu m^2$)	SD	SEM	Mean PD after Method #2 ($P/\mu m^2$)	SD	SEM	Mean PD after Method #3 ($P/\mu m^2$)	SD	SEM	Mean PD after Method #4 ($P/\mu m^2$)	SD	SEM
M77/1-459/MUC-25	0.0049	0.00210	0.00148	0.0023	0.00051	0.00036	0.0016	0.00012	0.00009	0.0016	0.00012	0.00009
M77/1-487/MUC-39	0.0064	0.00042	0.00013	0.0055	0.00064	0.00019	0.0031	0.00030	0.00009	0.0030	0.00030	0.00009
M77/1-553/MUC-54	0.0062	0.00085	0.00025	0.0053	0.00045	0.00013	0.0031	0.00045	0.00013	0.0031	0.00052	0.00015
M77/1-565/MUC-60	0.0053	0.00045	0.00013	0.0033	0.00045	0.00014	0.0021	0.00029	0.00009	0.0021	0.00029	0.00009
M77/2-723/MUC-47-3	0.0053	0.00060	0.00018	0.0043	0.00061	0.00018	0.0025	0.00037	0.00011	0.0025	0.00042	0.00013

Table 4:

Mean pore densities (PD) of *P. limbata*, calibrated ages (Cal. age) from the age model and reconstructed bottom water O_2 concentrations ($[O_2]_{BW}$) for the downcore reconstructions in cores M77/1 406-MUC6 and M77/1 416-GC4. All PDs were determined after method #4, except in the one sample in *italic* letters. In this sample specimens were too small for size normalization and PD and $[O_2]_{BW}$ were determined using method #3. Only two specimens were found in 4.5 cm depth. PDs and reconstructed $[O_2]_{BW}$ are listed here for each individual instead as mean values for the whole sample. SD = Standard deviation; SEM = Standard error of the mean.

Core name	Depth (cm)	Cal. age (yr BP)	SD	PD ($P/\mu m^2$)	SD	SEM	$[O_2]_{BW}$ (µmol/kg)	SEM
M77/1 406-MUC6	0.5	86	42	0.0027	0.00024	0.00011	5.7	1.3
M77/1 406-MUC6	1.5	252	90	0.0027	0.00013	0.00005	6.0	1.0
M77/1 406-MUC6	2.5	361	100	0.0024	0.00038	0.00019	7.5	1.6
M77/1 406-MUC6	*3.5*	*461*	*102*	*0.0029*	*0.00024*	*0.00014*	*4.8*	*1.8*
M77/1 406-MUC6	4.5	559	96	0.0026	*	*	6.3	2.4(SD)
M77/1 406-MUC6	4.5	559	96	0.0023	*	*	8.3	2.2(SD)
M77/1 406-MUC6	7.6	1010	291	0.0022	0.00019	0.00010	8.5	1.2
M77/1 416-GC4	20.0	17432	203	0.0017	0.00022	0.00009	11.5	1.0
M77/1 416-GC4	30.0	17721	209	0.0016	0.00024	0.00011	12.1	1.1
M77/1 416-GC4	40.0	17943	196	0.0016	0.00011	0.00005	12.6	0.8
M77/1 416-GC4	50.0	18165	179	0.0017	0.00018	0.00008	11.8	1.0
M77/1 416-GC4	55.0	18288	161	0.0019	0.00034	0.00015	10.3	1.3
M77/1 416-GC4	65.0	18524	124	0.0017	0.00026	0.00012	11.7	1.1
M77/1 416-GC4	70.0	18582	120	0.0016	0.00012	0.00006	12.2	1.0
M77/1 416-GC4	75.0	18636	116	0.0015	0.00020	0.00010	13.0	1.1
M77/1 416-GC4	85.0	18737	108	0.0024	0.00029	0.00013	7.6	1.3
M77/1 416-GC4	90.0	18792	103	0.0017	0.00030	0.00014	11.5	1.2
M77/1 416-GC4	100.0	18922	85	0.0016	0.00016	0.00007	12.1	1.0
M77/1 416-GC4	110.0	19105	104	0.0018	0.00012	0.00005	11.3	1.0
M77/1 416-GC4	120.0	19191	107	0.0019	0.00025	0.00012	10.5	1.3
M77/1 416-GC4	135.0	19286	114	0.0019	0.00014	0.00006	10.7	1.0
M77/1 416-GC4	140.0	19318	117	0.0020	0.00021	0.00009	10.1	1.1
M77/1 416-GC4	150.0	19383	123	0.0020	0.00031	0.00014	10.2	1.2
M77/1 416-GC4	160.0	19467	132	0.0019	0.00027	0.00012	10.8	1.2
M77/1 416-GC4	180.0	19625	129	0.0020	0.00043	0.00019	10.2	1.5

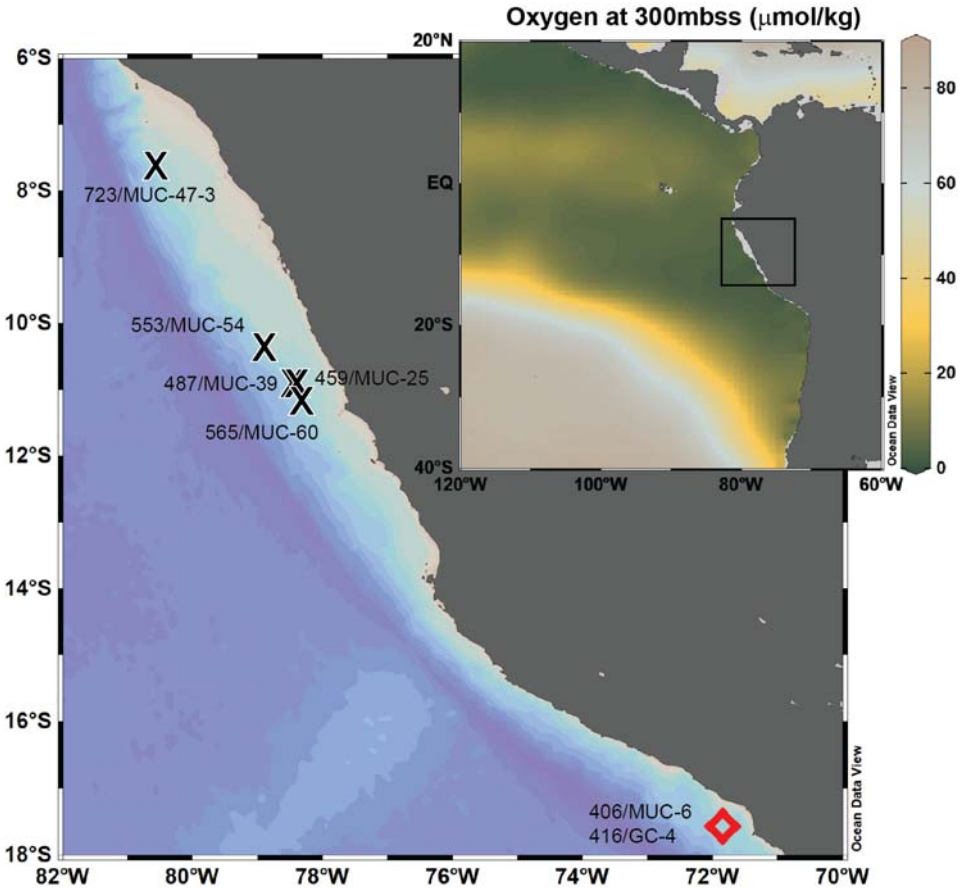


Figure 1: Map with sampling locations together with dissolved oxygen concentration at 300 mbss in the Southeastern Pacific Ocean (inset map). Data is obtained from World Ocean Atlas 2018[57]. Black crosses indicate the locations of MUC samples used for the core top calibration of PD vs $[O_2]_{BW}$. Red diamond shows the location of sediment cores M77/1-406/MUC-6 and M77/1-416/GC-4) used for the paleoreconstruction of $[O_2]_{BW}$. Prepared using Ocean Data View[61].

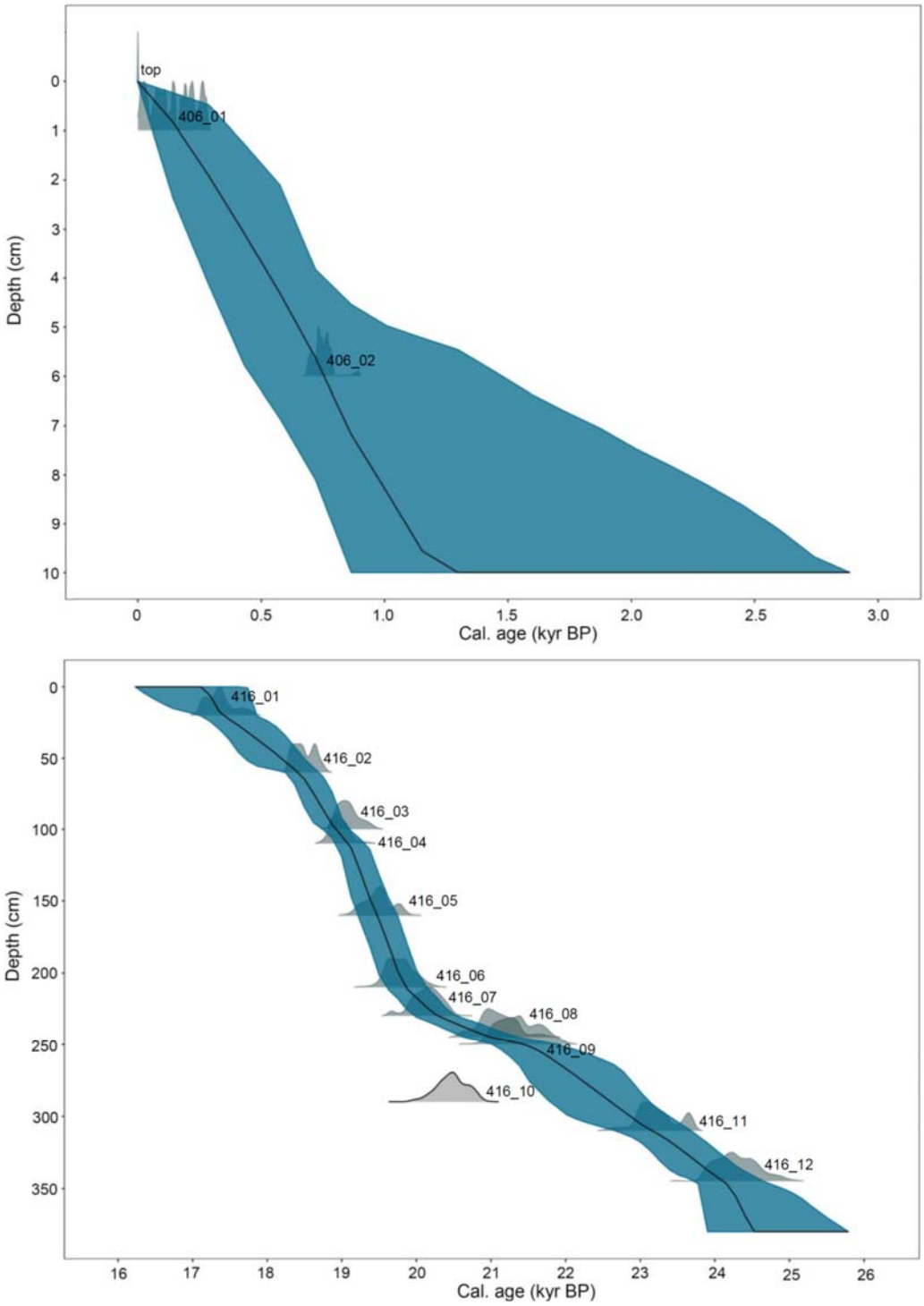


Figure 2: Age depth models for cores M77/1 406-MUC6 (A) and M77/1 416-GC4 (B). These models are based on ^{14}C dating and have been modeled using the Bchron software package[36]. Error bands show 95% confidence intervals. The probability distributions and highest density regions are shown for the ^{14}C age of each analyzed sample. Note that sample 416_10 has been excluded from the age model as an outlier (age reversal).

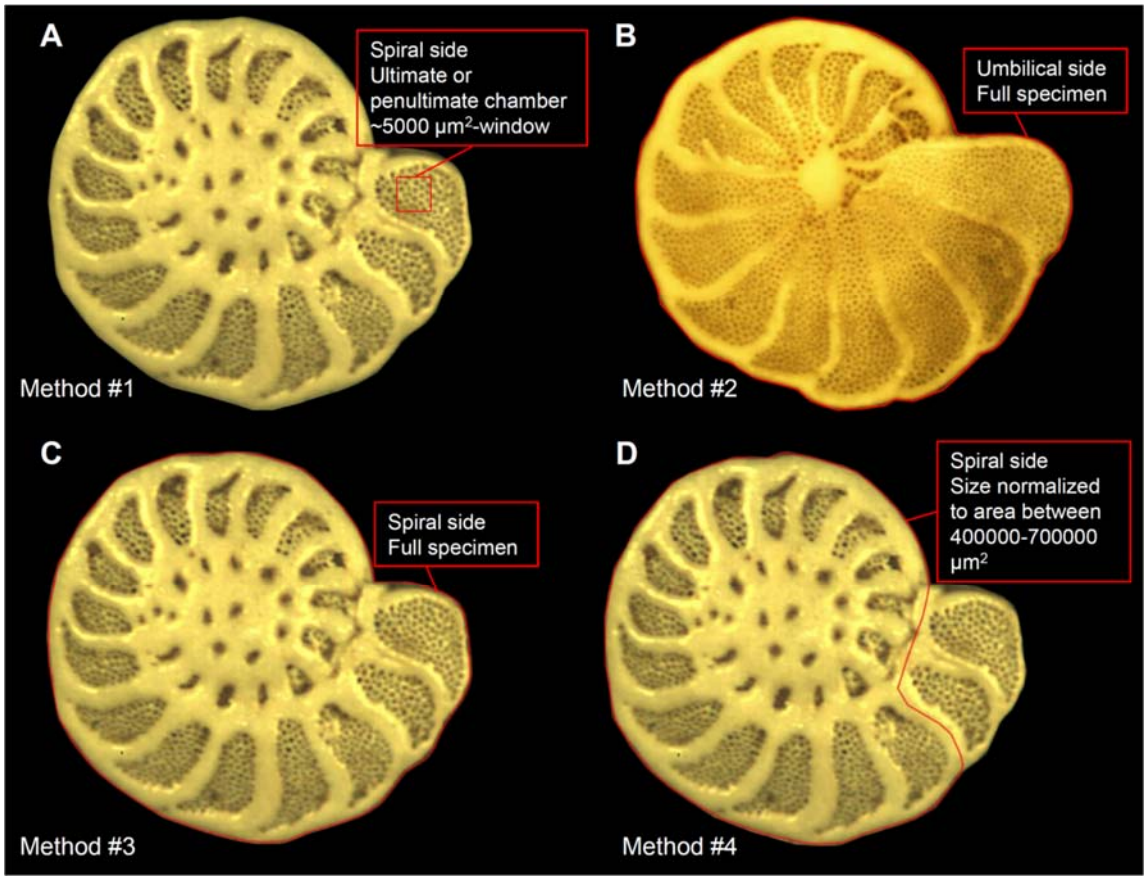


Figure 3: Visual description of the four methods that have been compared to determine the PD of *Planulina limbata*. For a detailed description of these methods see text. A: Method #1; B: Method #2; C: Method #3; D: Method #4.

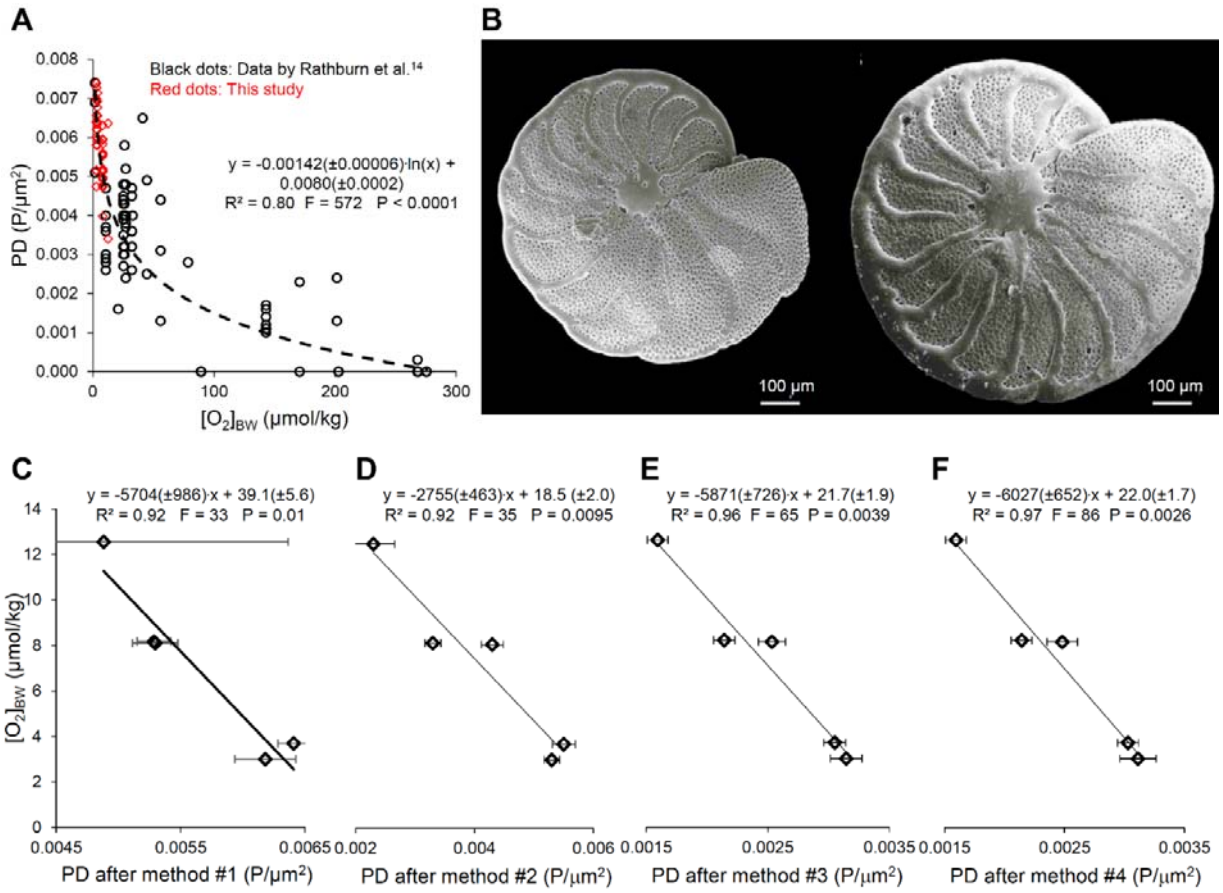
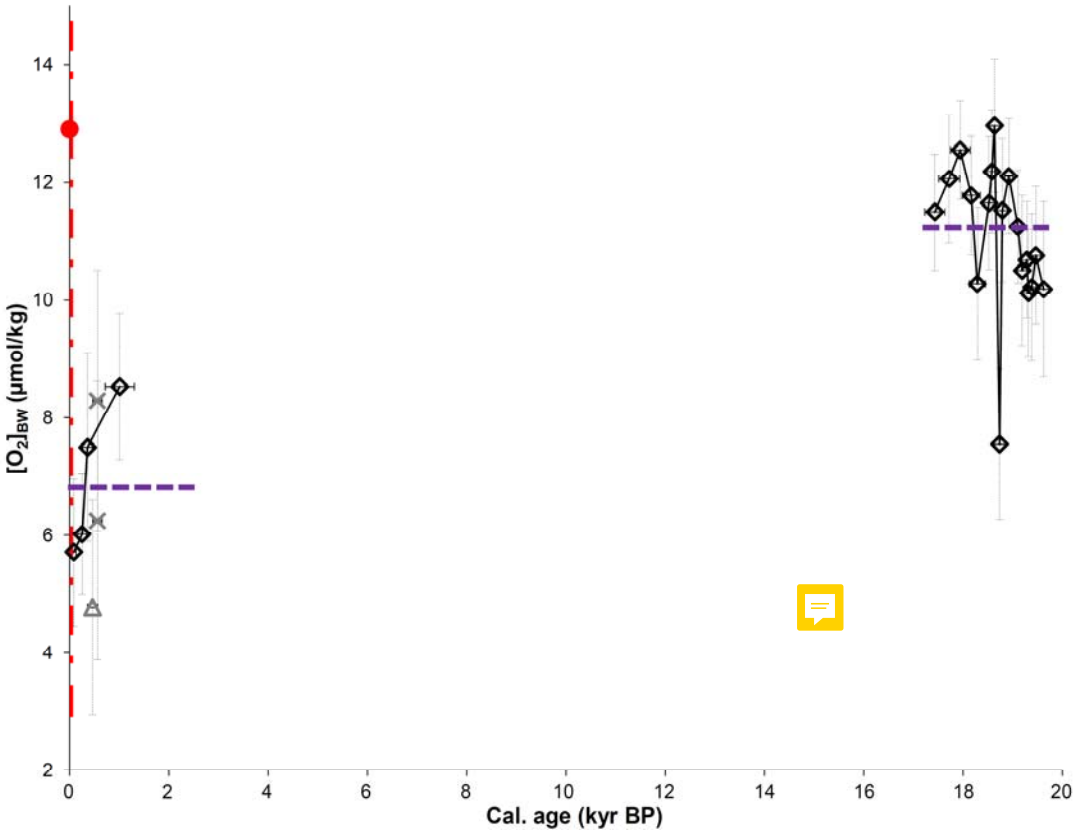


Figure 4: A: Comparison of epifaunal PD vs. $[O_2]_{BW}$ correlation between our study (red dots) and Rathburn et al.[15] (Black dots). PDs of each individual foraminiferal specimen are plotted. All PDs in this plot were determined after method #1. The dashed line is a logarithmic regression through all data points (Equation and statistics are shown in figure). **B:** Scanning electron micrographs of two epifaunal *Planulina limbata* specimens (umbilical side) with different porosity features. Specimen A (higher porosity) is from M77/1-487/MUC-39 ($[O_2]_{BW}$ = 3.70 µmol/kg); Specimen B (Lower porosity) is from M77/1-565/MUC-60 ($[O_2]_{BW}$ = 8.17 µmol/kg). **C-F:** Comparison of the four methods that have been tested to determine the correlation between $[O_2]_{BW}$ and the mean the PD of *Planulina limbata* in each sample. For a detailed description of these methods see text. C: Method #1; D: Method #2; E: Method #3; F: Method #4. Solid lines are linear regressions (Equation and statistics are shown in figure). Error bars are the standard error of the mean (1SEM).



692

693 **Figure 5:** Quantitative palaeorecord of mean $[O_2]_{BW}$ in cores M77/1 406-MUC6 and M77/1
694 416-GC4 using the PD of *Planulina limbata*. Note that the slice during the Late Holocene (LH)
695 is from M77/1 406-MUC6 and the slice from the Last Glacial Maximum (LGM) from core
696 M77/1 416-GC4. All PDs were determined after method #4, except in the one sample plotted
697 as a grey triangle. In this sample specimens were too small for size normalization and PD and
698 $[O_2]_{BW}$ were determined using method #3. Since only two specimens were found in one sample
699 each individual reconstructed $[O_2]_{BW}$ instead of mean values were plotted as grey crosses.
700 Horizontal errors are the standard deviation (1SD). Vertical error bars are standard error of the
701 mean (1SEM) except for the grey crosses (1SD). Mean modern $[O_2]_{BW}$ in this region is highly
702 variable in this region (range from 1-25 µmol/kg[55–58]). The red dot represents the mean modern
703 $[O_2]_{BW}$ (red dashed line = 1SD). Note that all the reconstructed $[O_2]_{BW}$ are within the range of
704 short time modern variability. Purple dashed lines indicate the mean $[O_2]_{BW}$ during the LH and
705 the LGM.

706

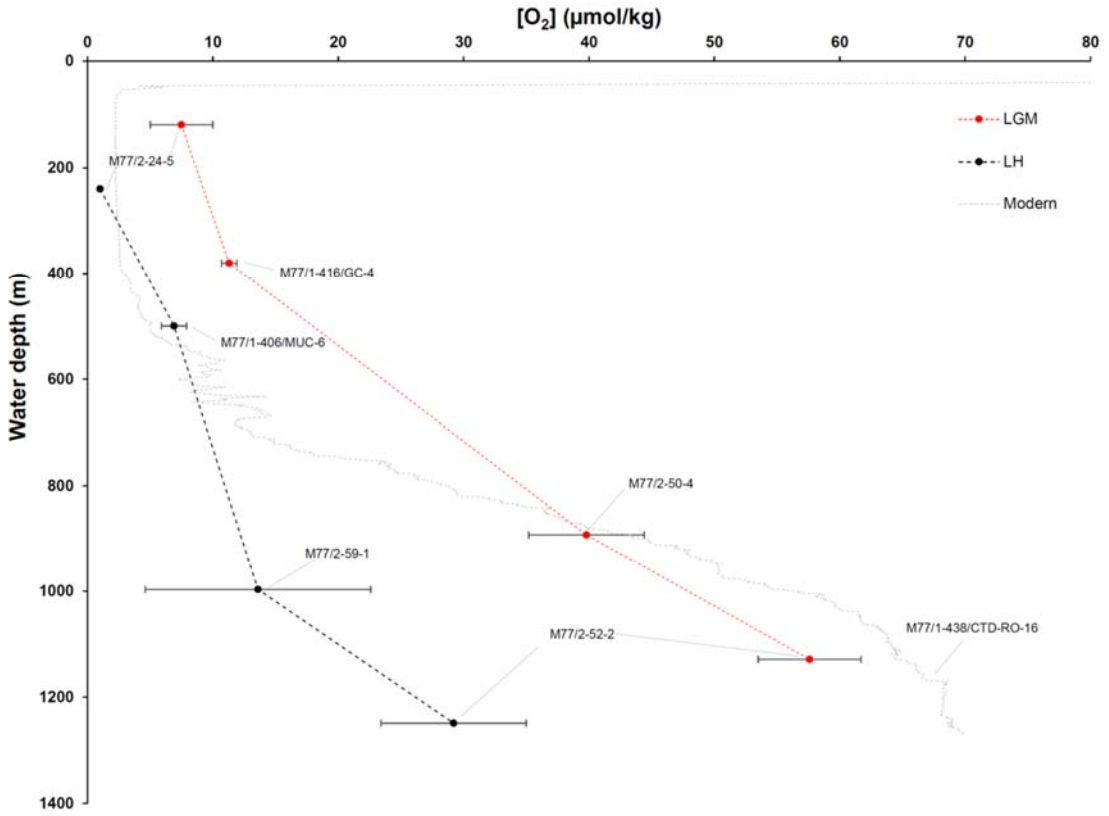
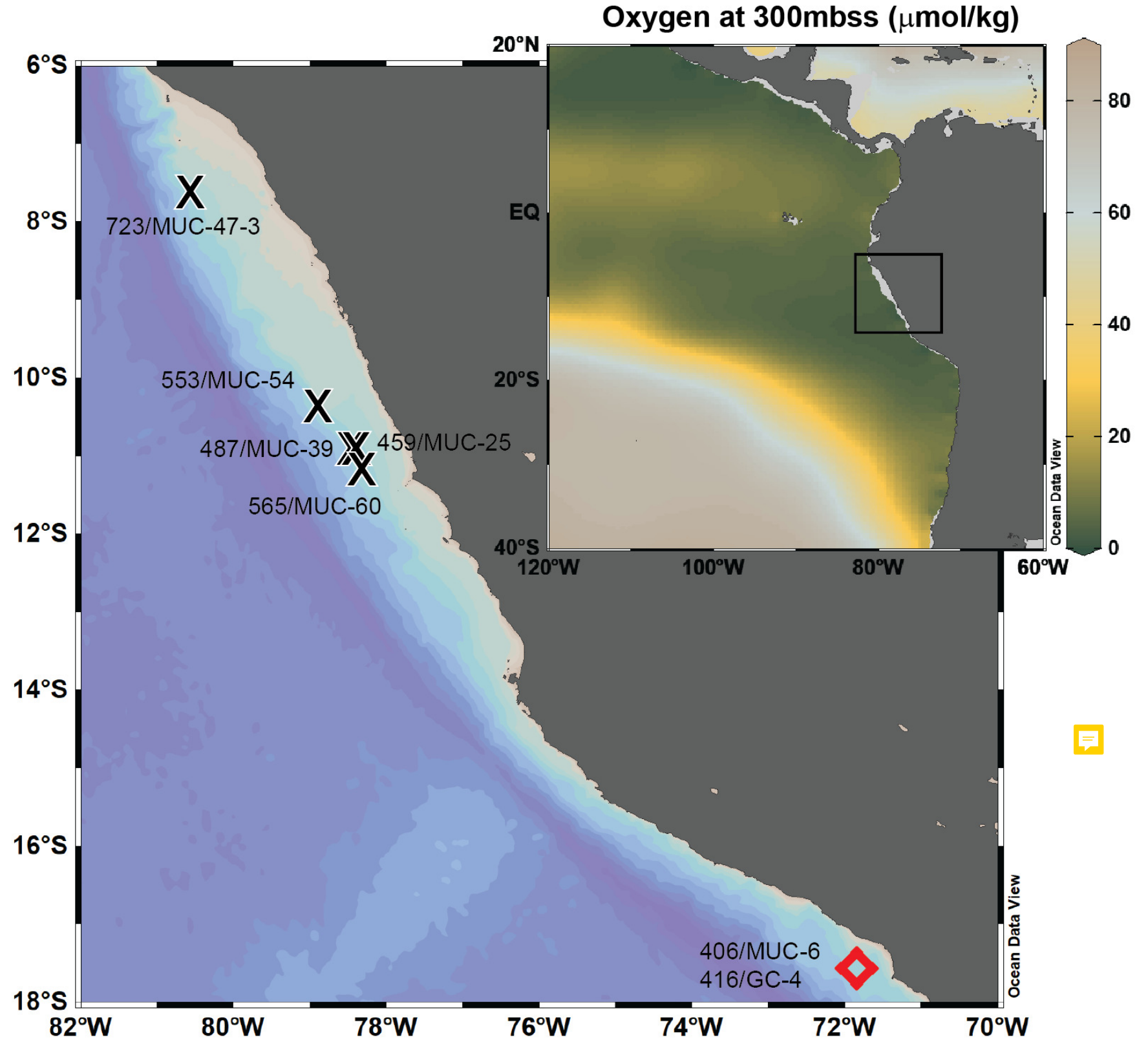
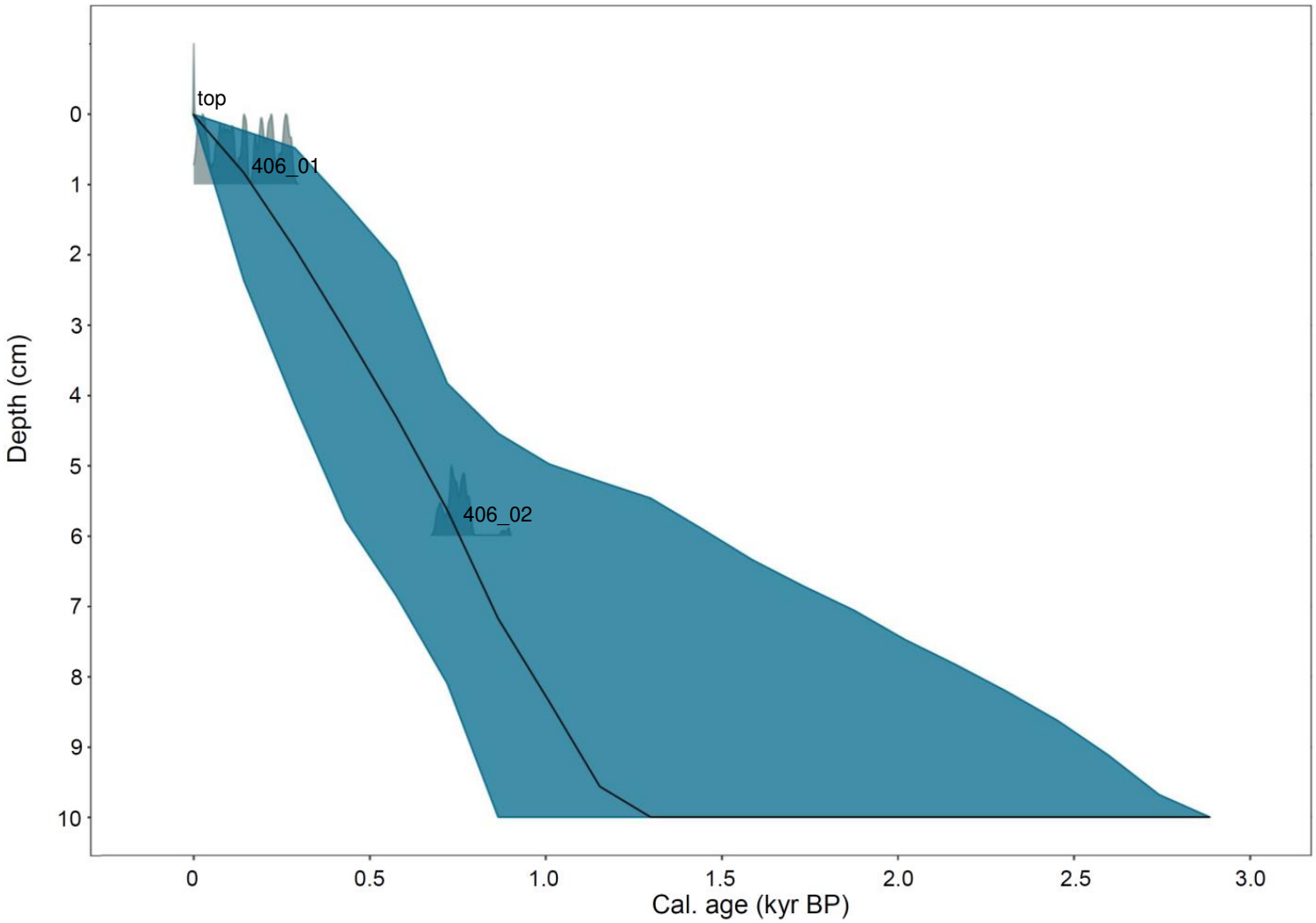
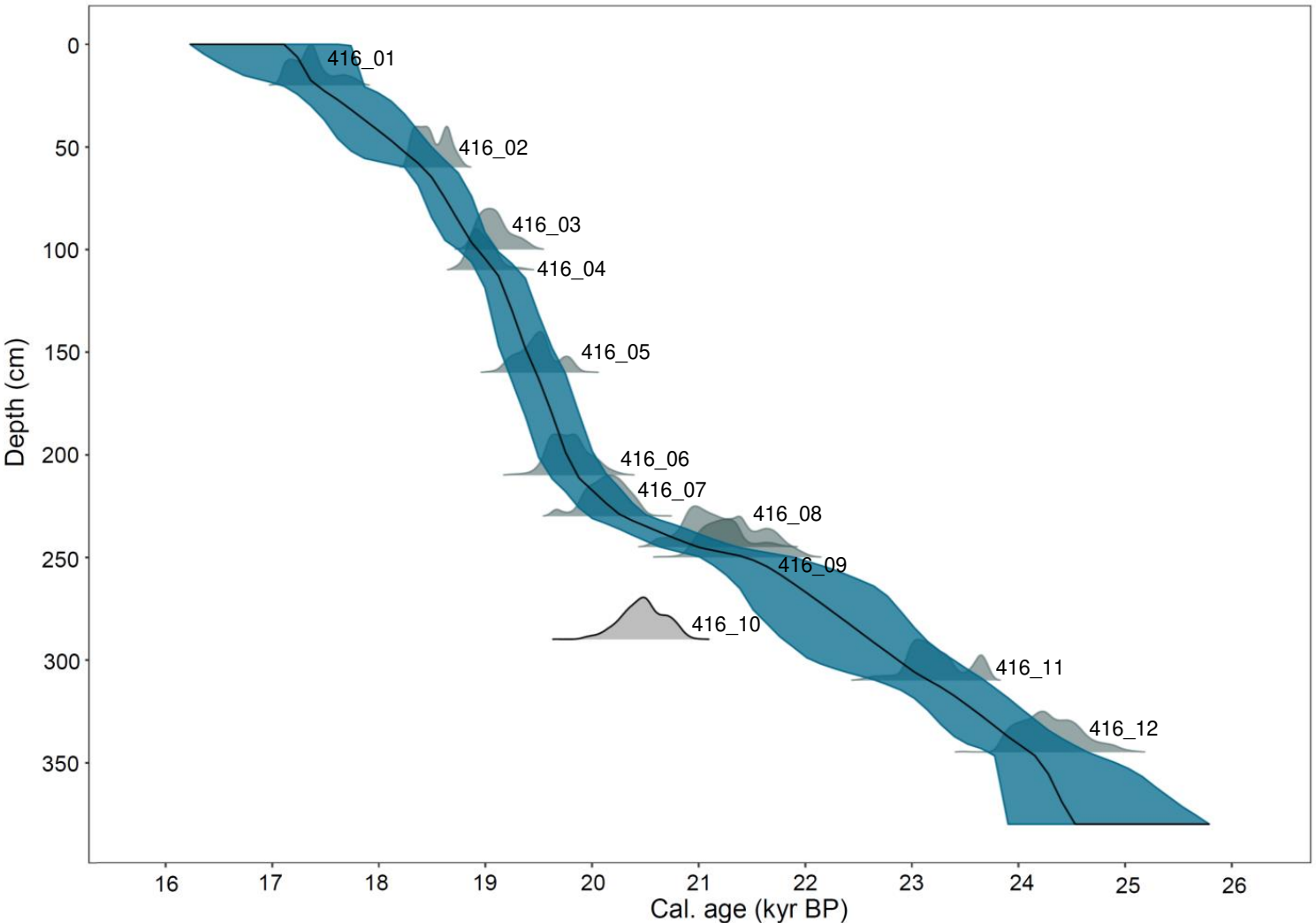
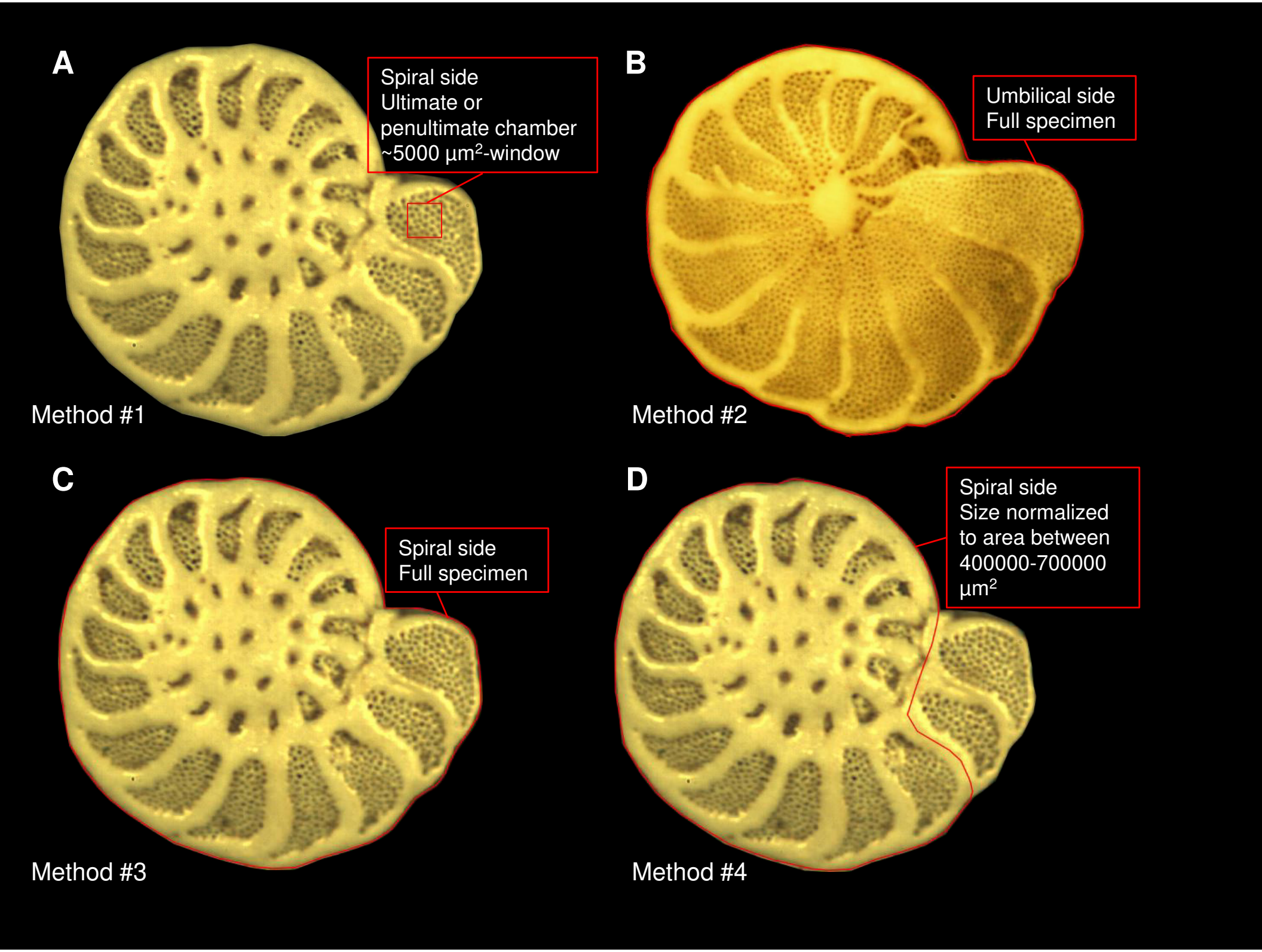


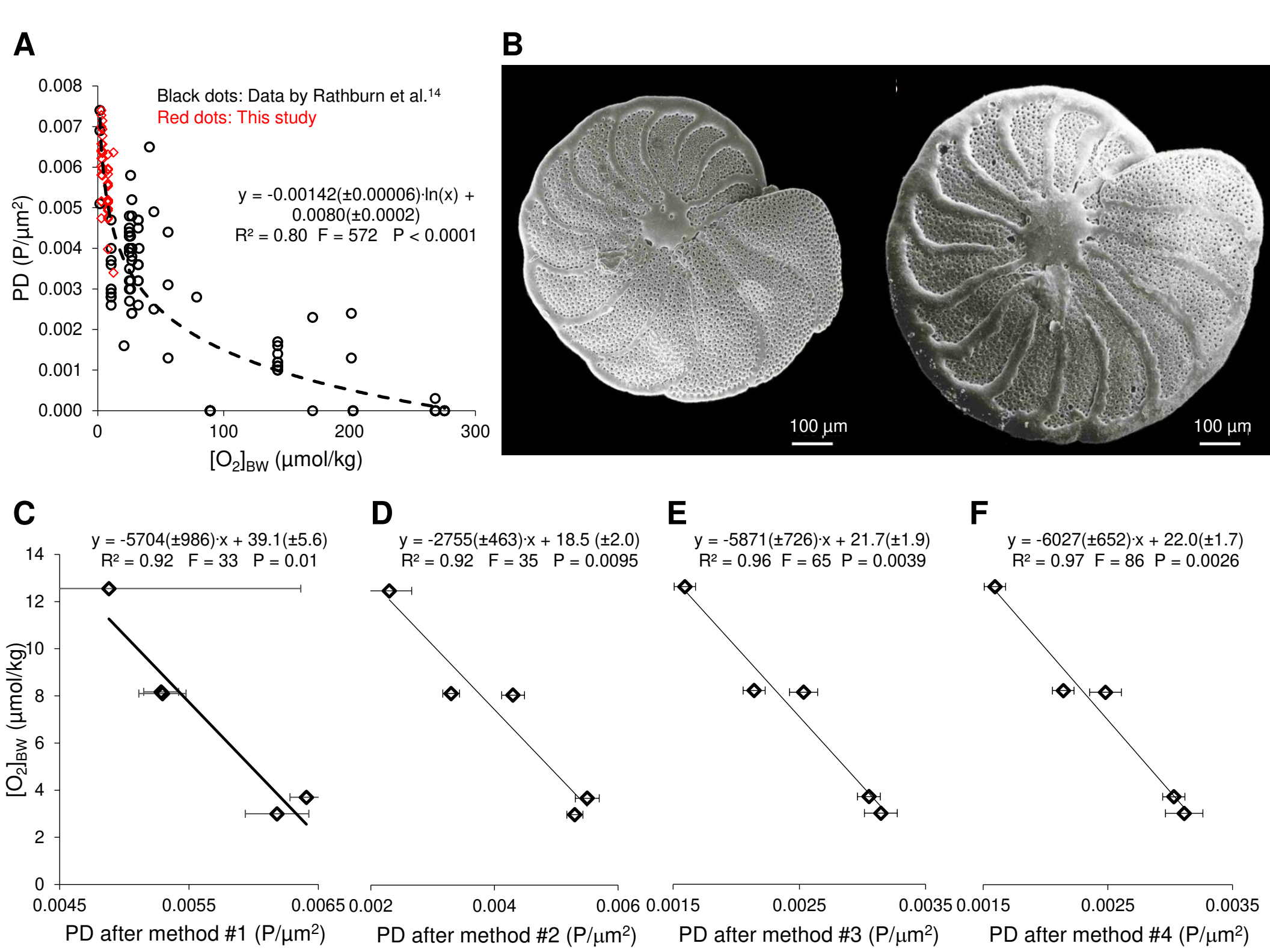
Figure 6: $[O_2]_{BW}$ reconstructed with different approaches for different depths at the Peruvian OMZ during the LGM (red) and the LH (Black). Data at 1000 – 1250 m is from Erdem et al.[12], at ~500 m from this study and ~240 m from Scholz et al.[13]. Modern data is from 11°S M77/1-438/CTD-RO-16[55]. Note that water depths during the LGM have all been corrected by the lower sea level of ~120 m[45]. Datapoints for our data and Erdem et al.[12] are the weighted mean for each time slice and error bars are the standard error for the weighted mean. Scholz et al.[13] indicated a range of 5-10 µmol/kg for the LGM (shown here as 7.5 ± 2.5 µmol/kg). The data for the LH from Scholz et al.[13] was calculated after their figure 1b and indicated always anoxic conditions (here shown as 1 µmol/kg without error bar).

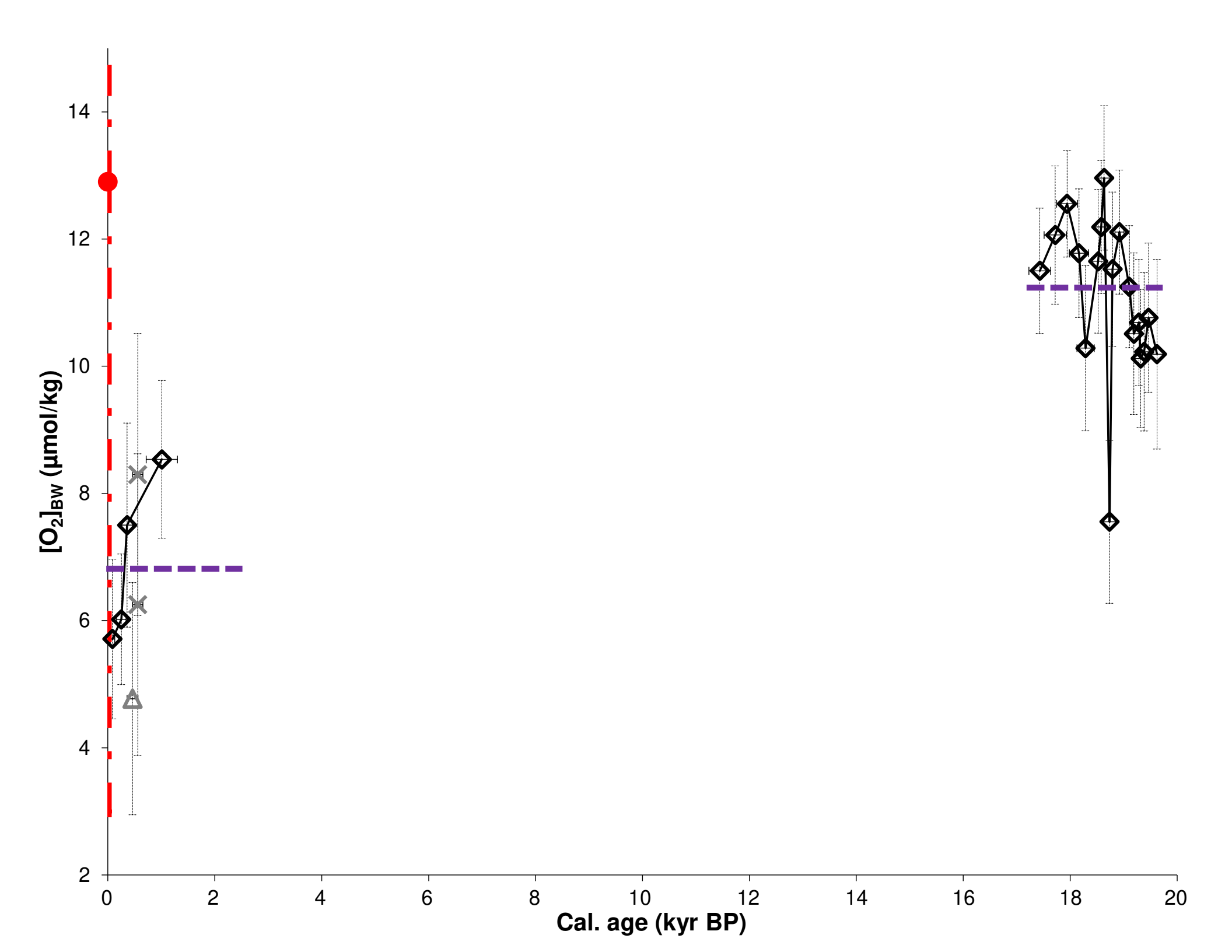

Oxygen at 300mbss (µmol/kg)
20°N
EQ
20°S
40°S
120°W
100°W
80°W
60°W
80
60
40
20
0
Ocean Data View
6°S
8°S
10°S
12°S
14°S
16°S
18°S
82°W
80°W
78°W
76°W
74°W
72°W
70°W
723/MUC-47-3
553/MUC-54
487/MUC-39
459/MUC-25
565/MUC-60
406/MUC-6
416/GC-4
Ocean Data View

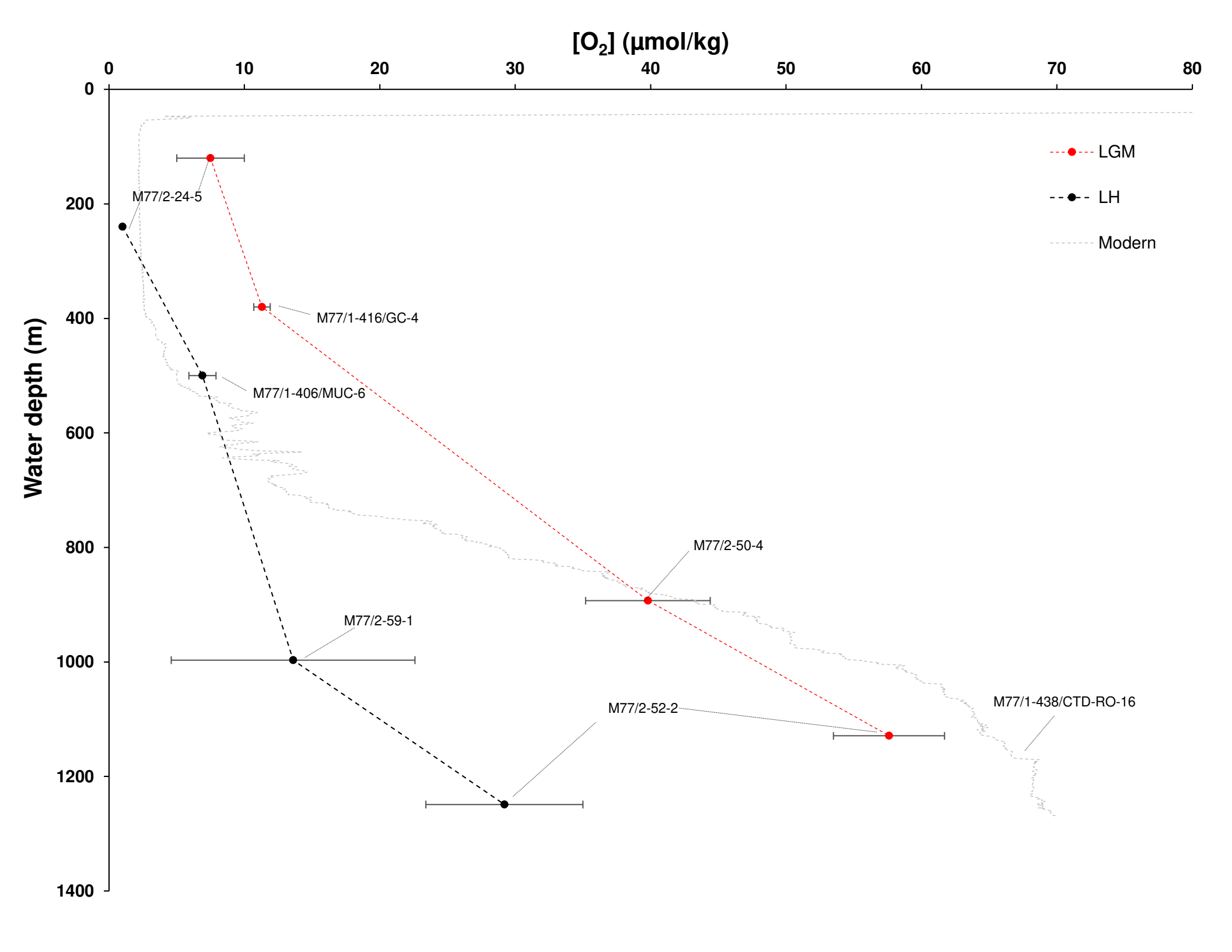

top
406_01
406_02
Depth (cm)
0
1
2
3
4
5
6
7
8
9
10
0
0.5
1.0
1.5
2.0
2.5
3.0
Cal. age (kyr BP)


416_01
416_02
416_03
416_04
416_05
416_06
416_07
416_08
416_09
416_10
416_11
416_12
Depth (cm)
0
50
100
150
200
250
300
350
16
17
18
19
20
21
22
23
24
25
26
Cal. age (kyr BP)


A
Spiral side
Ultimate or
penultimate chamber
~5000 µm2-window
Method #1
B
Umbilical side
Full specimen
Method #2
C
Spiral side
Full specimen
Method #3
D
Spiral side
Size normalized
to area between
400000-700000
µm2
Method #4


A
Black dots: Data by Rathburn et al.[14]
Red dots: This study
y = -0.00142(±0.00006)·ln(x) + 0.0080(±0.0002)
R² = 0.80 F = 572 P < 0.0001
PD (P/µm²)
[O2]BW (µmol/kg)
B
100 µm
100 µm
C
y = -5704(±986)·x + 39.1(±5.6)
R² = 0.92 F = 33 P = 0.01
D
y = -2755(±463)·x + 18.5 (±2.0)
R² = 0.92 F = 35 P = 0.0095
E
y = -5871(±726)·x + 21.7(±1.9)
R² = 0.96 F = 65 P = 0.0039
F
y = -6027(±652)·x + 22.0(±1.7)
R² = 0.97 F = 86 P = 0.0026
[O2]BW (µmol/kg)
PD after method #1 (P/µm²)
PD after method #2 (P/µm²)
PD after method #3 (P/µm²)
PD after method #4 (P/µm²)


14
12
10
8
6
4
2
0
2
4
6
8
10
12
14
16
18
20
[O2]BW (µmol/kg)
Cal. age (kyr BP)


[O2] (µmol/kg)
0
10
20
30
40
50
60
70
80
Water depth (m)
0
200
400
600
800
1000
1200
1400
LGM
LH
Modern
M77/2-24-5
M77/1-416/GC-4
M77/1-406/MUC-6
M77/2-50-4
M77/2-59-1
M77/2-52-2
M77/1-438/CTD-RO-16

Rebuttal letter to the reviewers

We were really glad to receive such positive feedbacks by all of the three reviewers. The reviews were all really constructive and we think our manuscript has significantly improved by following the suggestions of the reviewers. In the revised version of our manuscript, we considered all their suggestions. Below, you can find a point by point response to the points of revisions.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

R1: The manuscript by Glock et al., aims to reconstruct shallow-intermediate water (~500 m) oxygenation in the Peruvian OMZ during time slices from the LGM and Late Holocene (LH). They first present several new calibrations of the pore density oxygen proxy for the foraminifer limbata from the Peruvian margin. These are compared and then applied to reconstruct oxygenation in the region. By combining this new data with previously published neighboring records the authors are able to convincingly show a present but weakened OMZ along the Peruvian margin in the LGM as compared to the LH. The manuscript is well-written and well-constructed. I could see the newly presented calibration being used in similar studies and the findings contribute to an important and rapidly evolving discussion of deglacial OMZ evolution on the Pacific margin.

My only major comment is in regards to the difference in inferred shape of the OMZ at present as compared to the LH (just 1-0 kya!). This is seen most clearly in Figure 6 and commented upon on lines 294-296. The difference in oxygenation and slope of the lower oxycline between the recent sedimentary and modern observational records is striking. Could this be elaborated upon? Is this indicative of very recent increases in oxygenation of deep-intermediate waters? Or something else? The difference between LH and modern oxygenation may also raise some skepticism around how reliable modern [O2]BW measurements may be for calibrating “recent” coretop material, which should be addressed.

Reply: We thank the reviewer for the detailed and positive feedback and the very constructive suggestions. We corrected and updated our manuscript accordingly and below we give a point by point response to the minor requests and editorial suggestions of the reviewer. We also slightly extended the discussion regarding the deep oxycline, which is obviously steeper in the modern observation than in the paleo reconstruction for the late LH as shown in figure 6. Regarding the scepticisism “around how reliable modern [O2]BW measurements may be for calibrating “recent” coretop material”: the paleoreconstructions for the deep oxycline (~900-1500 mbss) were done using transfer functions from foraminiferal assemblage compositions (Erdem et al., 2020). These have been calibrated, using the composition of living (rose Bengal) stained foraminiferal assemblages that were alive during sampling time and not just “recent” core top material. In the Erdem et al. (2020) paper, it has already been noted that the reconstructed $[O_2]_{BW}$ values might be biased to lower values, since most of the reference samples that have been used for calibration were from low $[O_2]$ locations. The flattened lower oxycline during the LH in Fig. 6 might thus be an artefact of the comparison of different paleo proxies. There still might be the possibility is that there has been a recent increase in oxygenation of deep to intermediate waters, which is also given credit to in the revised text of the manuscript. We added the following part:

“A comparison of the available quantitative $[O_2]$ paleo data with modern conditions indicates that the oxycline below the OMZ is steeper today than during the LGM or the LH. This might indicate that the intermediate to deep water masses at the Peruvian Margin have been ventilated very recently. The $[O_2]_{BW}$ below 800 mbss are based on foraminiferal assemblages[14]. In the original study it is discussed that the reconstructed $[O_2]_{BW}$ might be biased to lower values, because the majority of reference surface samples used for the calibration were from shallower locations (e.g. lower $[O_2]_{BW}$

than the stations, used for the paleoreconstructions). Thus, we cannot exclude that the flattened lower oxycline during the LH might be an artefact, related to results of multiple [O_2] paleo proxies being compiled in fig. 6."

Also, the modern short time [O_2] variability at our downcore station for the PD reconstruction is high and concentrations sometimes exceed the whole $[O_2]_{BW}$ paleorecord, which already has been mentioned in the first version of our manuscript. This is now much further discussed, also including suggestions by reviewer 2. It might be that *P. limbata* always adapt to the lowest $[O_2]_{BW}$ they experience or to the environmental conditions during their embryonic state in general as suggested by Belanger (2022). This is discussed now in detail in the second last paragraph of the discussion in the revised manuscript (see response to Reviewer 2 below).

Below you can find our response to the minor points of revision.

R1: Other comments are as below:

15: "a proxy"

Reply: done

R1: 27: no "the"

Reply: done

R1: 30: no "the"

Reply: done

R1: 37: Given the importance of deeper water masses to this story, could intermediate water hydrography be added here as well?

Reply: We added a brief section to summarize the intermediate water hydrography in this region:

"The Chile-Peru Deep Coastal Current prevails at ~500 m water depth near the coast and transports relatively low-saline and cold Antarctic Intermediate Water northwards[11]. Depending on the latitude this current concurs with the Peru-Chile undercurrent that is dominant ~500 m between 16°S and 17°S[11]. At greater depths, the Antarctic Intermediate Water competes with North Pacific Intermediate Water, which results in different mixing flavours around Eastern Equatorial North and South Pacific[12]."

R1: 55-57: This requires a reference

Reply: Since we cannot ultimately prove this statement with data from the literature, we rephrased this sentence to tone it down and added a reference: "Epifaunal *Cibicides* spp. seem to require O_2 for aerobic respiration, since they increase their porosity under O_2 depletion to optimize the uptake of O_2[15]."

R1: 60: to -> too

Reply: In this case we disagree. "…able to denitrify…" should be right and not "…able too denitrify…"

R1: 63-64: "had been assumed that"

Reply: done

R1: 66-68: "depend" doesn't seem quite the right word given this is just the observation of individuals at higher O2. Could this be rephrased?

Reply: rephrased to "seem to prefer O2 respiration"

R1: 68: Is there any information available on the ecology on limbate for comparison?

Reply: We are not aware of any literature data about the ecology of *P. limbata* even after a thorough recherché. The species is not mentioned by Stace Beaulieu in his work on the colonisation of glass sponge stalks in the abyssal NE Pacific. It is recorded as being there in the Marine Life of Costa Rica checklists and it has been reported to occur at the coast of both Americas (https://eol.org/pages/6993703). The preference of the sister species *Planulina ariminensis* to elevated substrates has been mentioned in our manuscript already. Even though affiliation to a certain genus is not a guarantee that all species of that genus pursue the same mode of life, most of them do, as shown by species of the closely related genera *Hanzawaia* and *Cibicides*.

R1: 69: remove comma

Reply: done

R1: 70: as well -> also AND remove comma

Reply: done

R1: 71: at -> in

Reply: rephrased to "from"

R1: 75: remove comma

Reply: done

R1: 76: What is the rationale behind developing a local calibration? If the relationship between PD and O2 is highly spatially variable, would this relationship not also be expected to vary through time?

Reply: The reviewer makes a good point here. Though, we think that a local calibration might still be more accurate compared to a global calibration that statistically shows a wider spread. Another advantage of our new calibration might be that it is species specific which also minimizes vital effects of the different species. Thus we rephrased the sentence to "…our new local and species-specific calibration…". Regarding a variation through time, we respectfully disagree. The pore density is a matter of chemical processes related with the cell physiology, and it has been evolved millions of years ago (Woehle et al., 2022). *Planulina* species showed long ranges in the geological record (Jones, 1994) and no morphological, evolutionary variations that could be used for biostratigraphic adaptations. As such, the above mentioned relationship is regarded as being stable through time, at least since the Pliocene (Kucera and Schönfeld, 2007).

R1: 86: "samples contained"

Reply: done

R1: 87: "model for core"

Reply: done

R1: 86 & 89 & throughout: check for consistency in "planktic" and "planktonic"

Reply: We stayed with "planktic" and removed one "planktonic"

R1: 224: Is it so destructive that shells could not be used even for geochemical analyses?

Reply: The tests are likely still usable for some other analyses. The sentence has therefore been rephrased: "Though, this method is destructive and it is not possible to archive the specimens. Also, the use of the specimens for other analyses might be limited."

R1: 229: "elaboration" isn't quite right. "test of"?

Reply: done

R1: 272: "concentration of preformed"

Reply: done

R1: 278: “change in”

Reply: done

R1: 307-308: Could this be elaborated upon? I am struggling to understand how this observation connects with seasonality. Is the suggestion that limbata are living preferentially in higher O2 seasons? If so, why would this impact only part of the record? Clarification would be helpful.

Reply: This is indeed a peculiar observation. Seasonality in the life cycles of *P. limbata* might be one explanation for this phenomenon. For example, it could be that *P. limbata's* reproduction is coupled to the main upwelling season, hence periods of high food availability. In this case, it would record lower O2 concentrations than the annual mean. This is only a hypothesis, though, and we are in strong need of further ecological studies on the key species that we use as archives in our paleorecords. Actually, reviewer 2 came up with an excellent idea, how this data could be explained as well. We extended the discussion about this aspect in our revised manuscript accordingly:

“This might be related to seasonality in the life cycle of *P. limbata*. If the reproduction of *P. limbata* is coupled to the main upwelling season, the PD likely records the lower $[O_2]_{BW}$ during that season. It also might be possible that foraminifera adapt their pore density to the lowest seasonal $[O_2]$ they experience. The higher O_2 pulses would not matter in that case, since the foraminifera are already adapted to withstand even lower $[O_2]$. The lowest modern $[O_2]_{BW}$, documented close to the coring sites (M77/1-416/GC-4 and M77/1 406-MUC6) was ~1 µmol/kg, which is below the range of reconstructed $[O_2]_{BW}$ using the PD proxy. This might indicate that the seasonally lowest $[O_2]_{BW}$ continued to decrease during the LH. A recent study offered an alternative hypothesis: Belangers (2022) found that the adult morphology of benthic foraminifera might already be predetermined by the environmental conditions that the individual experiences during the embryonic state[61]. If this applies to the foraminiferal PD as well, it would corroborate that *P. limbata´*s life cycle is coupled to the main upwelling season and that the PD is consequently adapted to lower $[O_2]_{BW}$ than the annual mean. Another explanation for the fact that the highly variable modern $[O_2]_{BW}$ sometimes exceeds the range of our paleorecord could be an observation that bottom waters at the Peruvian shelf became more oxygenated over the last ~100 yr[62]. “

R1: Figure 5: This figure would be more legible with some of the white space between intervals removed and data expanded horizontally. I’d recommend removing ~4-15 kyr from the x axis and replacing with a clearly visible axis break. Alternately, the two intervals could be shown in adjacent panels with a shared y axis.

Reply: done. X-axis has been broken from 3-17 kyr BP.

Reviewer #2 (Remarks to the Author):

R2: The study investigates the possible use of foraminifera pore density as proxy for bottom water oxygen concentration during LGM and late Holocene in the Peruvian OMZ region. Oxygen past reconstruction is crucial in the current context of global oceanic deoxygenation.
The authors compare different methodologies to measure the pore density on the shell of foraminifera specimens using an optic microscope. Then, they calibrate modern bottom water oxygen concentrations with pore density of modern specimens from different locations along an oxygen concentration gradient. Using long sediment records on which age models were determined, the authors reconstruct the past bottom water oxygen concentrations using pore density of foraminifera shell following the former calibration. Results are coherent with other studies investigating past oxygen concentrations in the bottom water in this region (but at other periods), arguing for a decrease in oxygenation between LGM and late Holocene. Authors then explore the reasons for this decrease, contrasting with other oceanic regions.

I found the manuscript clear, straightforward, and well written. I think that data acquisition and statistical treatment procedures are suited for the purpose of the study, and that the study is a significant advancement in the field of past oxygen concentrations reconstruction. This work will be of interest for the community interested in foraminifera and their use as proxy, but also to all researchers interested in past climate reconstruction. For these reasons, I think this work is worth publishing in Communications Earth & Environment.

Reply: We thank the reviewer for this very detailed and constructive review and appreciate the positive feedback on our manuscript. We are especially grateful about the suggestions regarding the discussion about the variability of modern [O2]BW and the possibility that *P. limbata* might adapt its pore density to the lowest oxygen concentrations it experiences and not to elevated concentrations during certain seasons. We included these ideas into our discussion.

R2: I have few comments and suggestions about the study, listed in detail below and also in the pdf file attached. Briefly, I suggest moving the first part of the section line 142 ("Downcore [O2]BW reconstruction using the pore density epifaunal P. limbate") to the method section.

Reply: The reviewer is completely right that the description of the propagation of uncertainty is purely methodological. We therefore moved the part 145-159 to a new chapter in the methods section. The rest of this paragraph already presents some results. So we decided to keep lines 143-145 and 160-166 in the results section.

R2: I also suggest few ideas, but I let the author choose if it might be interesting or not to discuss it in their manuscript, especially about two things that could impact the proxy used:
- Shell thickness, which is greater in oldest chambers (if I am right?), hampering passive oxygen diffusion through pores. This questions the efficiency of oxygen uptake in the oldest chambers compared to the newest ones, and the benefit to include these chambers in the calculus of PD (for proxy purpose). Exclusion of the youngest chambers (done in method #4 if total area was higher than 700 000 µm2) that are usually the biggest ones and showing the highest porosity. Since they seem should play a major role in oxygen uptake, building a proxy ignoring them is questionable. On the other hand, I understand why the authors proceed this way: significant ontogenetic effect might be problematic in the calibration and further use of such proxy.

Reply: The reviewer made a good point. Though, even if diffusion might be hampered by the increasing wall thickness of the older chambers, pores often show a larger diameter in the older parts of the test, which again might improve diffusion. Also, it has to be considered that the old parts of the test were once young. We agree that using the ultimate chamber might record the latest oxygen concentration that the individual experienced during its ontogenesis. Contrastingly, using a normalized part of the older part of the test most likely records the average concentrations during most of the individuals lifetime. In our opinion it is necessary to focus on a normalized part of the older test to minimize ontogenetic effects. If the analyses would focus on the ultimate or penultimate chambers, it would be also possible to minimize ontogenetic effects by just using individuals of the same size only. This might not be feasible, since the number of individuals is limited in a given sample. We also would like to address the new study of Belangers (2022). The results suggest that the final morphology of a foraminiferal test is predetermined by the first environmental conditions it experienced during the embryonic state. If this is true, the pore density (even in the ultimate chamber) would record the first and not the last oxygen concentration that the individual experienced. We included this aspect into the discussion of our manuscript (see above in the answer to reviewer #1)

R2: The idea that foraminifera PD (and by extension porosity) tracks the lowest oxygen concentrations in the bottom water allowing individuals to survive instead of an "averaged" [O2]BW. This would argue in favour of the fact that bottom water oxygen concentrations at the Peruvian shelf have continued to decrease until today. However, this process might only be accurate if youngest chambers (the ones that theoretically represent the compromise between improving oxygen uptake

by increasing porosity and assuring mechanic integrity of the shell by limiting porosity increase) are considered in the proxy calibration.

Reply: The idea that the pore density is adapted to the lowest O2 concentrations that the specimen experiences is very interesting and we added this into our discussion. It is now discussed together with the Belangers (2022) results, which we mentioned above.

R2: I would like to inform the editor that I am not comfortable with the age model determination since it is out of my field of expertise. For this reason, I cannot fully assess the quality of this part in the manuscript.
I recommend minor revisions for this manuscript since my suggestions and comments are not going against the interpretations of results and the conclusions of the study.
Because it is not double anonymised, I require my name to be attached to this review.
Julien Richirt

Comments and suggestions

Abstract

Line 16: “mbss” or “mbs” later in the manuscript on line 144, 250, 253, 254, 256, and Figure 1 caption line 550 & 646. Please if you mean something different precise it or homogenise the spelling.

Reply: We changed everything to “mbss”, done.

R2: Introduction

Lines 54-55: “species-specific” or “species specific”. Homogenise in the manuscript if needed. I think you mean that the responses of foraminifera to different environmental factors are species-specific. I am not sure you can say that environmental factors are species-specific. Reformulate please.

Reply: We changed to “species specific” along the manuscript and rephrased the sentence to “In addition, the factors that influence the porosity of benthic foraminifera also appear to vary between different species.”

R2: Lines 57-58: Please be more specific about what pore characteristic B. spissa adapt to nitrate concentrations.

Reply: done. Changed to “pore density”.

R2: Line 69: Please change “porosity” for “pore density” on line 69. If I understood correctly you test for pore density (PD, pore number per unit of surface) in your study, and not porosity (area covered occupied by pores in %) since you state line 181-183: “This is a good option for high resolution SEM images but our study is based on light micrographs that do not have a resolution allowing to accurately determine the pore area. Thus, we focused on the PD instead”. Please change accordingly through the manuscript, since depending on the species, pore density and porosity might be negatively correlated.

Reply: done

R2: Methods
Lines 336-338: Is there a specific reason why you used this mesh size to sieve? How did you check that the specimens you used for the modern calibration (only the top layer of the small cores) were alive when you picked them and not dead or transported from elsewhere?

Reply: This is a problem indeed for species that live on elevated substrates such as stones or worm tubes. *Planulina limbata* is found in the Peruvian OMZ only at water depths between ~450 and 1000 mbss. Sessile megafauna and larger phosphorite nodules start to appear at these depths. We did several studies on living foraminiferal faunas in the Peruvian OMZ (Mallon et al., 2012; Erdem et al. 2020). We did not find any living (rose Bengal stained) specimens of P. limbata in our samples

although dead, empty tests are very frequent. The only living specimen of P. limbata that I saw by myself was attached to a phosphorite nodule with a diameter of ~ 5 cm.

It is the same with Cibicides species. I recently took samples from the Mid Atlantic Ridge and living Cibicides were very rare, except in a sample where they were attached to a sessile, 5-cm large xenophyophore. Rathburn et al. (2018) found living Cibicides spp. for their calibration but those were also mainly attached to elevated substrates (stones). We cannot be sure whether the specimens we used for our calibration were not redeposited at all. However, we used only the most pristine individuals we found. In addition, we used up to 10 specimens per sample to minimize the influence of individual specimens that might have been transported.

R2: Lines 364-366: "Due to the low number of specimens in the depths 5.5 cm, 7 cm and 9 cm, we decided to pool the specimens to one datapoint in fig. 5." What calibrated age did you choose for these specimens, an average of the 3 samples? Please specify in the text.

Reply: We used the average depth of these samples to calculate the age (7.6 cm). Added the following sentence "The average depth (7.6 cm) was used to calculate the age of this data point."

R2: Results

I consider that lines 143-166 are rather method description than results. Consequently, this part should be moved to the Methods section.

Reply: The reviewer is completely right that the description of the propagation of uncertainty is purely methodologic. We therefore moved the part 149-159 to a new chapter in the methods section. The rest of this paragraph already presents some results. So we dicided to keep 143-148 and 160-166 in the results section.

R2: Lines 138-141: You state "In addition, the variability of the PD after method #1 was very high at station M77/1-459/MUC-25, which had the highest [O2]BW and the uncertainties of the regressions are also relatively high (Fig. 4C)." For station M77/1-459/MUC-25, you measured 2 specimens only, which is too few to describe variability or uncertainty for a regression in my opinion. I suggest removing this statement since the highest correlation (coupled with its significance) for method #4 using all specimens from all stations is convincing enough that this is the method to use in your case.

Reply: We removed the respective sentence.

R2: Lines 145-147: You state "Since method #4 showed the best correlation between PD and [O2]BW, we mainly used this method for the downcore reconstructions." Later in the manuscript you state on lines 379-380 "All four methods have been applied to the core top samples and only method #4 was used for the downcore PD analyses in M77/1 416-GC4 and M77/1 406-MUC6." Please precise if you mainly or only used the method #4 for downcore reconstructions.

Reply: We specified this accordingly: "All four methods have been applied to the core top samples and mainly method #4 was used for the downcore PD analyses in M77/1 416-GC4 and M77/1 406-MUC6. Only for one downcore data point we used method #3, since the specimens were too small for the size normalization (see tab. 4)."

R2: Line 168: If this is equivalent to a Welch's T test, then change "heteroscedastic Student's T-test" by "Welch's T-test".

Reply: indeed that´s the same test. We changed it to "Welch´s T-test"

R2: Discussion

Line 236: Change "porosity" by "pore density" please.

Reply: We are not really sure, which sentence the reviewer is referring to, since "porosity" was not mentioned in line 236.

R2: Lines 268-270: I have difficulties to understand this sentence. Is it the lower Fe burial that is due to a decrease in sediment deposition and increased erosion? Please rephrase more clearly.

Reply: we understand that the phrasing was somehow confusing. We deleted "… the lower Fe burial…" for clarification.

R2: Lines 266-267: unclear: is oxygen concentrations higher in intermediate water masses?

Reply: OMZs typically develop in areas where nutrient rich shallow to intermediate waters are upwelled. This fuels primary productivity and remineralisation of the exported organic matter draws down the oxygen at depth. The source waters for this are typically formed at high latitudes (for example Antarctic Intermediate Water in the Southern Ocean). Those are typically a higher in [O2], since they are relatively young water masses. This might be too detailed for the discussion of the paper and, thus, we would only like to refer to references in this sentence.

R2: Lines 271-272: "pre-formed" or "preformed", homogenise spelling.

Reply: done

R2: Lines 307-308: "This might be related to seasonality in the life cycle of P. limbata." In what way? Could it be also related to a possible different respiration pathway in this species? Below a certain oxygen concentration, the species might shift to alternative electron acceptor (nitrate for example?). Additionally, could oxygen uptake though pseudopods occur when they are extruded? Could this represent an active and easy way for foraminifera to finely adjust their ability to uptake oxygen.

Reply: We refer to our answer to reviewer 1 who also gave a similar comment (see above).

Regarding the comment for alternative respiration pathways we added the following sentence into our revised manuscript: "We cannot exclude, though, that *P. limbata* as well as other *Planulina* and *Cibicides spp.* might be able to switch to denitrification under severe O_2 depletion. Several *Cibicides spp.* cluster in the phylogenetic tree close to foraminiferal species that are known to denitrify[30].

Regarding the comment with the pseudopodia: There are earlier observations showing mitochondria in the pseudopodia of some species. The idea Reviewer 2 mentioned therefore may be right. I would like to mention here some observations I made on denitrifying bolivinids: They often have "pore plates" covering the pores in the younger chambers. In the old chambers the pore plates are perforated. I would hypothesize that they might fill their demand for nitrate in the young chambers mainly through seawater vacuolization, while they take up nitrate through the pores in the older chambers. Could it be that this is similar for *P. limbata*? They take up O_2 via pseudopodial network for the younger part of their tests, while they sustain the cytoplasm in the older parts of the test through the pores? This is just a hypothesis and we definitely need more studies related to this topic!

R2: Lines 308-310: "Another explanation for this phenomenon could be an observation that bottom waters at the Peruvian shelf became more oxygenated over the last ~100 yr."
Alternatively:
- If we assume that PD is related to oxygen content with a negative correlation.
- Increasing PD is assumed to be an adaptation to better cope with low oxygen concentration.
This means that foraminifera adapt their PD regarding the lowest oxygen concentrations they have to cope with (why would they increase PD further if not needed?).
- This implies that PD might be correlated with the lowest oxygen concentrations specimens are exposed to, instead of an average oxygen concentration value (kind of threshold effect, below this value of oxygen concentration the foraminifera cannot cope, above -during pulses- it can survive).
- The modern lowest oxygen concentrations recorded are about 1 µmol/kg in the region. This value is below the oxygen concentration values indicated by the proxy using foraminiferal PD.
This would argue for a continuous decrease of the lowest oxygen concentrations occurring in the region during LH.

Reply: We thank the reviewer for this idea and added this hypothesis to out discussion! Reviewer 1 also commented about this, so we extended the text in the discussion about this part in our revised manuscript (see above).

R2: References

Line 445: correct ref. 28

Reply: done

R2: Figures & Tables
Line 574, 583 and 623: I was confused by the use of SEM acronym for 2 different things (Standard Error of the Mean and Scanning Electron Microscope lines 181, 345 and 347). I suggest changing one of the 2 acronyms to avoid confusion for the reader.

Reply: Since we did not use SEM so often for scanning electron microscope, we avoided to abbreviate this.

R2: Figure 1: I suspect the black square in the top right panel to be a little shifted north compared to the biggest map panel

Reply: Yes, the reviewer is right. The black box accidently shifted slightly. This is now corrected.

R2: Figure 5: in the caption you state "Since only two specimens were found in one sample each individual reconstructed $[O_2]_{BW}$ instead of mean values were plotted as grey crosses." It is unclear, which sample?

Reply: Added into brackets ("4.5 cm")

R2: On the figure itself: I suggest making a discontinuous x axis by removing the period between 4 and 14 kyr BP. It would make the data easier to read and avoid a figure where 70% is blank. Alternatively, I understand that the authors made the choice to keep continuous x axis to keep time scale coherent for the reader.

Reply: We added an axis break from 3 to 17 kyr BP (see above).

Reviewer #3 (Remarks to the Author):

R3: Glock et al evaluate and expand upon the foraminiferal pore-density oxygenation proxy and apply it back in time to a core collected from the Peruvian margin. It can often be difficult to unravel the effects of productivity and oxygenation on our traditional oxygenation proxies, yet records of oxygenation can give us key insight on past changes in deep-ocean respired carbon storage and shallow-ocean OMZ expansion. However, we tend to have few studies that actually take the time to evaluate and improve upon our methods in a clear and practical way as was done in this study. This study is a great introduction to the pore-density proxy that will be of immense value to others who would like to apply this proxy to their own research areas.

Reply: We thank the reviewer for the positive feedback. When writing this paper, we were hesitant to combine a strongly methodological paper with a paleoceanographic results and a detailed paleoceanographic discussion. We are pleased to hear that all reviewers appreciated this approach.
R3: I have no major issues with the methods or results in this study, but I think it could use some revision for clarity and some expanded discussion. As I was reading, it felt like I sometimes had to go back and forth to different sections in the paper because parts of one idea were split across sections resulting in things being repeated in some spots and left out of others. It would help to bring these ideas together in one place. Specifically, I noticed this when it came to an explanation of the different pore density methods. The methods are described in the results, the discussion, and again in the methods section. It would clarify things if you bring these different pieces together in one section focused on describing in detail the four different methods. I think this portion of the paper is

extremely valuable, and if we want to get more people to try out these methods and apply this proxy then you want to make it as easy to follow as possible.

Here's my suggestion for reorganizing the PD methods (take it or leave it). Before the section you have comparing the four different methods add a section describing the four pore density methods in detail (include figure 3), the pros and cons of each method, how to do the method, the practicalities etc. Move the methodological recommendations you have later in the paper up to this section. You could also add an additional summary chart of the pros and cons of each method, that would be a great way to reinforce the info quickly and clearly. I also think your current description of methodological recommendations can probably be edited down a bit, it starts to get a bit verbose in some spots. This might be a great section to take advantage of things like bullet points or numbering or charts to show the information more clearly.

Reply: We completely understand this point of critique, which might actually the related to the fact, that we combined the methodological paper directly with the application of the method. Otherwise the sections would be closer to each other. We followed the suggestion of the reviewer and moved the whole part that described the four approaches to determine the pore density from the methods section at the end of the manuscript before the section that describes the results of the different approaches. We then deleted some redundancies in the part that described the results. We hope that the editor appreciates this change, although now a significant methodological part is presented in the results section.

Though, we hesitate to move the whole discussion about methodological recommendations also into this part of the paper. This would be different, if the paper would be organized with a combined "results and discussion" section. As it is at the moment, this part would dominate the whole paper and take weight and value from the other results of our study.

R3: I really enjoyed reading your core stratigraphy section. You were working with very challenging core material but did a great job breaking down each of the challenges you faced and explaining how you tackled those challenges and the caveats that come with dealing with imperfect core material. One small thought about your stratigraphic methods- Could you use the reservoir ages from the peru-chile transect of Martínez-Fontaine et al. (2019) rather than Bova et al? Or are they perhaps less suitable? Either way this is nothing that would affect your results, I was just curious why you chose the reservoir ages that you chose. I found this section to be very well researched and explained.

Reply: Yes, it was challenging only to find benthic foraminifera in our samples and even being forced to use sedimentary organic matter for radiocarbon datings. The only reason why we have chosen the core from Bova et al. for comparison was the fact that this was the only one with published benthic-planktic offsets from our study area off Peru. We are aware, though, that their core was taken at greater depth and further north. The Martínez-Fontaine et al. cores would have been an alternative but they are located off Chile and even further away from our study sites.

R3: The downcore O2 reconstruction section seems to be a mix of methods and results, it might be worth splitting these up a bit.

Reply: This was already addressed by reviewer 2. We moved the whole part about the error propagation into the methods section (see above).

R3: The section on deoxygenation reads a bit like a results section with some added literature review, but I would have liked to see more discussion in this section. The other sections have proven your expertise, so when I got to this section I was eager to hear more about why these results are interesting and important. Expand upon the big-picture implications of a well oxygenated glacial eastern tropical Pacific.

Reply: We agree that it is important to expand upon a bigger picture and we added a paragraph

where we discussed the implications of a well oxygenated, glacial Eastern Tropical Pacific as follows. Actually, we turned the discussion around to "the implications of ocean deoxygenation from the cold Glacial to the warm LH:

"The observation that the Peruvian OMZ was more oxygenated during the LGM in comparison to the Holocene and modern conditions (Fig. 6) is in line with recent observations of on-going ocean deoxygenation and OMZ expansion related to global warming[1,2]. The Peruvian OMZ is at present in a highly productive state the abundance of anchovies actually increased over the past ~1 kyr, following the trend for other proxies for subsurface ocean deoxygenation[16] and our own data (fig. 5). The optimum in anchovy production off Peru during the modern warm period is related to the enhanced nutrient supply that increases primary productivity and the related preferential development of large plankton[16]. Although the current warm period seems to be favourable for the Peruvian anchovy population and the related commercial fishery, some periods during the LH that are characterized by a very intense OMZ are disadvantageous for anchovy populations[16]. Indeed, there is evidence that smaller goby like fish species dominated the Peruvian upwelling region in a very warm and severely O_2 depleted phase during the Eemian[63]. Ocean deoxygenation will likely continue under the current trend of global warming and indeed anchovy biomass steadily decreased again during the past decades[2,63]. Thus, there is a high risk that the ecosystem at the Peruvian upwelling region reaches a tipping point for the fish community. This might potentially result in jellyfish outbreaks leading to a trophic dead end, as observed in other ecosystems where fisheries have collapsed, such as the Benguela Upwelling[64]. Our results indicate deoxygenation at the Peruvian OMZ from the cold LGM to the warm LH, and the current warm period and thus provide further evidence for concerns related to the foreseeable future ocean deoxygenation."

In addition, we added a sentence that addresses the implications that the Peruvian OMZ did not vertically shift, such as the OMZ in the Eastern Equatorial Pacific:

"We found no evidence for a severe vertical shift of the Peruvian OMZ over the last deglaciation which might have connected intermediate to deep reservoirs of old carbon to the atmosphere as it has been observed for the Eastern Equatorial Pacific[55]."

R3: Methods: How many forams do you use for each sample? What is a good representative number?

Reply: We added the following sentence to the methods: "We used 10 – 12 specimens for the core top PD vs. $[O_2]_{BW}$ calibrations except in core M77/1-459/MUC-25, where only two well-preserved specimens of *P. limbata* were available. For the downcore PD record, we used an average of five *P. limbata* specimens."

R3: Table 1: It was a bit hard to tell which names were italicized. Maybe draw a line between the coretops and long cores?

Reply: done

R3: Tables 2-4 could maybe be shifted to supplemental information.

Reply: We respectfully disagree. Data transparency is a major concern and presenting the tables in the main text makes them much better visible and easier accessible. The readers would not have to switch between supplements and main text to find the relevant data. Thus, we would prefer to keep the tables in the main text.

R3: Figure 1: Add the location of the bova core to the inset map

Reply: done

R3: Figure 2: It might be worth expanding the x-axis on the top figure to match the bottom figure.

The error initially looks a bit alarming compared to the lower figure, but it's just a function of the axes.

Reply: done

R3: Figure 4: Add the species to the legend in A.

Reply: We added the species name into the figure caption and specified that the data of Rathburn et al. is from mixed epibenthic species.

R3: Add labels to the photographs in B to indicate the high and low PD specimens.

Reply: We specified in the figure caption that the left specimen has the high porosity and the right specimen has the low porosity.

R3: Shouldn't oxygen go on the x-axis because it's the independent variable? Also, why is the error on the >12 umol/kg method 1 PD so high?

Reply: We decided to show the pore density on the x-axis because like this we can show the equation of the correlation with oxygen as the dependent variable. Then, oxygen can easily be calculated from the pore density for paleo-reconstructions without the need to transform the equation. The >12 µmol/kg PD error for method 1 is so high, because the pore density in the ultimate chamber of the specimens in this sample was very different between the individuals.

References added by Joachim

Jones, R.W., 1994. The Challenger Foraminifera. The Natural History Museum. Oxford University Press, London.

Kucera, M., Schönfeld, J., 2007. The origin of modern oceanic foraminiferal fauna and Neogene climate change. In: Williams, M., Haywood, A.M., Gregory, J., Schmidt, D.N. (eds.), Deep-Time Perspectives on Climate Change: Marrying the Signal from Computer Models and Biological Proxies. The Micropalaeontology Society Special Publications. The Geological Society, London, 409-425.

Woehle, C. Roy, A.S., Glock, N., Michels, J., Wein, T., Weissenbach, J., Romero, D., Hiebenthal, C., Gorb, S.N., Schönfeld, J., Dagan, T., 2022. Denitrification in foraminifera has ancient origins and is complemented by associated bacteria. PNAS, 119, No. 25, e2200198119, 11 pp., doi: 10.1073/pnas.2200198119.

14th Oct 22

Dear Dr Glock,

Your manuscript titled "Foraminiferal pore densities reveal similar but weaker Peruvian oxygen minimum zone during Last Glacial Maximum" has now been seen by our reviewers, whose comments appear below. In light of their advice I am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

Please note that it may still be possible for your paper to be published before the end of 2022, but in order to do this we will need you to address these points as quickly as possible so that we can move forward with your paper.

EDITORIAL REQUESTS:

Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table". Please outline your response to each request in the right hand column. Please upload the completed table with your manuscript files as a Related Manuscript file.

If you have any questions or concerns about any of our requests, please do not hesitate to contact me.

SUBMISSION INFORMATION:

In order to accept your paper, we require the files listed at the end of the Editorial Requests Table; the list of required files is also available at https://www.nature.com/documents/commsj-file-checklist.pdf .

OPEN ACCESS:

Communications Earth & Environment is a fully open access journal. Articles are made freely accessible on publication under a CC BY license (Creative Commons Attribution 4.0 International License). This license allows maximum dissemination and re-use of open access materials and is preferred by many research funding bodies.

For further information about article processing charges, open access funding, and advice and support from Nature Research, please visit https://www.nature.com/commsenv/article-processing-charges

At acceptance, you will be provided with instructions for completing this CC BY license on behalf of all authors. This grants us the necessary permissions to publish your paper. Additionally, you will be

asked to declare that all required third party permissions have been obtained, and to provide billing information in order to pay the article-processing charge (APC).

Please use the following link to submit the above items:
[link redacted]
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Alienor Lavergne, PhD
Associate Editor
Communications Earth & Environment

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Thank you for providing a thorough response to all reviewer comments. I look forward to seeing this manuscript published.

One minor comment is that on line 361 the author's name should be "Belanger" (no 's').

Reviewer #2 (Remarks to the Author):

Since the authors answered clearly to all comments and adapted the manuscript accordingly, I have no further remarks and support publication in Communications earth & environment.

Julien Richirt

Reviewer #3 (Remarks to the Author):

The authors have done a nice job addressing all of my comments. I have no further comments to add.

Below you can find the reviewers´ comments to our manuscript. As you can see, there was only one minor remaining comment regarding an author name in a citation. We corrected the name in the revised manuscript. Otherwise, we followed all the editorial requests for our paper. A point by point response can be found in the editorial requests table.

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Thank you for providing a thorough response to all reviewer comments. I look forward to seeing this manuscript published.

One minor comment is that on line 361 the author's name should be "Belanger" (no 's').

Reviewer #2 (Remarks to the Author):

Since the authors answered clearly to all comments and adapted the manuscript accordingly, I have no further remarks and support publication in Communications earth & environment.

Julien Richirt

Reviewer #3 (Remarks to the Author):

The authors have done a nice job addressing all of my comments. I have no further comments to add.