Environmental Controls on the Earliest Animal Ecosystems

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Introduction

- The Cambrian Explosion was an event that occurred in the early Cambrian Period, ~540 Mya, and is marked by the rapid rise and diversification of metazoa.
- The traditional interpretation of this event is that marine oxygen levels approached modern values for the first time, allowing animals to colonize the ocean depths.
- However, recent geochemical work suggests a new interpretation: that the oceans remained primarily anoxic through the Cambrian, Ordovician, Silurian, and into the Devonian.

Model 1: First, then…
lots of oxygen → lots of animals

Model 2: Stepwise
Some oxygen → some animals → more oxygen → more animals

Fig.1. Artist's rendering of environment preserved by the Burgess Shale. Representatives of most modern phyla can be traced to the time of the Cambrian Explosion. Credit: John Sibbick

Can we find evidence that oxygen levels limited the spatial occurrence of animals during their early evolution?

Background

The Mt. Isa-1 drill core from the Georgina Basin in Australia intersects well preserved shallow marine sedimentary units from the mid-Cambrian, ~ 510 Ma.

- Currant Bush Limestone
- Inca Formation
- Thorntonia Limestone

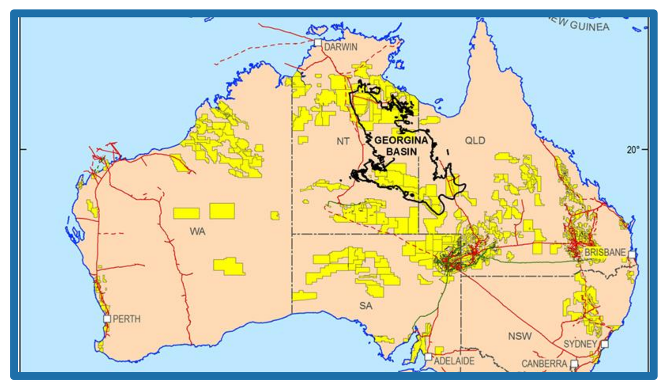


Fig.2. Map of Australia showing location of the Georgina Basin, where the Mt. Isa drill core was obtained. Source: Geoscience Australia

This core was previously studied by Pages et al., who analyzed organic biomarkers at low stratigraphic resolution. They concluded that the environment was predominantly anoxic and identified two potential intervals of photic zone euxinia.

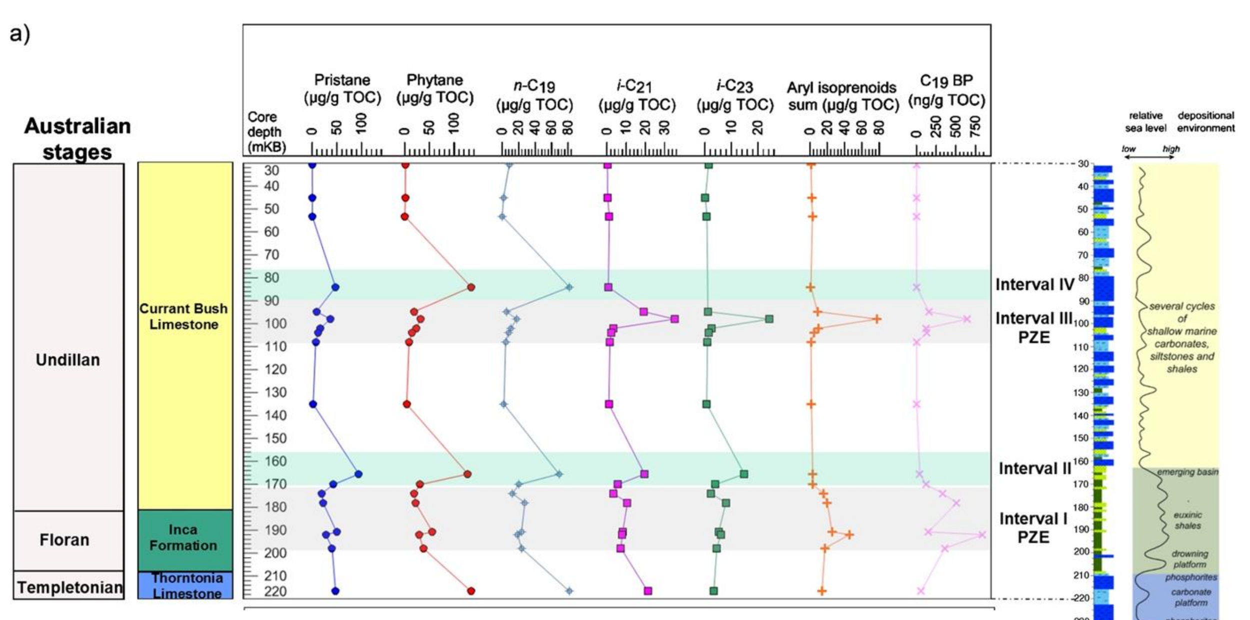
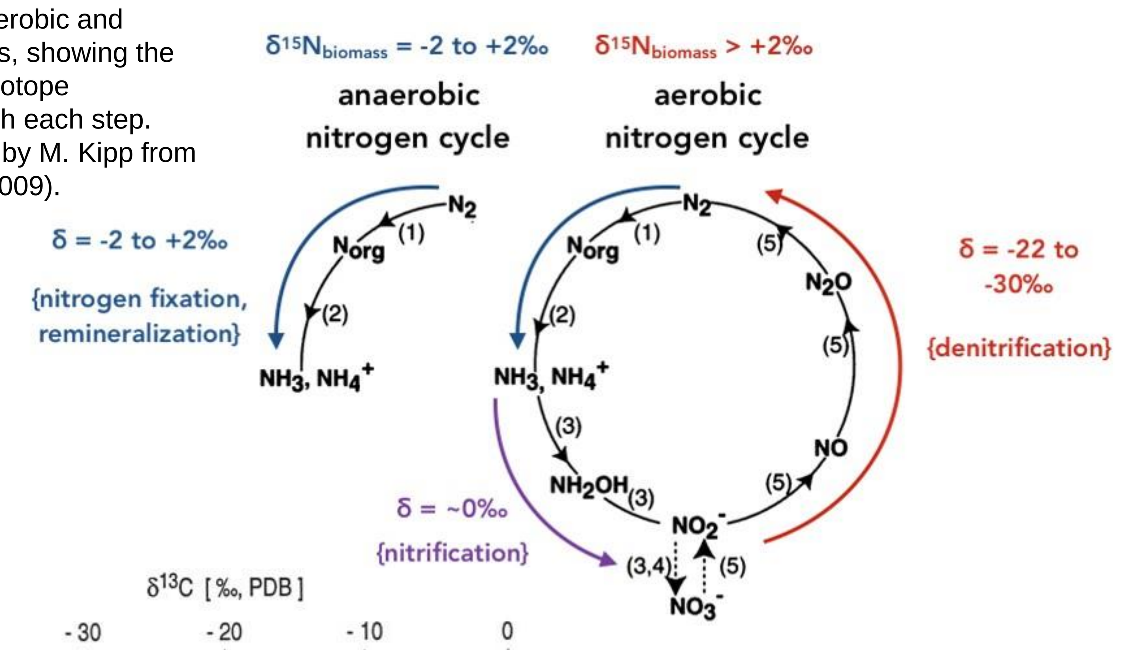


Fig.3. Figure from Pages et al., (2016). Photic zone euxinia (PZE) intervals, marked in grey, imply strongly anoxic and sulfidic surface waters. These were identified by aryl isoprenoid peaks. Aryl isoprenoids are organic biomarkers from the membranes of anaerobic photosynthetic sulfur bacteria. Due to their dependence on sulfur and light they are a strong indicator of PZE.

Methods

- In the UW IsoLab we measured organic carbon and bulk nitrogen isotope ratios as environmental proxies to reconstruct paleo-redox conditions using an isotope ratio mass spectrometer and elemental analyzer. We also measured the C/N ratio the total organic carbon.
- Isotope fractionation occurs due to enzyme preference, typically for lighter isotopes, in biochemical pathways. For nitrogen, atmospheric N_2 is the standard. Anaerobic N fixation results in biomass with a δ^{15}N of -2 ‰ to 2 ‰. The aerobic N cycle has a significant fractionation due to the denitrification step, which causes the NO_3^- to become enriched with the heavier isotope.
- For carbon, a marine carbonate is the standard, therefore inorganic C has a δ^{13}C of approximately 0‰. Most organisms have a slight preference for light C, resulting in slightly negative δ^{13}C values. Values greater than -35‰ are typical of methanogenesis, while extreme negative values indicate methanotrophy.
- Our collaborators at The Australian National University, Jordan Kinsley and Jochen Brocks, are characterizing biological community and environmental conditions using organic biomarkers.

Fig. 4. The anaerobic and aerobic N cycles, showing the differences in isotope fractionation with each step. Figure adapted by M. Kipp from Garvin et al., (2009).



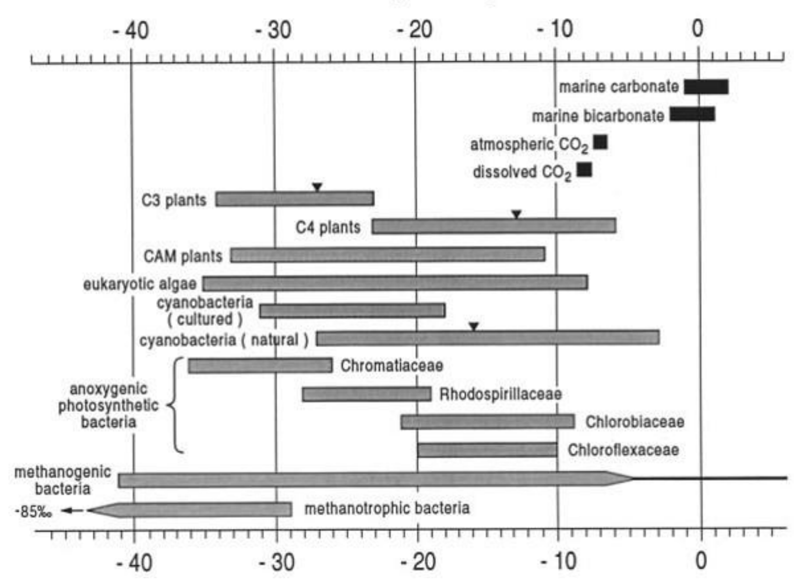


Fig. 5. The δ^{13}C for various sources, including both organic and inorganic carbon. Values more negative than - 20 ‰ is typically needed to clearly identify a biological signal. From Schidlowski, (2001).

Results

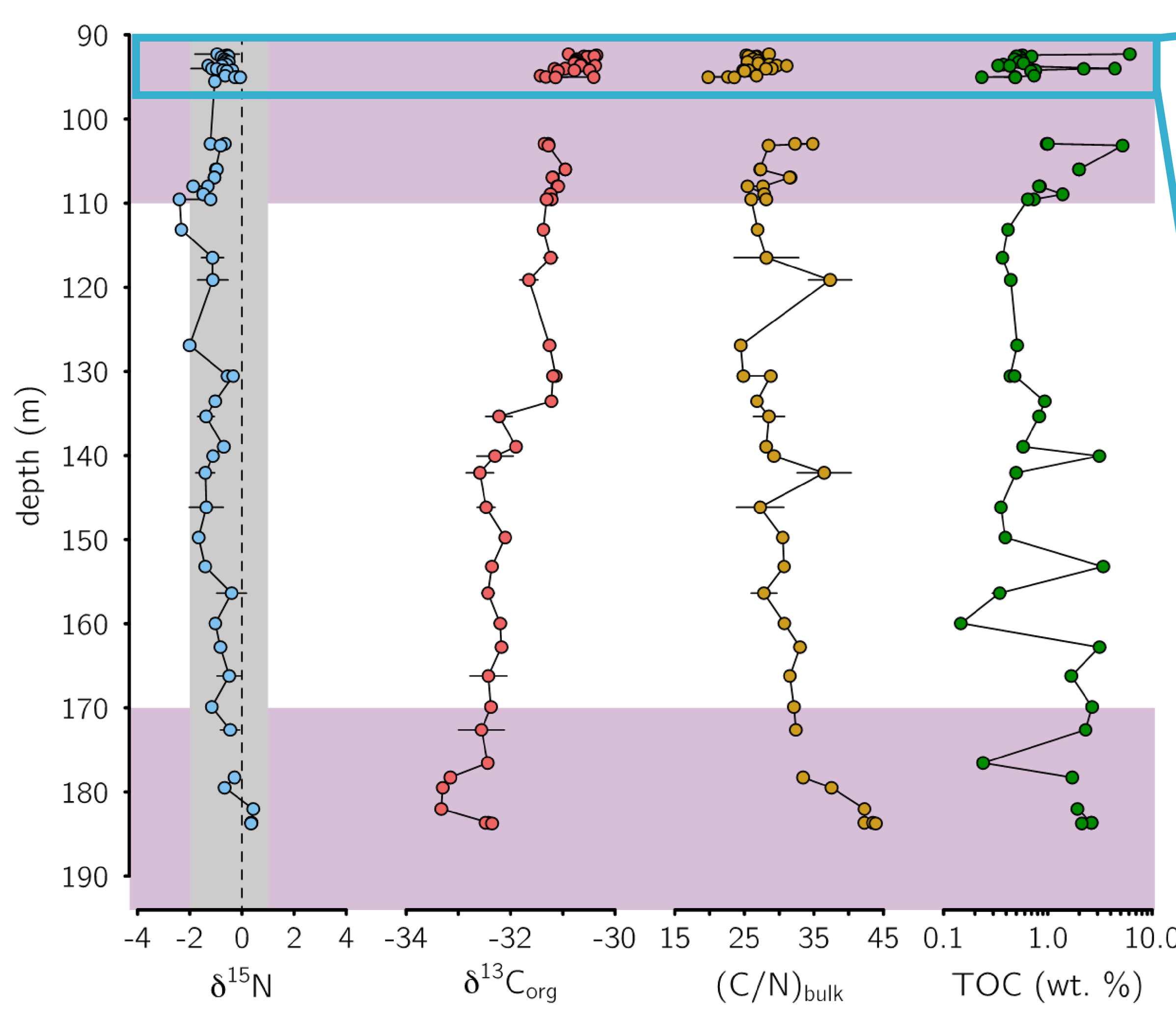


Fig. 6. Changes in δ^{15}N, δ^{13}C, C/N bulk, and TOC throughout the core. The purple sections mark the intervals of photic zone euxinia identified in Pages et al., (2016).

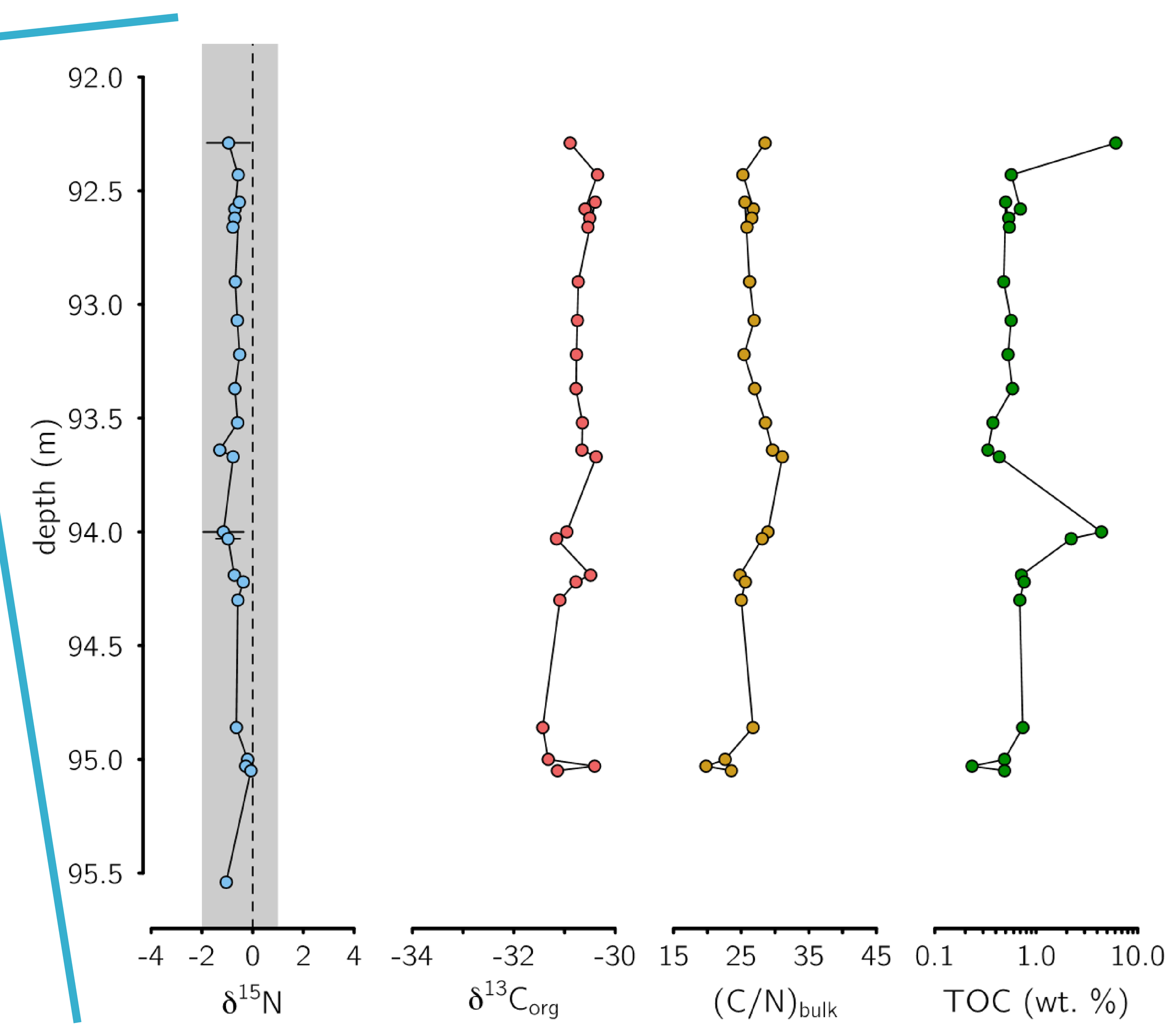


Fig. 7. A high resolution analysis of the top ~ 3 m of the core. We can see that the trends observed in this segment are consistent with what we saw in the overall core.

- In the δ^{15}N column, the grey region indicates the range for N-fixation dominated ecosystems. Nearly all of our points fall within this range. Since N fixation is only performed by prokaryotes, this ecosystem was likely prokaryote-dominated, with limited eukaryotes present. This is consistent with strongly anoxic waters.
- For δ^{13}C, the upper core has values near -30‰, which is characteristic of primary producers and is not necessarily suggestive of strong anoxia. However, deeper in the core the δ^{13}C becomes more negative, approaching -35‰. These more negative values may be indicative of methanogenesis and stronger anoxia.
- Modern marine biomass has a C/N of 6-8, while modern anoxic sediments are typically 10-15. Our ratios are significantly higher, potentially indicating a degree of anoxia greater than that found in modern anoxic regions.
- The purple region indicates the area of PZE identified in the Pages et al. study. The transitions between PZE and background intervals show no clear difference in redox signals, with the possible exception of the lowermost core.

Conclusions

There is evidence for persistently anoxic conditions.

- δ^{15}N values from 0 to -2‰
- $\delta^{13}C_{org}$ values near -35‰
- C/N ratios: 20 to 45
- low variability across the hypothesized PZE events

Our findings suggest primarily anoxic oceans during the mid-Cambrian, ~510 Ma, with animals limited to oxygenated refugia in shallow waters.

Future work for this project will include analyses of samples from below ~190 m depth. This will allow us to examine the apparent larger redox fluctuations towards the bottom of the core. We will also perform kerogen extraction to determine the C/N ratio of preserved organic matter and compare it to modern marine settings. The limited redox fluctuations observed across the supposed PZE intervals could imply that biological changes were decoupled from oxygen levels. The pairing of isotopic data with biomarker data from ANU will further elucidate the environmental conditions of this site.

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