A synthesis of Cenozoic paleoceanographic proxies for seawater oxygenation

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Bergen, Norway, 3 September 2022

Workshop motivation and aim
Deoxygenation is a pressing problem in the world's oceans, impacting global biogeochemical cycles and marine ecosystems. Oxygen time series only span decades (a maximum of ~60 years at their longest), and touch upon a small subset of at-risk ecosystems. The use of paleo-oxygen proxies allows us to explore long-term oxygen trends, including the scope of natural variability and response to warming, and ultimately to inform model simulations and projections.

While interest in paleo-oxygen reconstructions has been rapidly growing, our current proxy landscape often poses limitations. There are multiple established and emergent proxies available, but their scope, limitations, and relation to one another are often poorly constrained.

The aim of the PLO2P (Proxies for Low Oxygen Paleoenvironments) Workshop in Bergen, Norway, in September 2022 (pastglobalchanges.org/calendar/128968), was to convene and build a community of scientists working on paleo-oxygen proxies to begin to address these limitations in a way that was accessible to the larger paleoceanographic community, and collectively map a way forward. Together we decided to begin a review of the state-of-the-art in established and emergent Cenozoic paleoceanographic proxies used for assessing seawater oxygen concentrations.

Workshop structure
The workshop was held in a hybrid mode to allow for broader participation, with a total of 33 participants. Hybrid mode was particularly useful because some in-person participants had to self-isolate due to COVID-19, but were still able to access the meeting from their conference accommodation. There was a focus on inclusion of early-career researchers (ECRs) actively working with paleo-oxygenation proxies. In total, 19 ECRs attended the workshop, and were also well-represented among the organizing committee (Dharma Reyes Macaya, Katrina Nilsson-Kerr, Jorge Cardich). Five ECRs received funding from PAGES to support their in-person participation at the workshop.

Following introductions, participants joined two (a morning and an afternoon) breakout sessions, based on the proxies they wished to focus on (see Figure 1 for a schematic). Established proxies for oxygen reconstructions include sedimentary features, like laminations, planktic and benthic foraminifera

assemblages, sedimentary redox trace elements, and bulk nitrogen isotopes. Emerging paleo-oxygen proxies include the morphology of benthic and planktic foraminifera, benthic foraminifera carbon isotope gradients, benthic and planktic foraminifera trace elements, planktic foraminifera bound nitrogen isotopes, and biomarkers. Many of the proxies may be used for bottom or pore water oxygenations, but, increasingly, proxies are being developed to reconstruct water column oxygen concentrations. Multiple experts on each proxy type were invited to lead and moderate the breakout group sessions. Every section was tasked with identifying recent developments, limitations, and current questions of their proxy type. For example, several sessions identified the need to reconcile proxies developed in

restricted basins, with open ocean settings, and vice versa.

Outcomes
The group identified several areas for development. Most proxies are currently only applicable to very low oxygen environments. Moreover, most proxies are qualitative rather than quantitative in nature, but steps are being taken to develop proxies more quantitatively and provide error assessments. The group concluded that more robust assessment of past seawater oxygen concentrations require multi-proxy analyses.

We are formalising our review in a paper using the framework established in the workshop (submission to *Biogeosciences* in August 2023). That review is now well underway, and the number of contributing authors has increased to include authors beyond the initial workshop participants who are experts on some of the proxies included in the review. The review will include descriptions of use and recommendations for best practices by proxy type, guiding those wishing to use paleo-oxygen proxies, and a roadmap for continuing expansion of this field.

Finally, we introduced the idea of forming a working group during the workshop, and are actively working on a PAGES working group proposal for past seawater oxygen assessments through paleoceanographic reconstructions and modeling.

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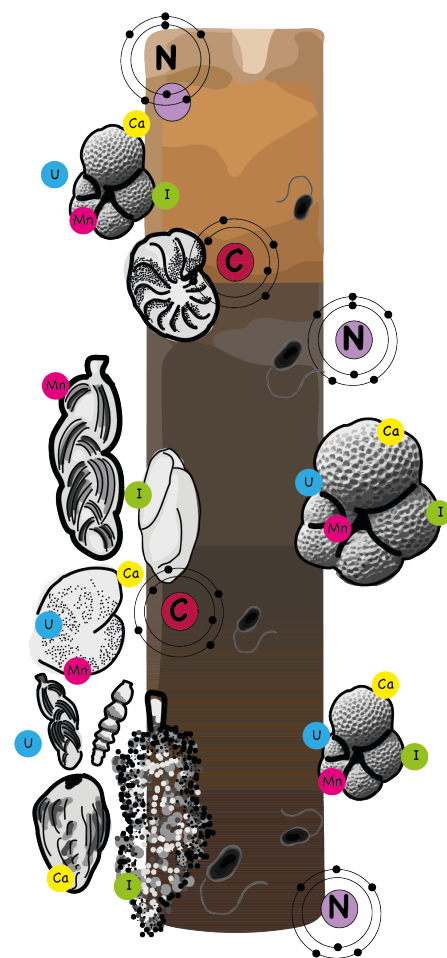
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Figure 1: Schematic illustration, made by Katrina Nilsson-Kerr, featuring the various paleo-oxygen proxies within a marine sediment core that were discussed during the meeting and will be covered in the review paper.