Linking paleogeography and Earth system dynamics to evolutionary innovation during the Cambrian Explosion

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1 Introduction

CAMBRIAN EXPLOSION (541-530 Ma)

Rapid diversification event during which major animal phylia first appear in fossil record.

Anomalocaris (Cambrian predator)

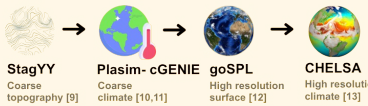
Key innovations [1,2]
- Larger body sizes
- Biomineralization
- Predation
- Complex ecosystems

ENVIRONMENTAL DRIVERS

- **Continental reorganisation**
- Expansion of **shallow** shelf environments
- Increased continental **weathering** and runoff
- Greater **nutrient** delivery to the oceans
- Increased productivity (**NPP**) [3,4]
- O_2 Rise in atmospheric **oxygen** [5,6]

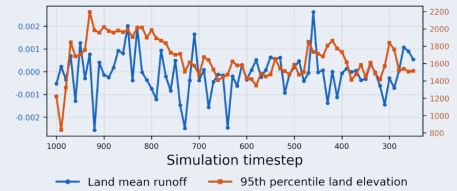
These changes set the stage for the evolution of complex animal life [7,8].

PANDORA EARTH SYSTEM MODELING FRAMEWORK



PANDORA provides high-resolution climate and surface fields.

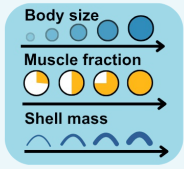
ENVIRONMENTAL VARIABILITY



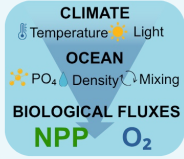
2 Trait-based viability model for early metazoans

INPUTS

A. TRAITS

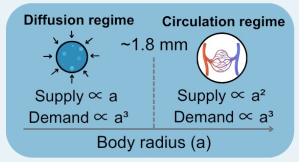


B. ENVIRONMENT

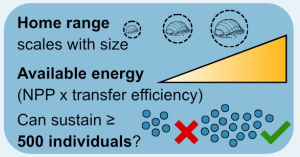


VIABILITY FILTERS

A. OXYGEN (individual constraint)

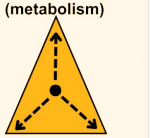


B. ENERGY (population constraint)



ENERGY TRADE-OFF

Surplus energy (supply - demand) allocates to:



Increasing one reduces others.

OUTCOME

Low O_2

Pre-Cambrian

- Small
- Soft-bodied
- Diffusion-limited
- Low trophic level

Cambrian

- Larger
- Shelled
- Active locomotion
- Predator

High O_2

HYPOTHESIS

O_2 Rising oxygen → Circulation evolves → Body size and foraging range increase → Emergence of large, mobile, armored metazoans

3 Environmental changes' impact on viable organisms

METABOLIC SHIFT

LOW NPP & O_2 diffusion → small size → Environmental changes → **HIGH NPP & O_2** Circulation evolves

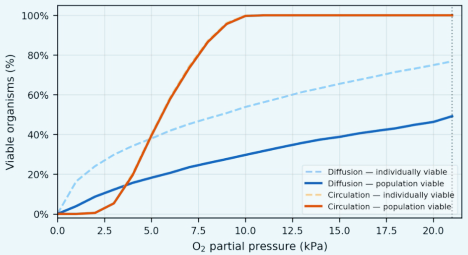


Figure 1. Percentage of individually and population-viable organisms in the diffusion and circulation regimes across increasing atmospheric oxygen.

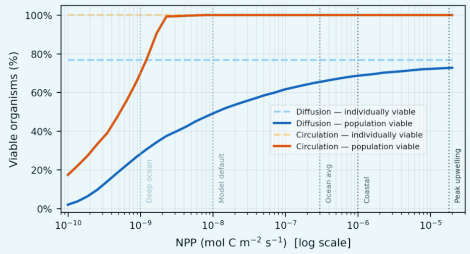


Figure 2. Percentage of individually and population-viable organisms in the diffusion and circulation regimes across increasing NPP.

SIZE AND SHELL INCREASE

O_2 Rising oxygen → Size increase and biomineralisation

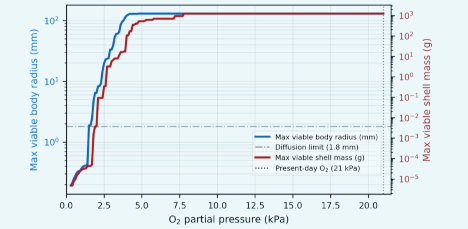


Figure 3. Maximum population-viable body radius and shell mass as atmospheric oxygen increases. Both y-axes are logarithmic.

ORIGINS OF PREDATION

O_2 Rising oxygen → Higher trophic levels → Predation

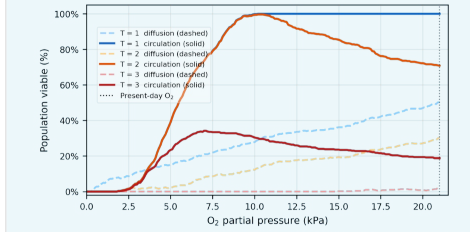


Figure 4. Fraction of population-viable organisms at trophic levels T=1, 2, and 3 for the diffusion and circulation regimes across increasing oxygen.

Future work *will couple the viability model directly to PANDORA's spatially explicit outputs, mapping viable trait space across evolving simulated topographies.*

References

[1] Erwin, D.H. et al. (2011) *Science*, 334, 1091–1097. [2] Marshall, C.R. (2006) *Annual Review of Earth and Planetary Sciences*, 34, 355–384. [3] Squire, R.J. et al. (2006) *Earth and Planetary Science Letters*, 250, 116–133. [4] Donnadieu, Y. et al. (2004) *Nature*, 428, 303–306. [5] Lyons, T.W., Reinhard, C.T. & Planavsky, N.J. (2014) *Nature*, 506, 307–315. [6] Catling, D.C. & Zahnle, K.J. (2020) *Science Advances*, 6, eaax1420. [7] Knoll, A.H. & Carroll, S.B. (1999) *Science*, 284, 2129–2137. [8] Sperling, E.A. et al. (2015) *Nature*, 523, 451–454. [9] Tackley, P.J. (2008) *Physics of the Earth and Planetary Interiors*, 171, 7–18. [10] Holden, P.B. et al. (2016) *Geoscientific Model Development*, 9, 3347–3361. [11] Salles, T. et al. (2018) *Geoscientific Model Development Discussions*. [12] Mills, B.J.W. et al. (2021) *Gondwana Research*, 67, 172–186. [13] Karger, D.N. et al. (2017) *Scientific Data*, 4, 170122.