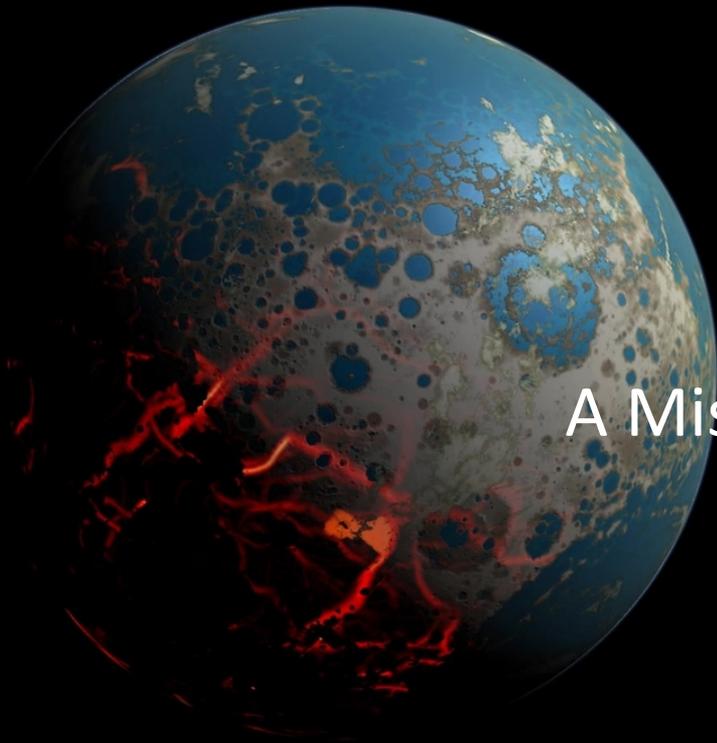
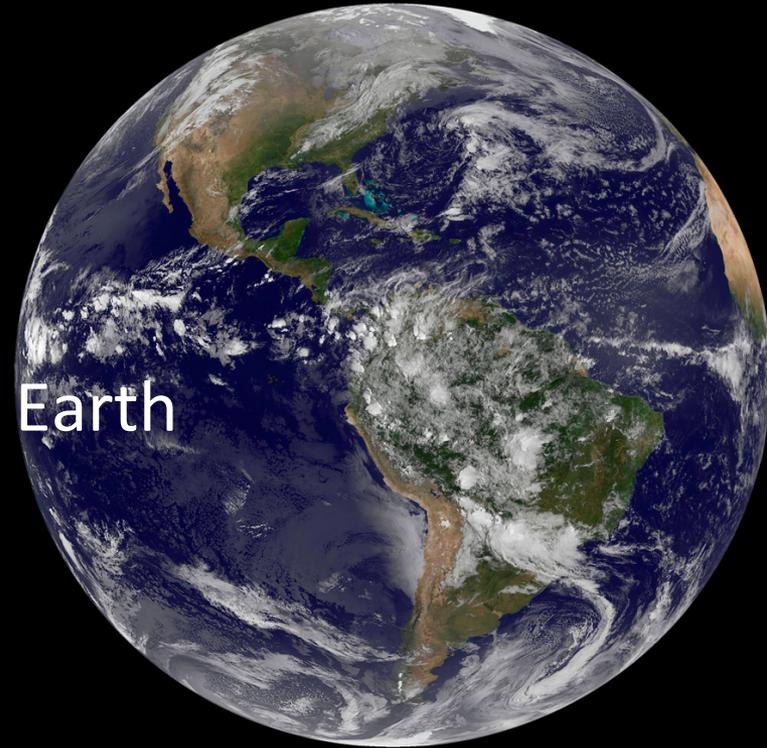


Alternative Earths

Explaining Persistent Inhabitation on a Dynamic Early Earth



A Mission to Early Earth



Yale University

J. Craig Venter™
INSTITUTE

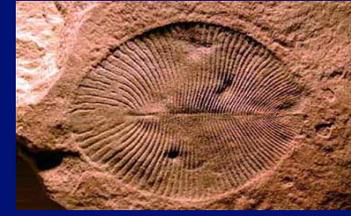
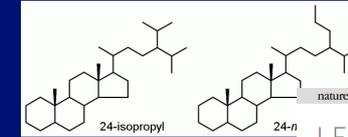
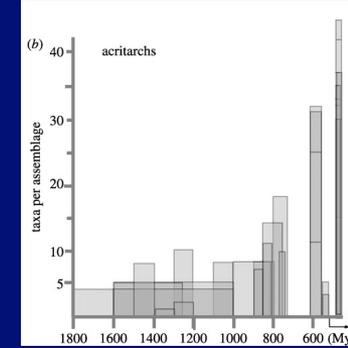
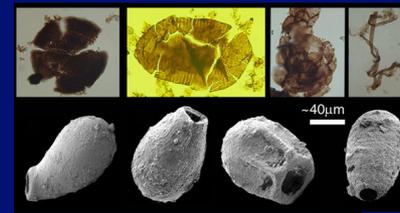
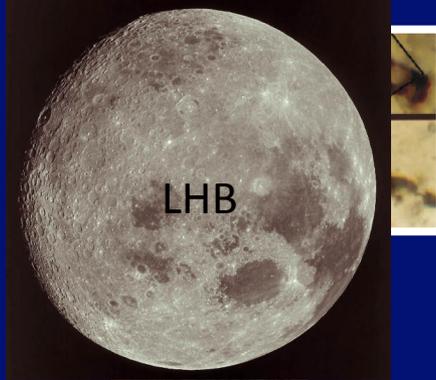
UNIVERSITY OF CALIFORNIA
UC RIVERSIDE



OREGON
HEALTH
& SCIENCE
UNIVERSITY

For billions of years Earth was teeming with simple prokaryotic and early complex life, constantly at work reshaping the chemistry of the oceans and atmosphere. These **records** may provide the most practical **templates** for cultivating a 'search engine' for life beyond the Earth.

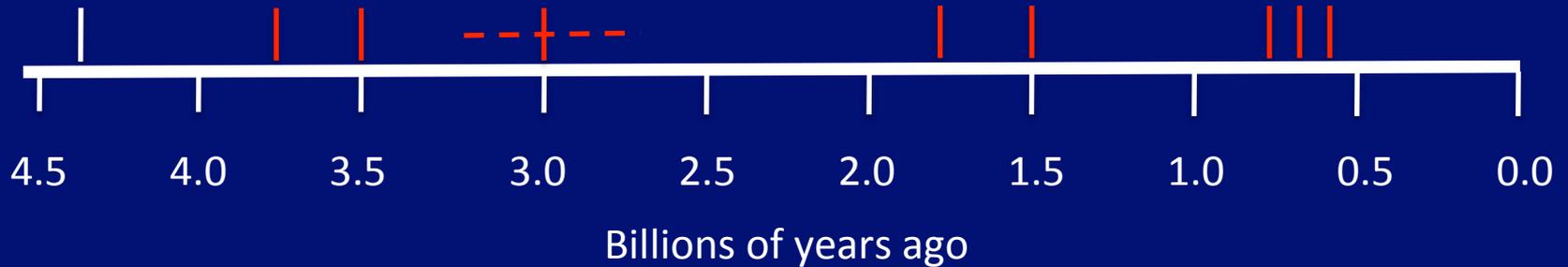
Milestones in Earth History



LETTERS

Fossil steroids record the appearance of Demospongiae during the Cryogenian period

Gordon D. Love^{1,2}, Emmanuelle Grosjean³, Charlotte Stalvies⁴, David A. Fike⁵, John P. Grotzinger⁵, Alexander S. Bradley⁶, Amy E. Kelly⁷, Maya Bhatia⁸, William Meredith⁹, Colin E. Snape⁶, Samuel A. Bowring², Daniel J. Condon¹⁰ & Roger E. Summons²



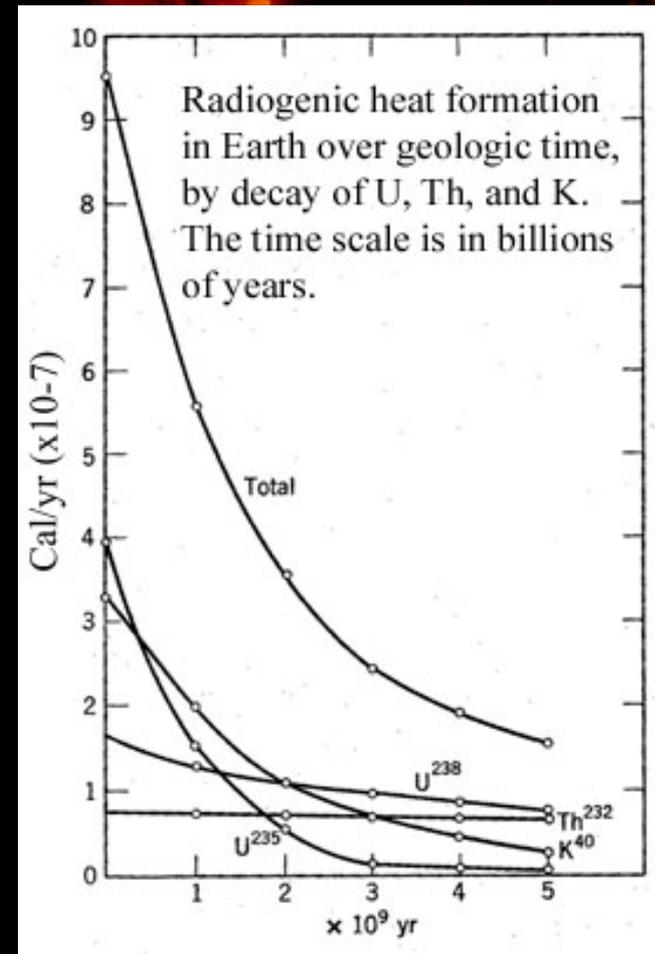
habitability

inhabitation

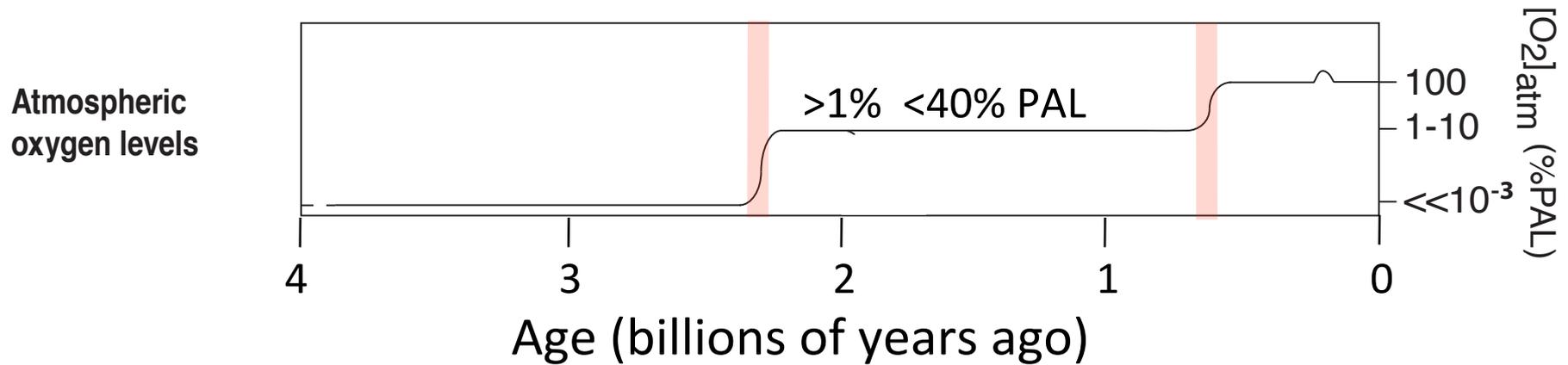
Warming sun

and cooling Earth

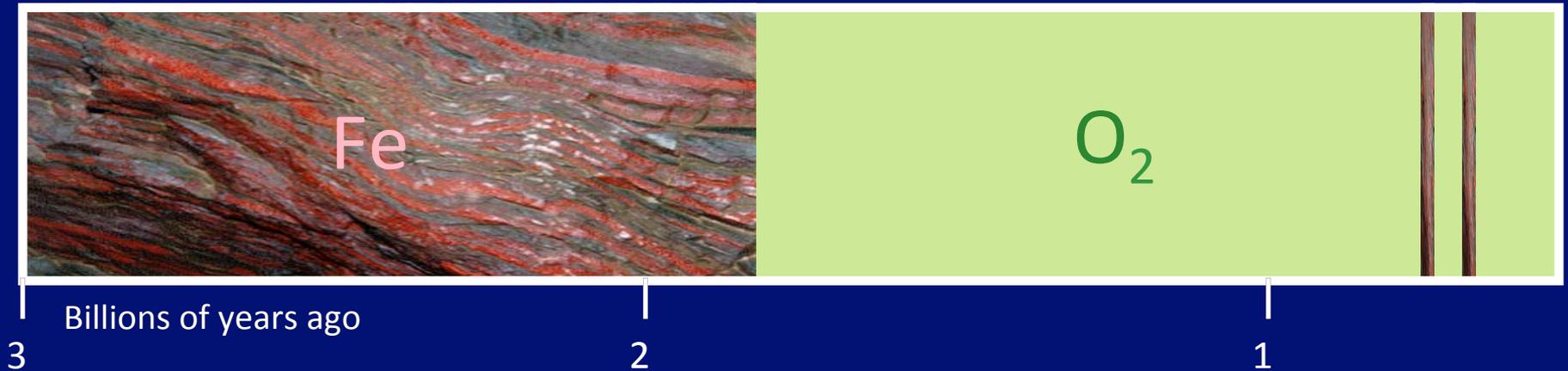
cause and effect relationships
between co-evolving life and
environment



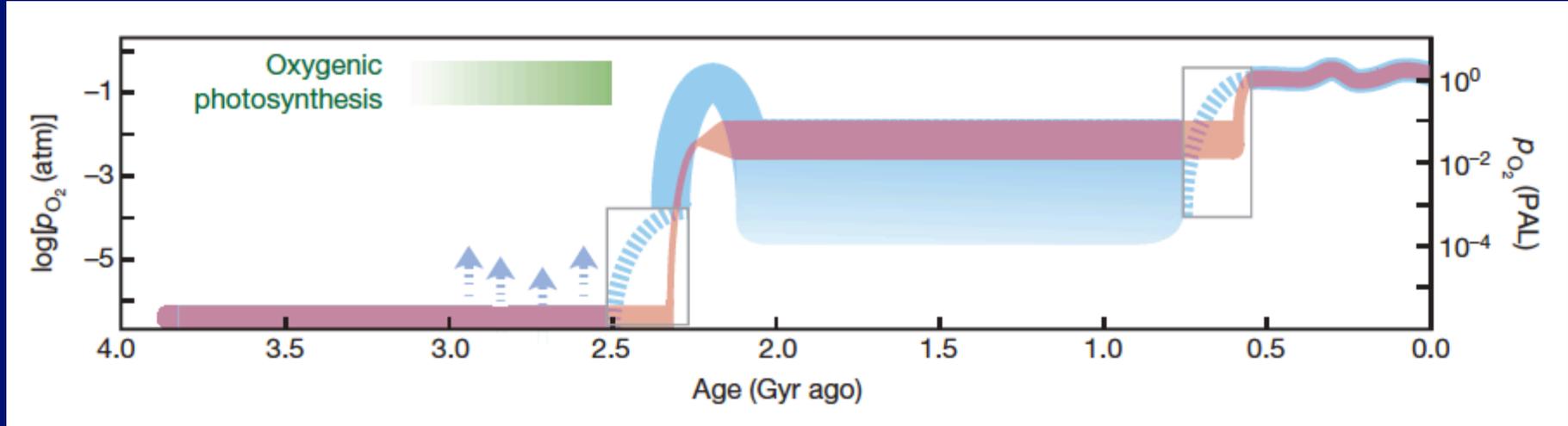
The History of Oxygen in the Atmosphere



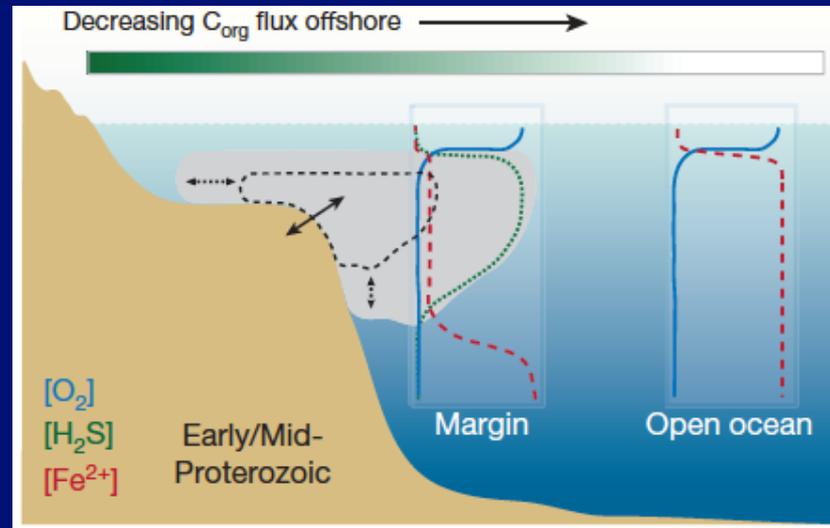
The early deep ocean

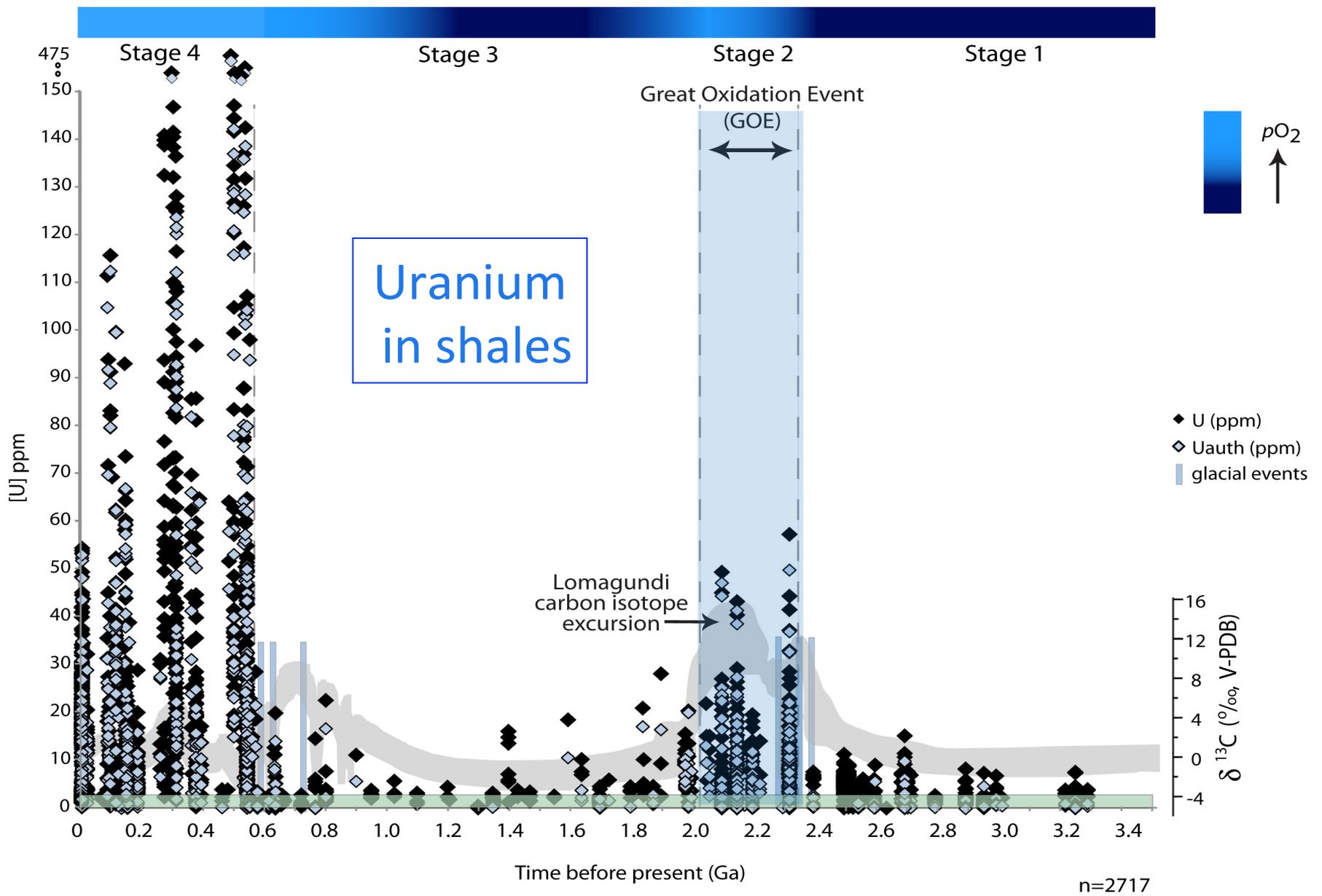


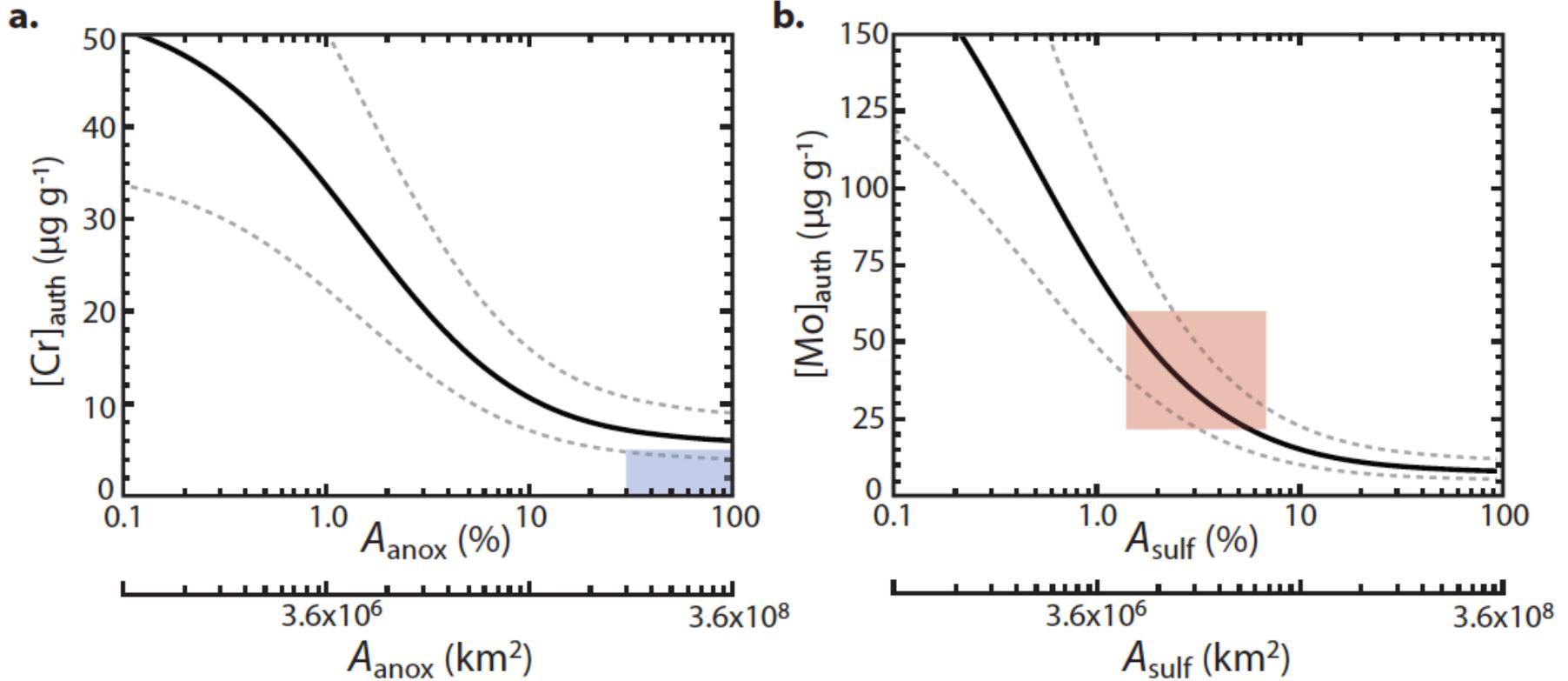
Evolving redox in ocean and atmosphere and co-evolving life now viewed with far more structure: **this is our starting point**



Lyons et al. (2014)



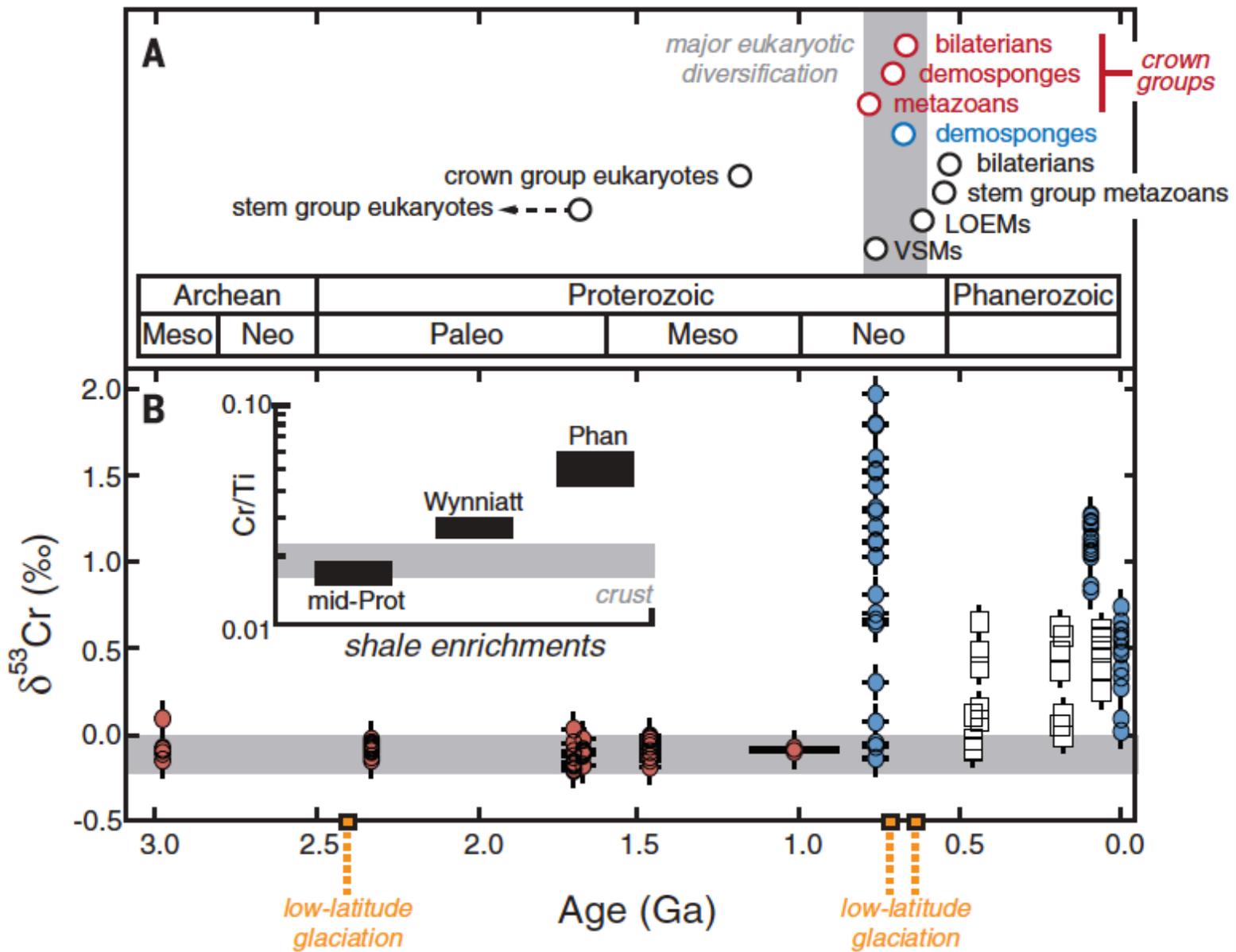


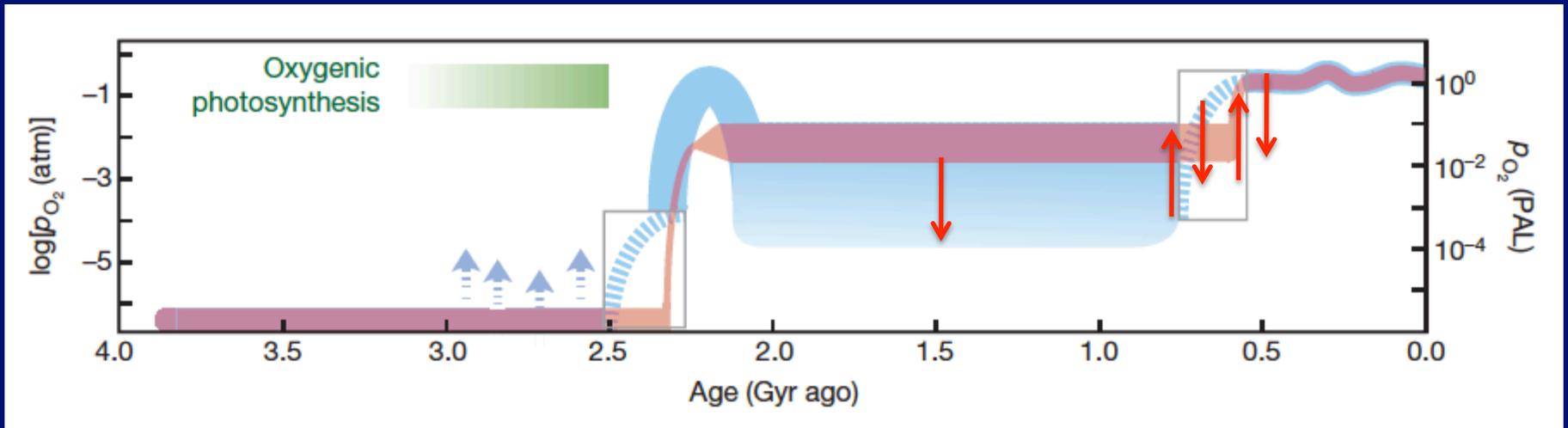


Anoxic: a minimum of $\sim 30-40\%$ of the seafloor and potentially much more.

Euxinic: less than $\sim 1-10\%$ of the seafloor area.

Estimate of globally averaged $[\text{Mo}]_{\text{sw}}$: ~ 10 nM, biologically limiting?



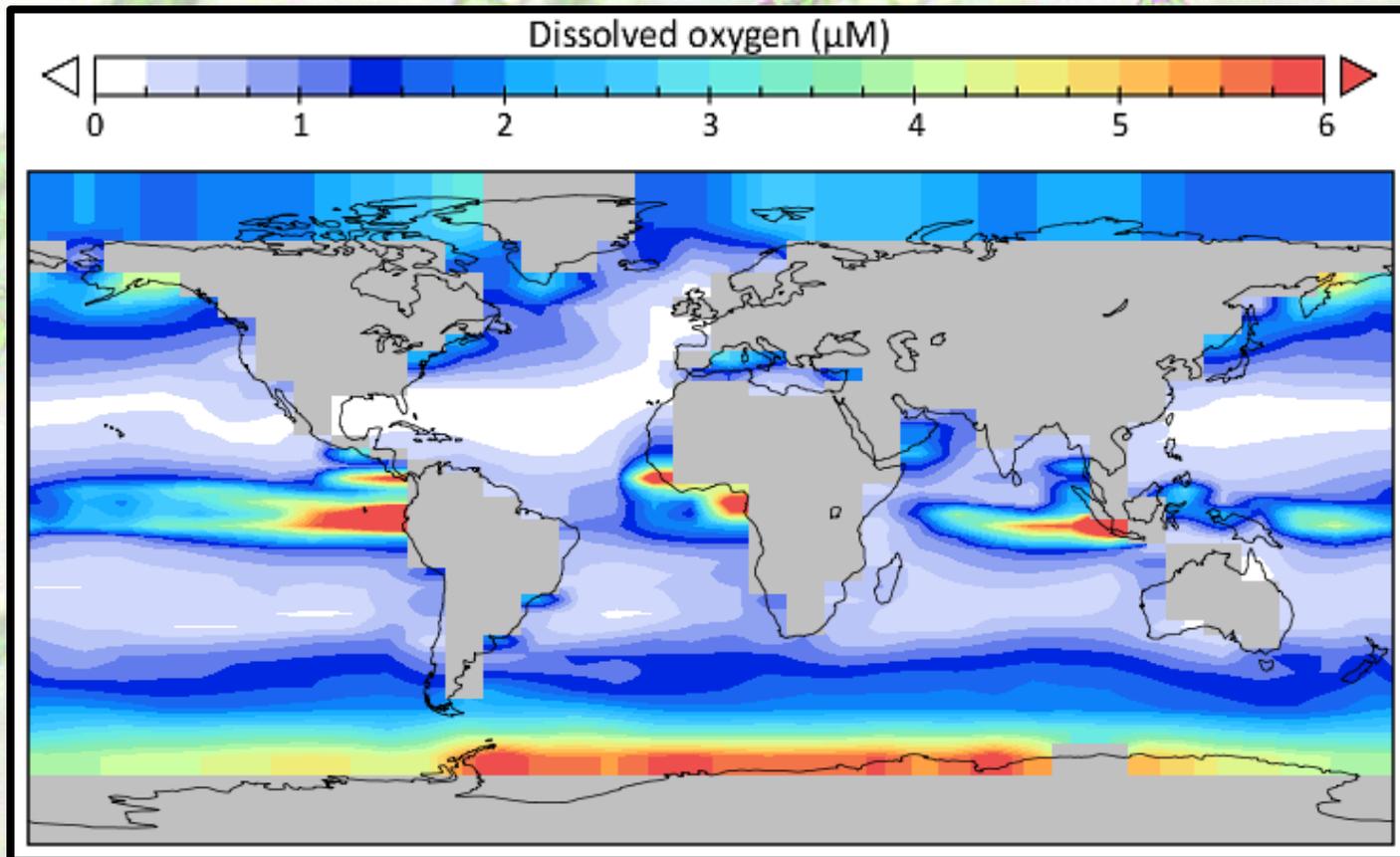


Lyons et al. (2014)

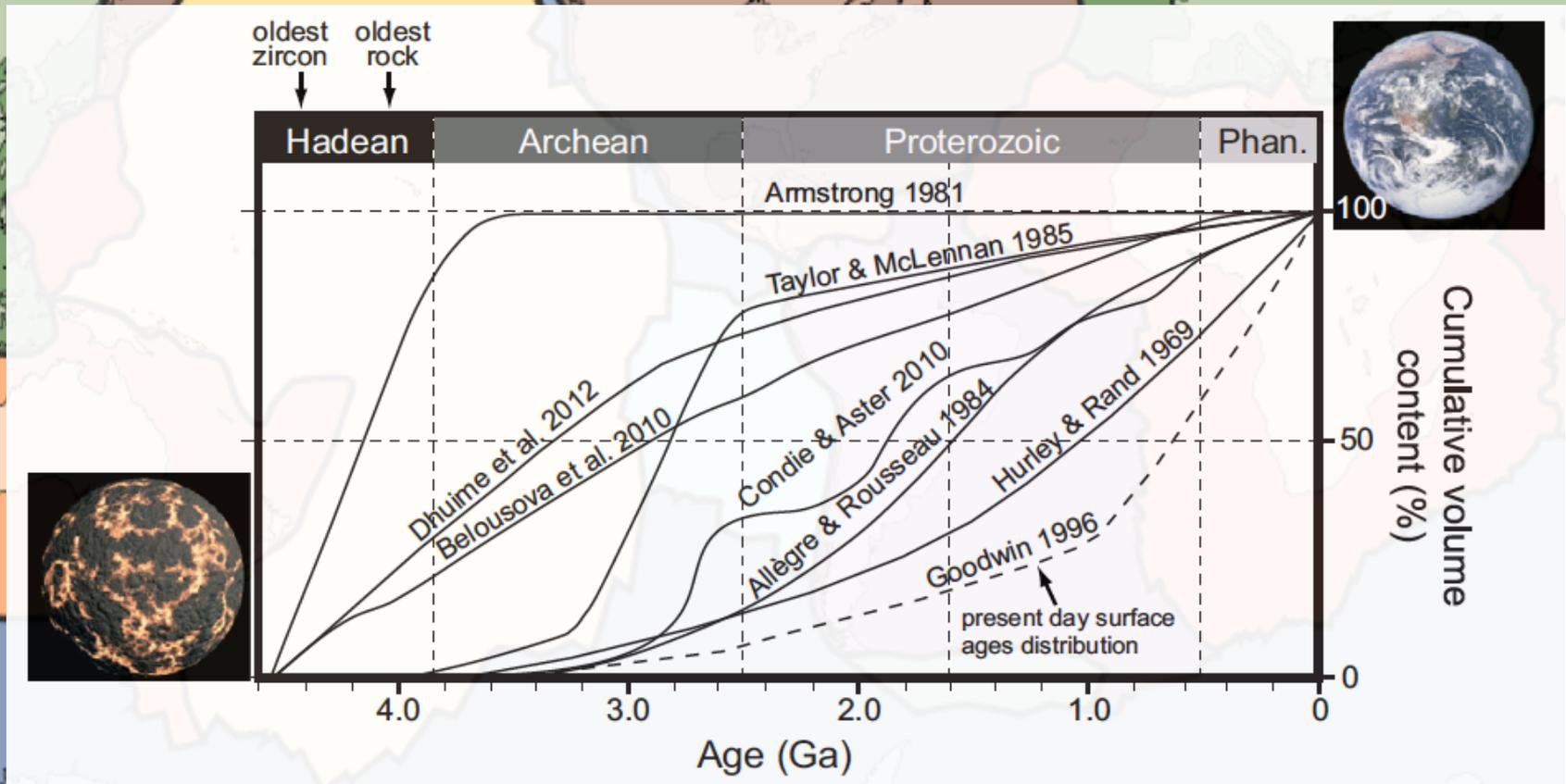
The goal: a comprehensive, systematic, interdisciplinary deconstruction of early Earth that yields a theoretical reconstruction of the coeval atmosphere.

Archean oxygen oases: aerobic ecosystems on an anoxic Earth

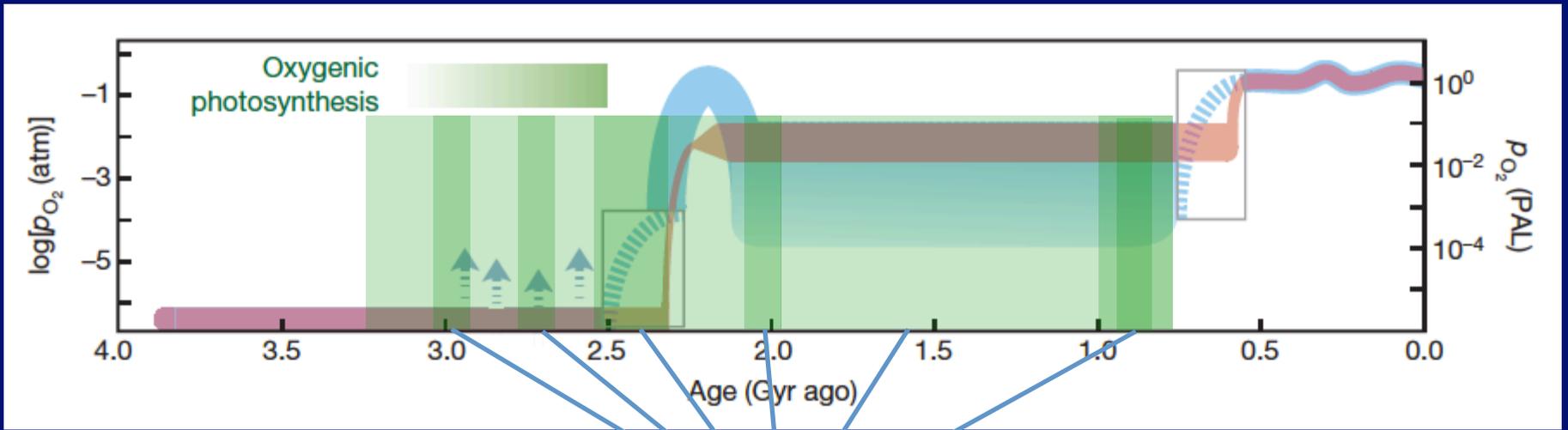
Stephanie Olson, Lee Kump, and Jim Kasting



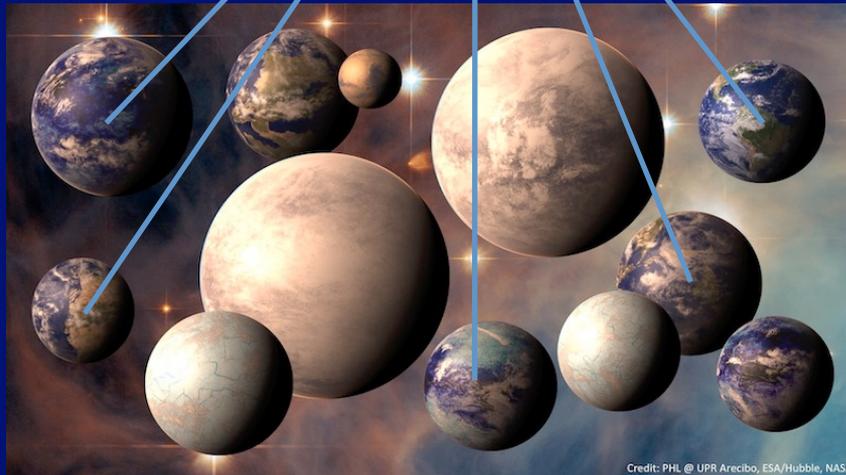
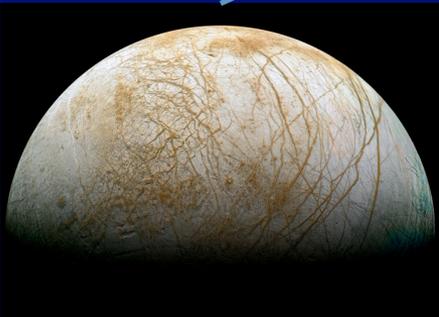
Origins of Continents and Plate Tectonics (nutrient recycling, C burial, CO₂ cycling, etc.)



Cawood et al. (2013)



Alternative Earths



How has Earth remained persistently inhabited through most of its dynamic history, and how did those varying states of inhabitation manifest in the atmosphere?

Research Context: What would Earth look like if analyzed remotely over its long history? **What** information about the tectonic, biotic, and extra-planetary processes that combined to sustain Earth's dynamic habitability over billions of years **can we glean from snapshots of our evolving planet?**

Earth's **rock record** provides a array of diverse windows into past states of inhabitation—what we can think of as **'Alternative Earths.'**

ALTERNATIVE EARTH 1 | Atmospheric Traces of Oxygenic Photosynthesis
mid-late Archean | 3.2 to 2.4 billion years ago

ALTERNATIVE EARTH 2 | Dramatic Oxygen Fluctuations
mid-Paleoproterozoic | roughly 2.3 to 2.0 billion years ago

ALTERNATIVE EARTH 3 | Oxygen Stasis and the Rise of Eukaryotes and Metazoans
mid-Proterozoic | 1.9 to 0.7 billion years ago

Alternative Earth 1	Resolve when oxygenic photosynthesis first left traces in Earth's atmosphere and whether (and, if so, why) there was a lag between oxygen's first biological production and its persistent accumulation.
Alternative Earth 2	Determine whether Earth's surface underwent a unidirectional oxygen rise—as typically envisioned—or whether (and why) this early history was characterized by a series of rises and falls.
Alternative Earth 3	Determine whether surface oxygen concentrations maintained sufficiently low levels, for perhaps a billion years of Earth's history, to play a direct role in when animals first hit the scene and diversified.

And multiple other 'Earths' and transitions:
known, predicted, and unknown

PROPOSED ANALYSES, EXPERIMENTS, AND METHODS — BY WORKING GROUP

Working Group 1 | Redox Tracers

Working Group 3 | Tectonic Drivers

Working Group 2 | Earth-Life Interface

Working Group 4 | Earth System Synthesis

Research Plan: To characterize Earth's **early oxygen history**, its **atmospheric evolution** more generally, and the coupled drivers and consequences of this record through **laboratory experiments** and **analysis of rock samples** collected all over the world—**emphasizing new and refined proxy approaches**.

Investigations will be coordinated among four interactive Working Groups:

Redox Tracers — chemical signatures of habitability

Earth-Life Interface — biomarkers, fossils, 'omics', evolving life

Tectonic Drivers — large-scale controls on environmental change

Earth System Synthesis — modeled atmospheres

1 | Redox Tracers

Application of Proxies for Oxidative Weathering » Biogeochemists and geologists will apply geochemical proxies to roughly three billion years of the rock record.

Sampling Strategies & Locations » Avoiding Diagenetic Overprints and Contamination »

Refinement of Proxies for Oxidative Weathering » Experimentalists and modern system biogeochemists will work in the lab and in modern marine and nonmarine settings to define, refine, and calibrate the next generation of paleoenvironmental proxies as tracers for atmospheric composition, tectonic processes, and nutrient delivery to the ocean.

Assessing an Alternative: Photochemical Oxidation »

2 | Earth-Life Interface

Eukaryotes: Coupled Biomarker/Microfossil Search » Paleontologists and paleobiologists will analyze records of evolving life over the three billion years of interest.

Evolution of Metalloenzyme Utilization » Nutrient Limitation » 'Omic' specialists and microbiologists will explore evolving life and parallel phylogenomic records that track metal utilization as informed by our independent tracers of metal availability and overall ocean redox.

3 | Tectonic Drivers

Tracers of Continental Weathering » Initiation of Plate Tectonics »

Proterozoic Continental Reconstructions » Geologists and geophysicists apply theoretical and data-based models for Earth's tectonic history as tied to first-order controls on the evolution of Earth's surface. It has proven difficult to meaningfully bridge tectonics and biogeochemistry.

4 | Earth System Synthesis

Bistability and Secular Oxidation » O_2/CO_2 Balance, Climate, and the Paleoproterozoic Record »

Mid-Proterozoic “throttle” and links between O_2 and climate » Numerical Earth system modelers will build a picture of evolving atmospheric composition as informed by the proxy data and who will steer our establishment of better proxies and protocols as the specific parameters essential to modeling the atmosphere and surface Earth through time become clear.

19 scientists from 11 institutions, including three international collaborators

PRINCIPAL INVESTIGATOR

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INSTITUTIONAL PRINCIPAL INVESTIGATORS (and working group leaders)

Noah J. Planavsky, Dept. of Geology and Geophysics, Yale University

Christopher T. Reinhard, School of Earth and Atmospheric Sciences, Georgia Tech

CO-INVESTIGATORS

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Andrey Bekker, **Mary L. Droser**, **Gordon D. Love**, **Andy Ridgwell**, Dept. of Earth Sciences, University of California, Riverside

Ruth E. Blake, **David A. D. Evans**, **Jun Korenaga**, Dept. of Geology and Geophysics, Yale University

Christopher L. Dupont, Microbial and Environmental Genomics Group, J. Craig Venter Institute,

Jennifer B. Glass, **Yuanzhi Tang**, School of Earth and Atmospheric Sciences, Georgia Tech

Bradley M. Tebo, Division of Environmental and Biomolecular Systems, Oregon Health and Science University

COLLABORATORS

James F. Kasting, Dept. of Geosciences, Pennsylvania State University

Cin-Ty A. Lee, Dept. of Earth Sciences, Rice University

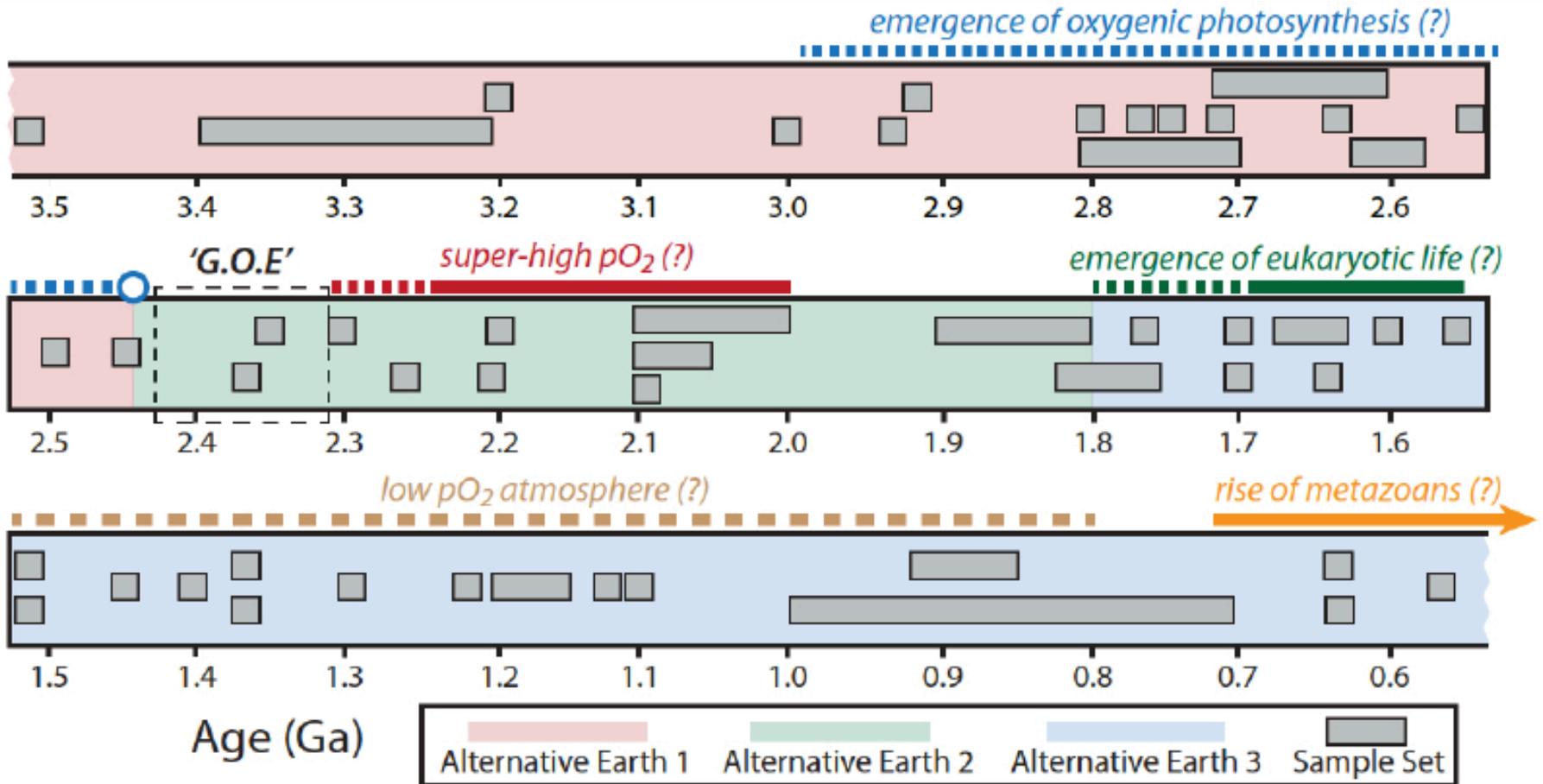
INTERNATIONAL COLLABORATORS

Donald E. Canfield, Dept. of Biology, University of Southern Denmark

Emmanuelle J. Javaux, Université de Liège, Belgium

Niels Peter Revsbech, Aarhus University, Denmark

Sample Distribution Through Time



| HIGHLIGHTS OF PROPOSED CENTER

Expected Results and Significance » The proposed center will seek to provide a fundamentally new and more cohesive view of Earth's history of planetary inhabitation and will serve as a benchmark for approaches for interdisciplinary exploration of planetary systems.

Integration with CAN6 NAI teams » We envision the goals and expected results of our team as being uniquely complementary to the existing CAN 6 NAI teams. We feel that one of the greatest strengths of center proposed here is its balance between lack of redundancy and synergistic overlap and thus the likelihood for true, substantive cross-NAI collaboration and reinforcement.

Professional Community Development » Our rigorous **student exchange program**, intended to cross pollinate the next generation of astrobiologists, will strengthen and support the development of the profession of astrobiology.

Leading Minority-Serving Institution » UC Riverside is designated as a Hispanic Serving Institution. UCR's student body predominantly female (51%), with exceptional ethnic diversity—Hispanic (31.3%), Asian (35.6%), and African-American (6.6%) students combine to form the strong majority of students at the lead institution.

Emphasis on Undergraduate Training » Undergraduate training is a long-standing emphasis at the proposing institutions and is included in the budget. The lab of PI Lyons, for example, has a long and productive history of employing and training numerous undergraduate students, many of whom have gone on to pursue graduate studies. Similar traditions pervade the team.

Large number of early to early-mid career scientists