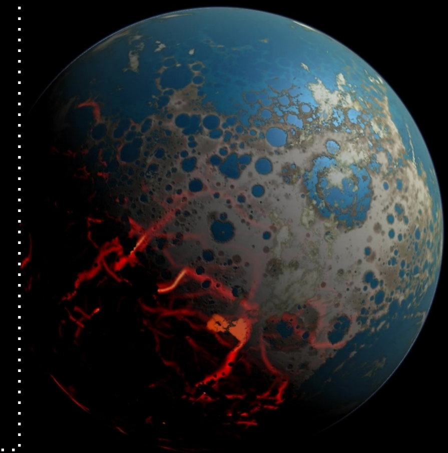
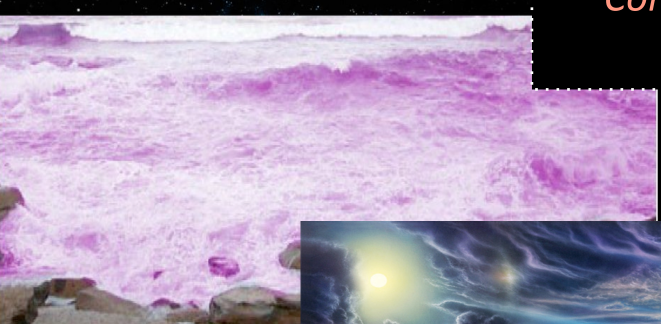
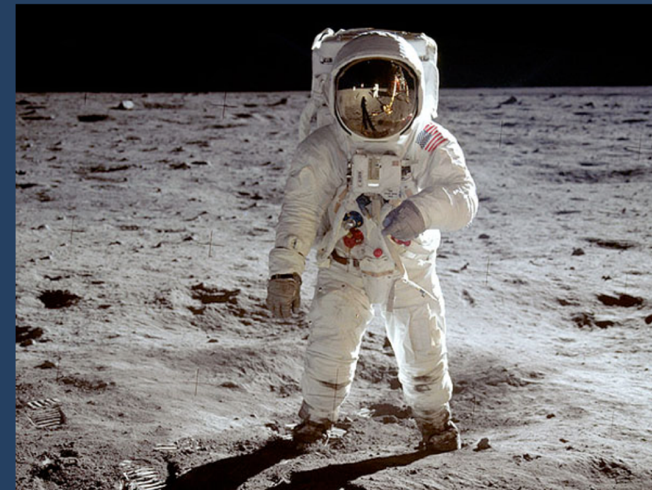
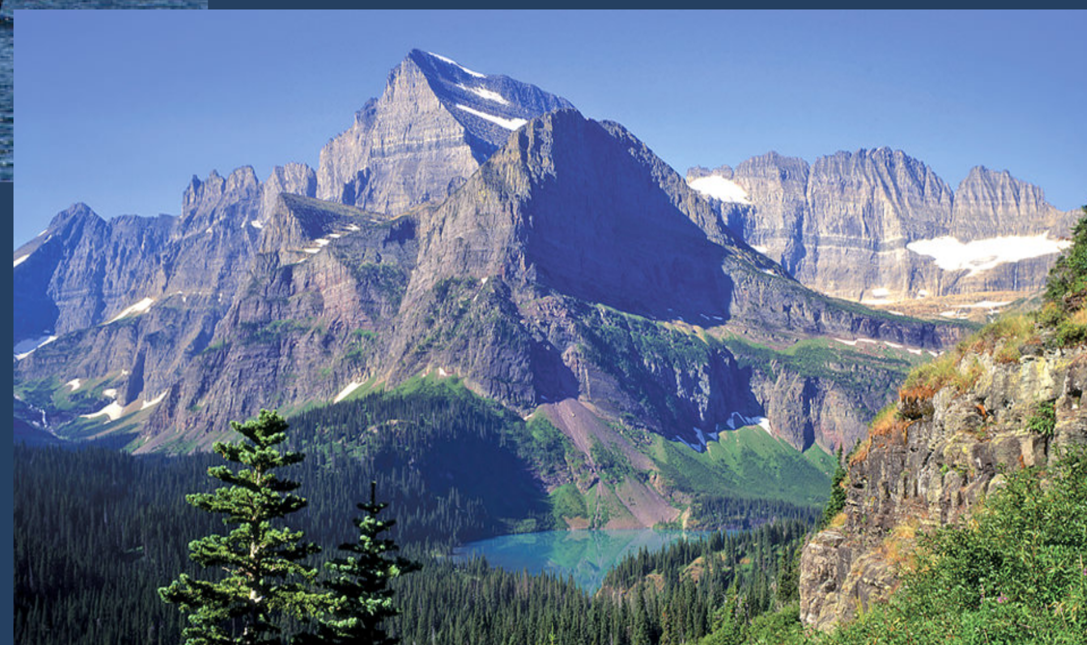


Rise of Oxygen on Earth and Detectable Biosignatures

T.W. Lyons, *Alternative Earths Team of the NASA Astrobiology Institute*, *Department of Earth and Planetary Sciences, University of California, Riverside*
and
Prebiotic Chemistry and Early Earth Environments Consortium of the NASA Research Coordination Network



NASA Astrobiology Institute

Understanding Life on Earth and Beyond







N = 1

Yale University
J. Craig Venter Institute
UC Riverside, University of California
Georgia Tech
ASU
Oregon Health & Science University

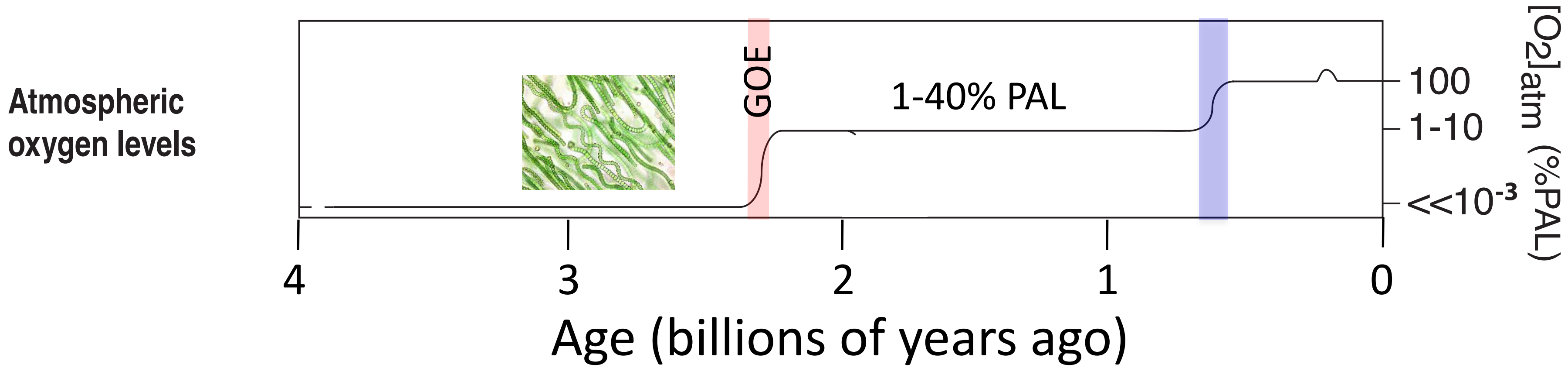
Exploring four billion years of persistent habitability on a dynamic early Earth…

…to guide NASA's mission-specific search for life on distant worlds.

4.5 billion years ago

The Hadean

Oxygen (O_2)



The Classic Two Step View

Archean Biomarkers: Chapters 1 and 2

Archean Molecular Fossils and the Early Rise of Eukaryotes

Jochen J. Brocks,[1,2*] Graham A. Logan,[2] Roger Buick,[1] Roger E. Summons[2]

(Science, 1999)

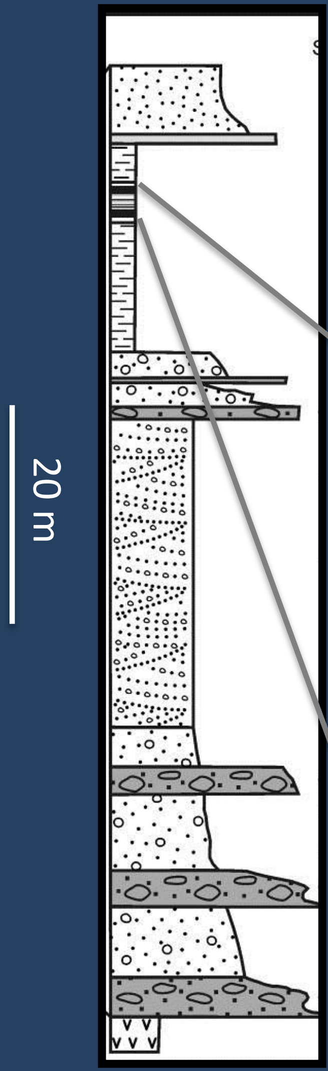
Reappraisal of hydrocarbon biomarkers in Archean rocks

Katherine L. French[a,1,2], Christian Hallmann[b,c], Janet M. Hope[d], Petra L. Schoon[e], J. Alex Zumberge[e], Yosuke Hoshino[f], Carl A. Peters[f], Simon C. George[f], Gordon D. Love[e], Jochen J. Brocks[d], Roger Buick[g], and Roger E. Summons[h]

(PNAS, 2015)

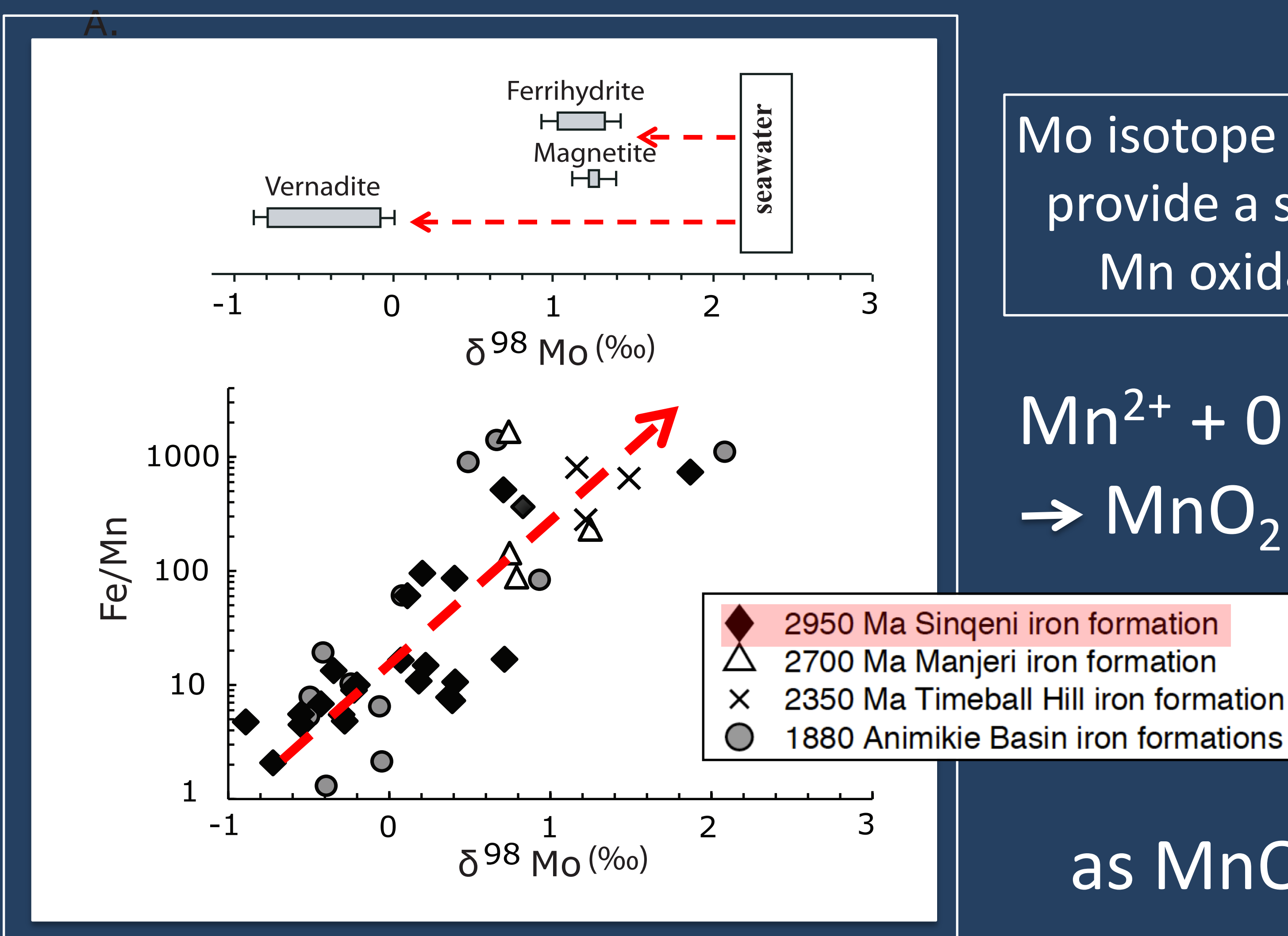
Inorganic Perspectives

Iron Formations and Mo Isotopes
The 2.95 Ga Pongola Supergroup:
The rise of oxygenesis?



Planavsky et al. (2014)

Mo Isotope Fractionation Coupled to Mn Cycling (ca. 3.0 Ga)



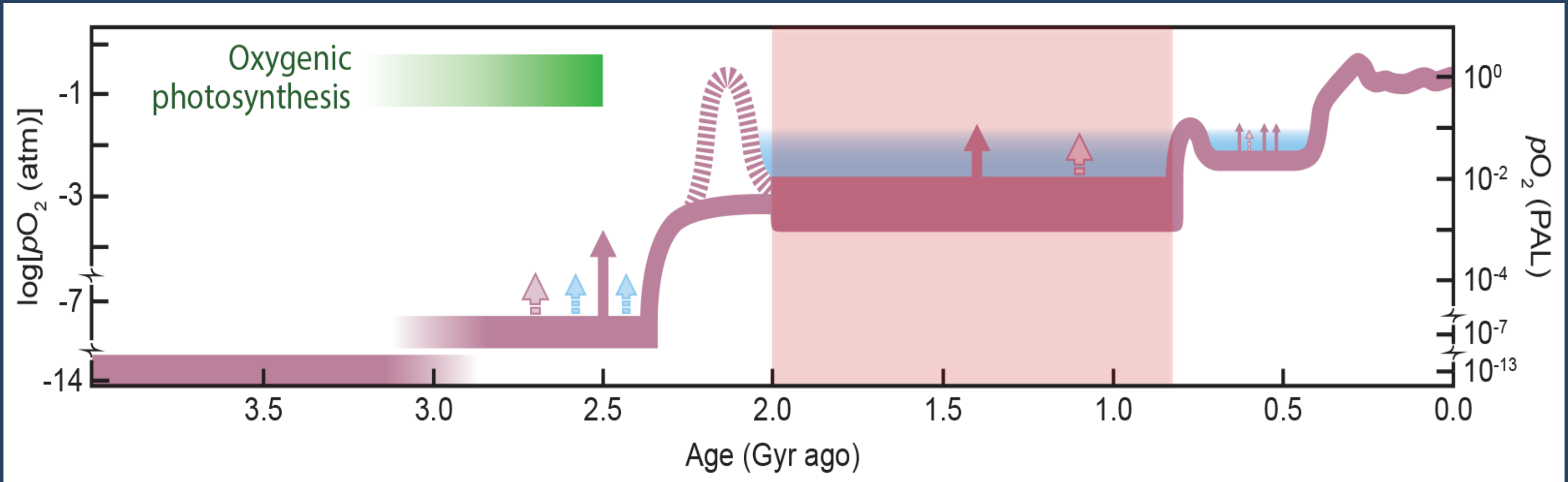
Planavsky et at. (2014)

Mo isotope values in BIFs provide a signature for Mn oxidation = O_2

$$Mn^{2+} + 0.5O_2 + H_2O \rightarrow MnO_2 + 2H^+$$

as $MnO_2\uparrow$ $\delta^{98}Mo\downarrow$

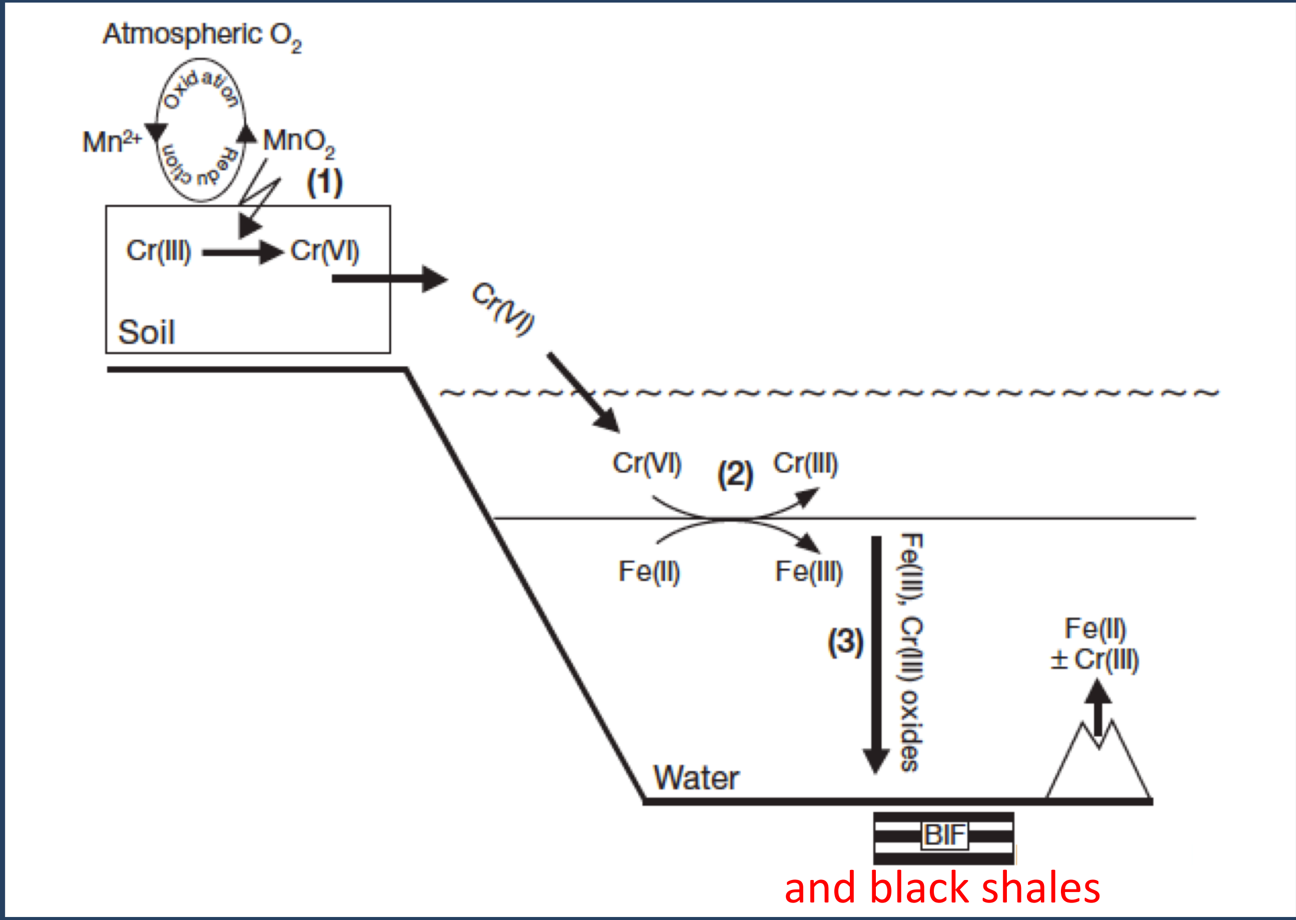
Earth's History of Evolving O_2



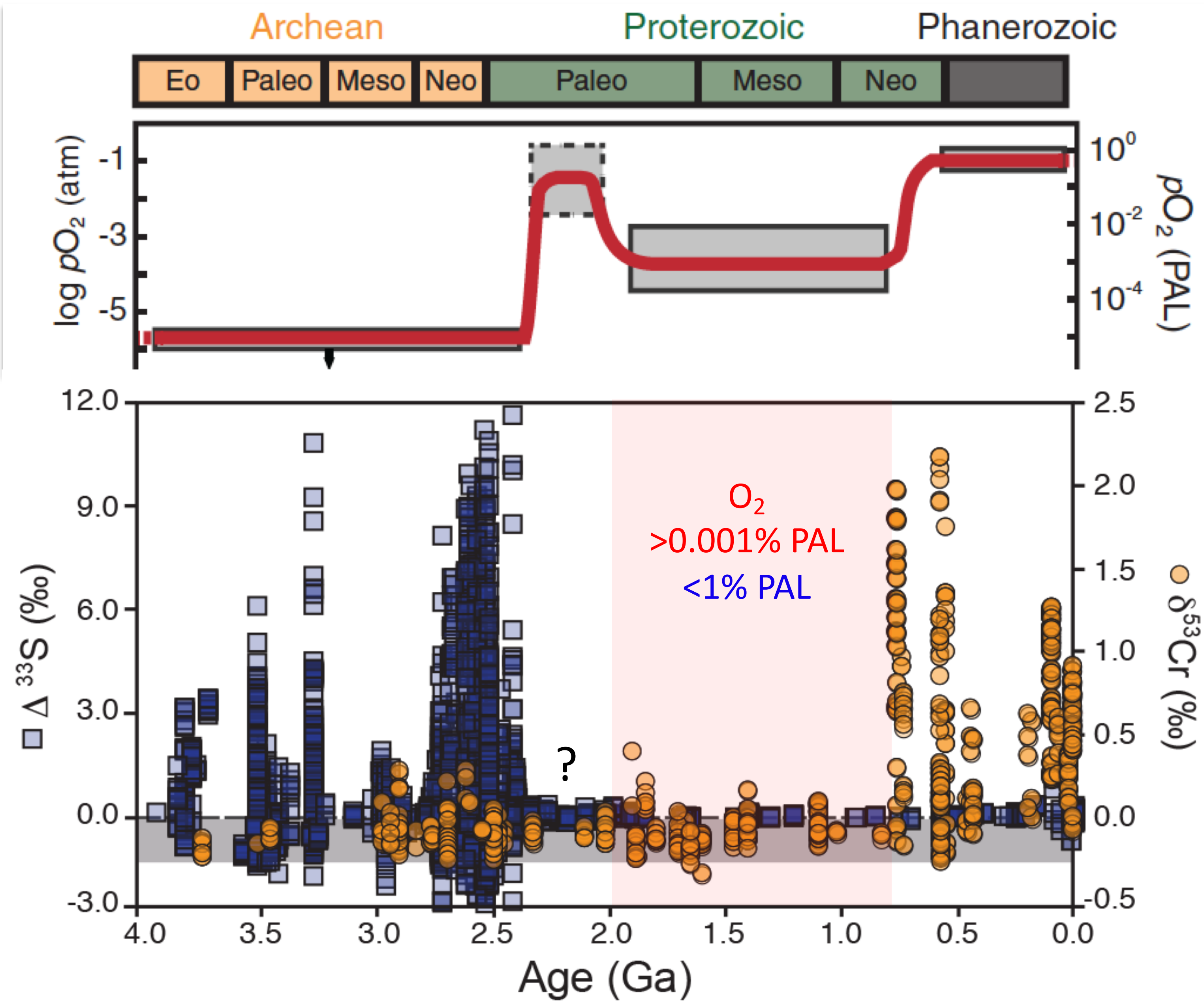
after Lyons et al. (2014)

The ancient atmosphere: Cr isotopes

$$Mn^{2+} + 0.5O_2 + H_2O \rightarrow MnO_2 + 2H^+$$



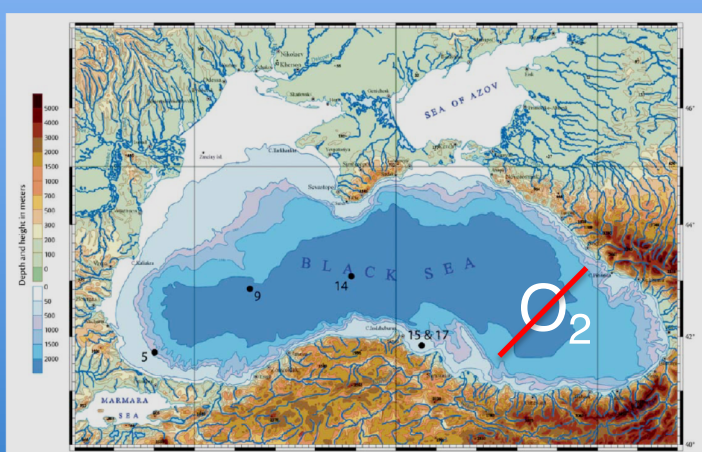
after Frei et al. (2009)

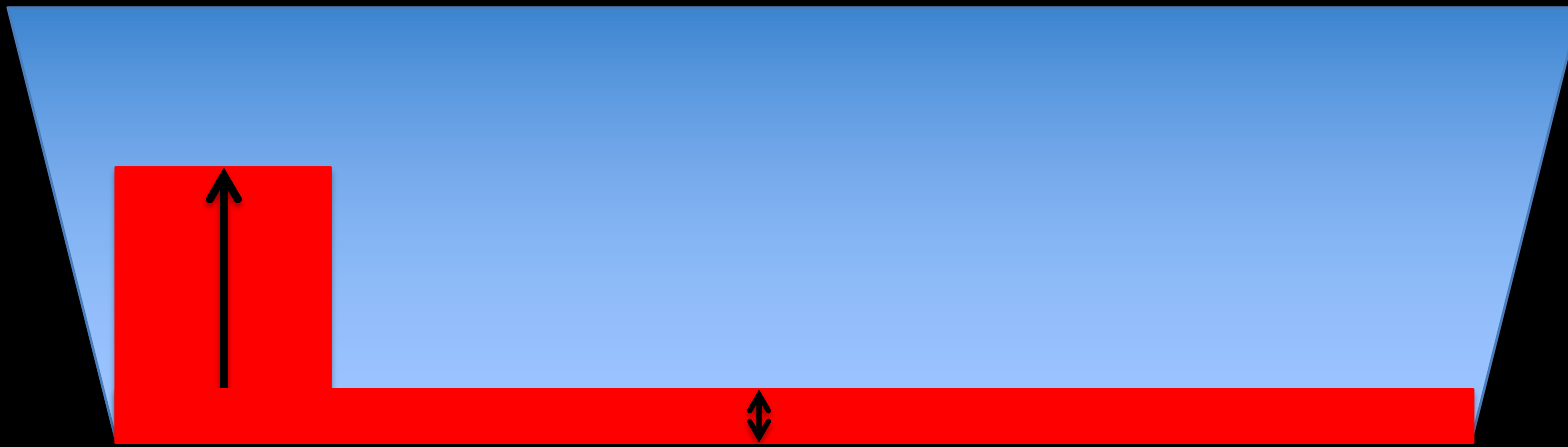


Archean
Proterozoic
Phanerozoic
Eo
Paleo
Meso
Neo
Paleo
Meso
Neo
log pO_2 (atm)
-1
-3
-5
10^0
10^{-2}
10^{-4}
pO_2 (PAL)
$\Delta^{33}S$ (‰)
12.0
9.0
6.0
3.0
0.0
-3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
$\delta^{53}Cr$ (‰)
?
O_2
>0.001% PAL
<1% PAL
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Age (Ga)

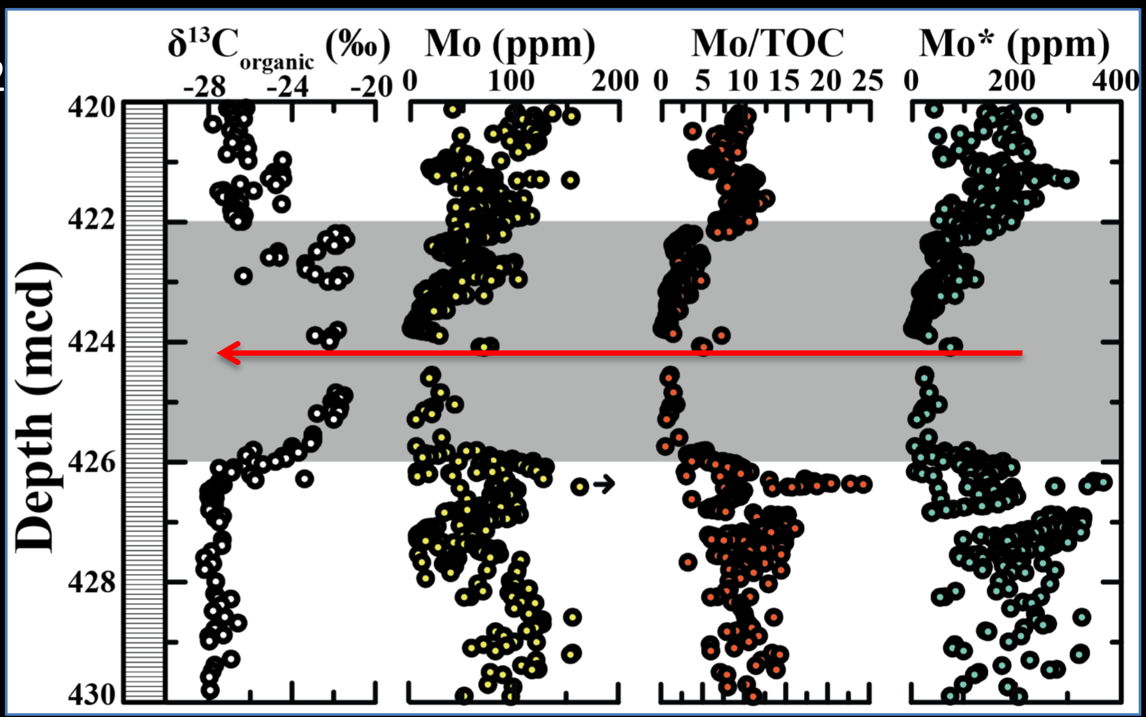
The deep ocean: Trace metal mass balance

Trace metals are delivered to the ocean via oxidative weathering of the continents and scavenged in low O_2 marine settings.

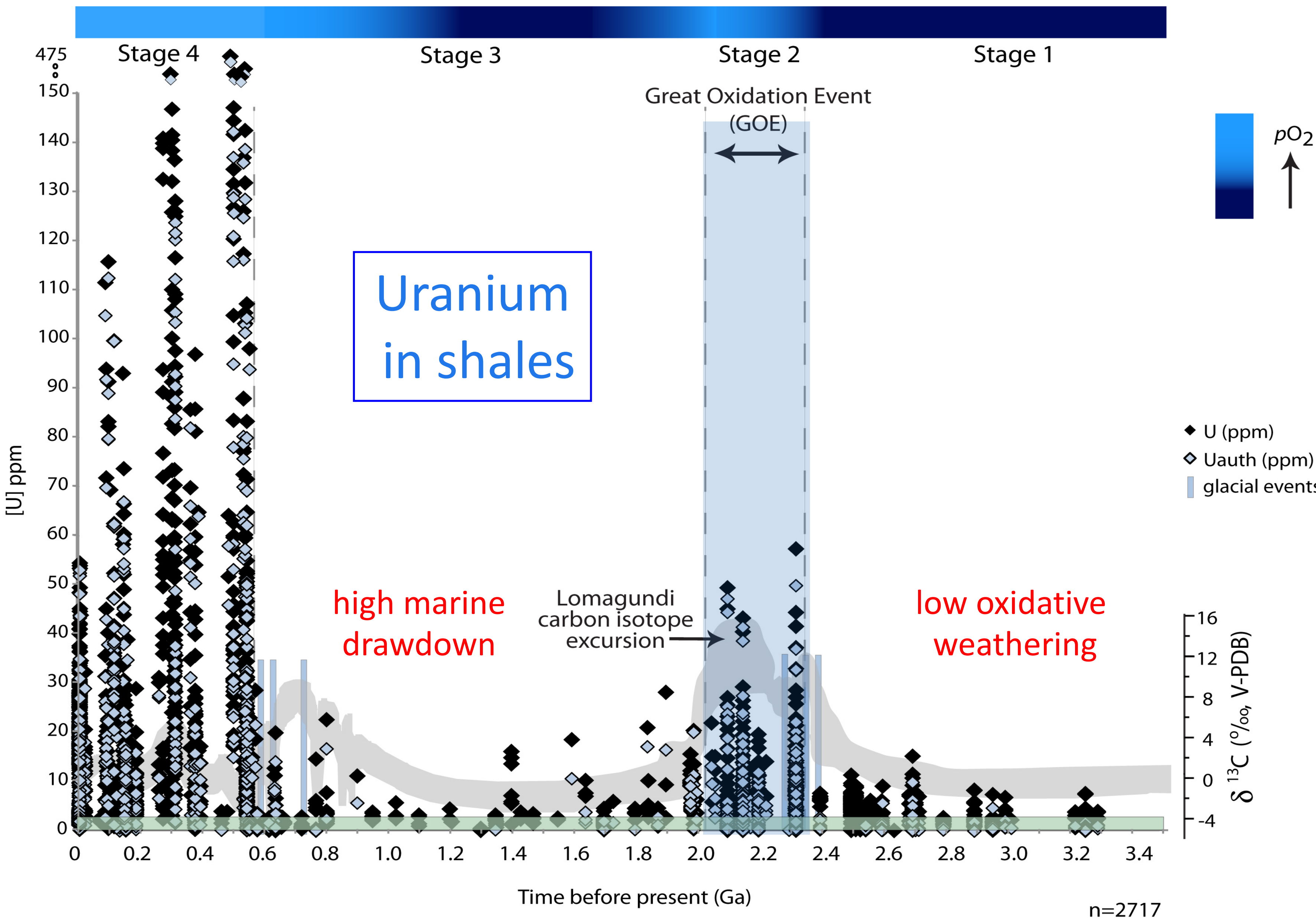




Proof of Concept:
Cretaceous OAE 2
Demerara Rise



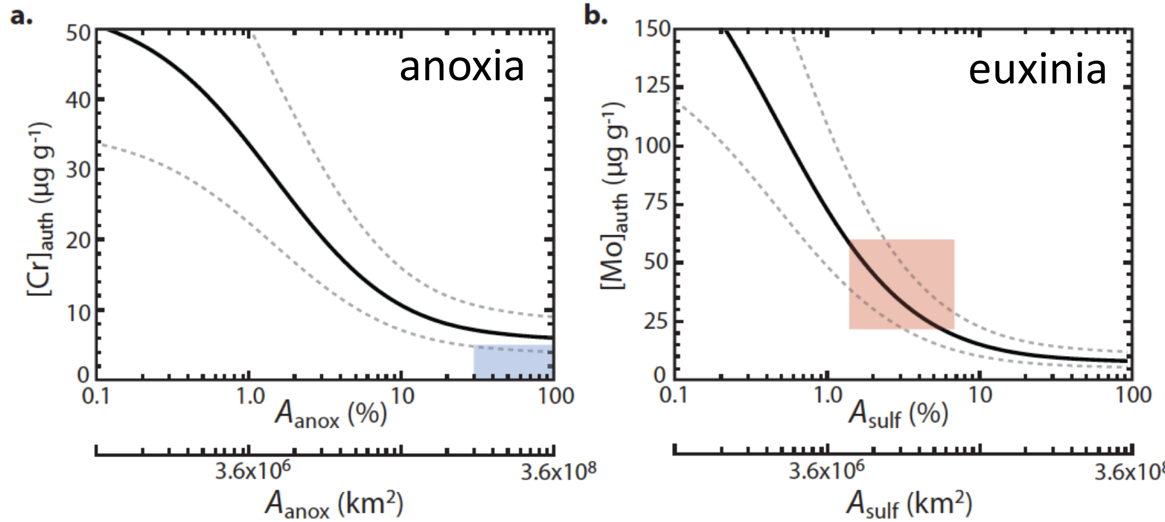
Owens et al. (2016)



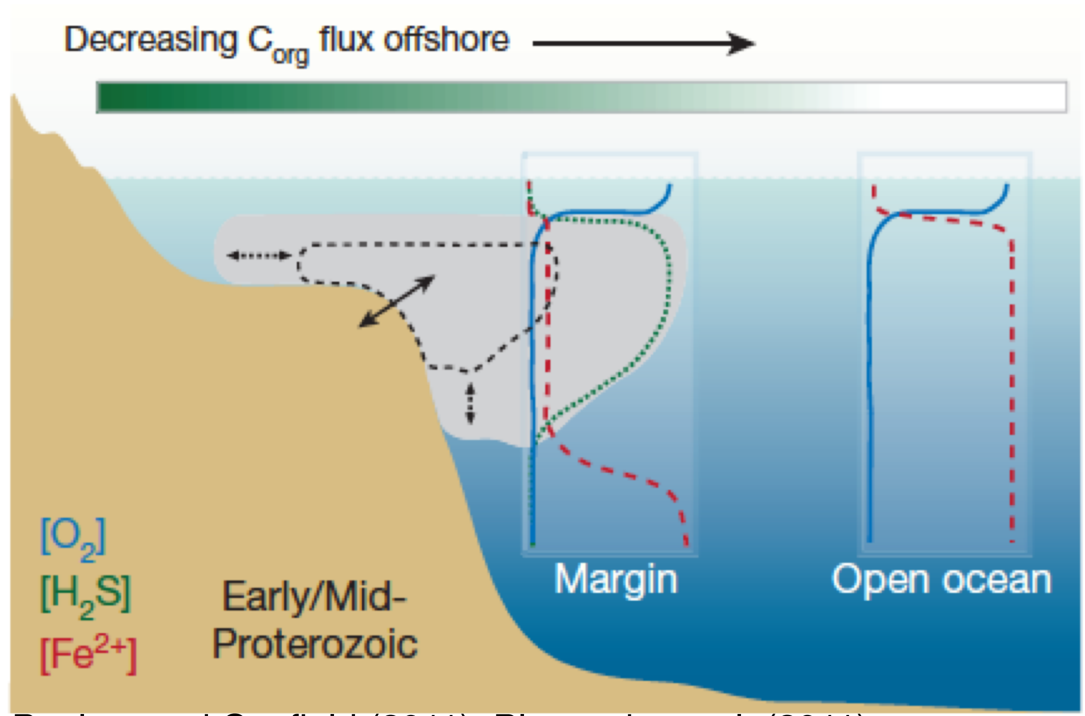
Partin et al. (2013)

Trace metal inventories

Reinhard et al. (2013)

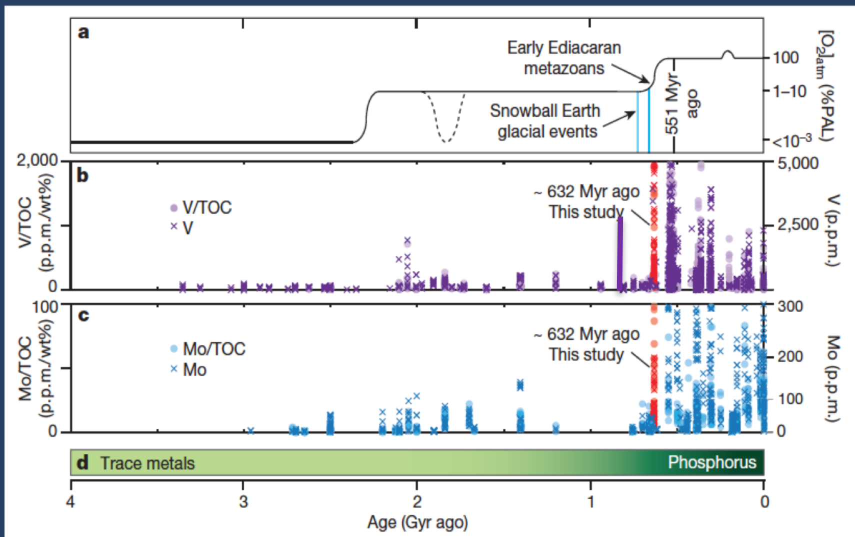


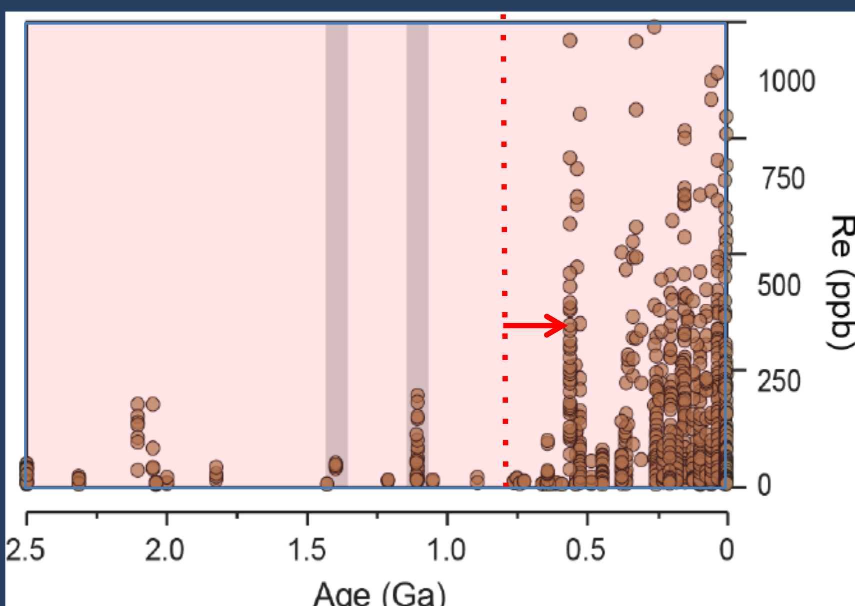
Stratified water column (iron proxies)

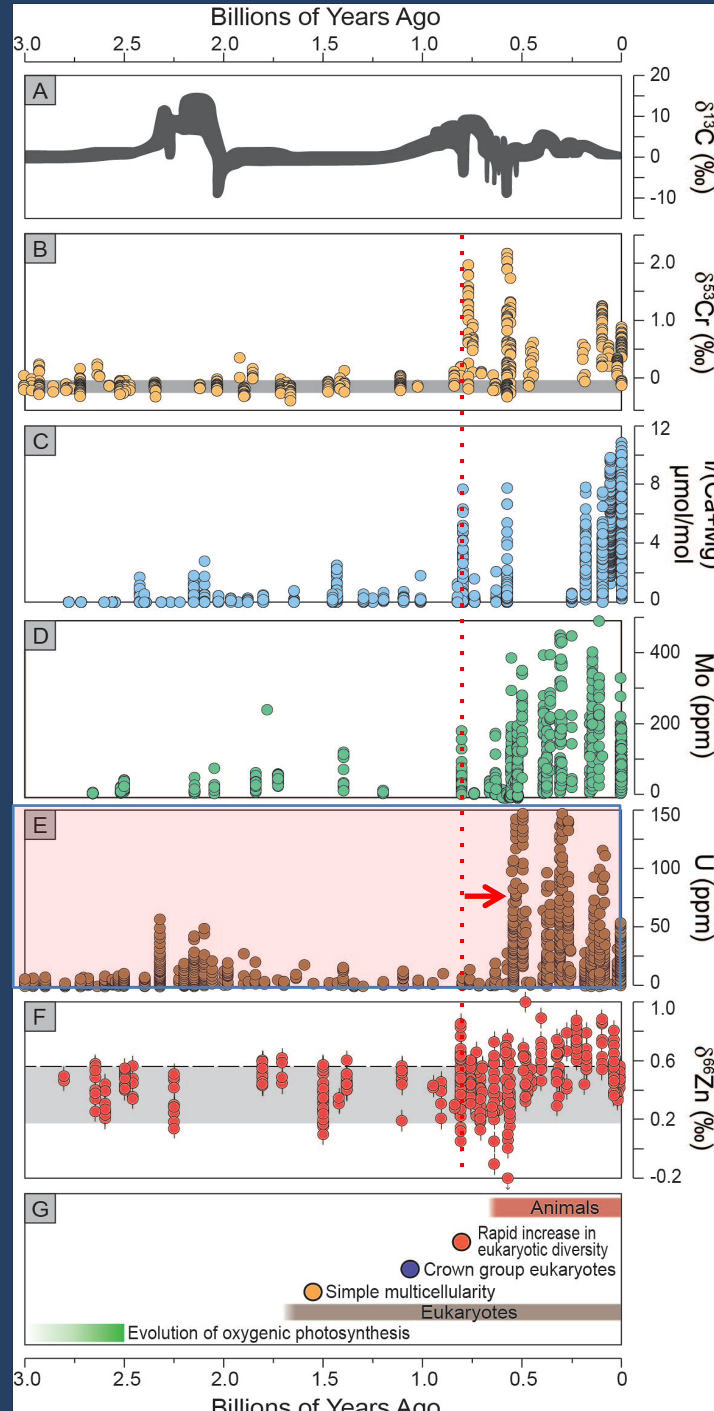


Poulton and Canfield (2011), Planavsky et al. (2011), Lyons et al. (2014)

ca. 800 Ma
The second step





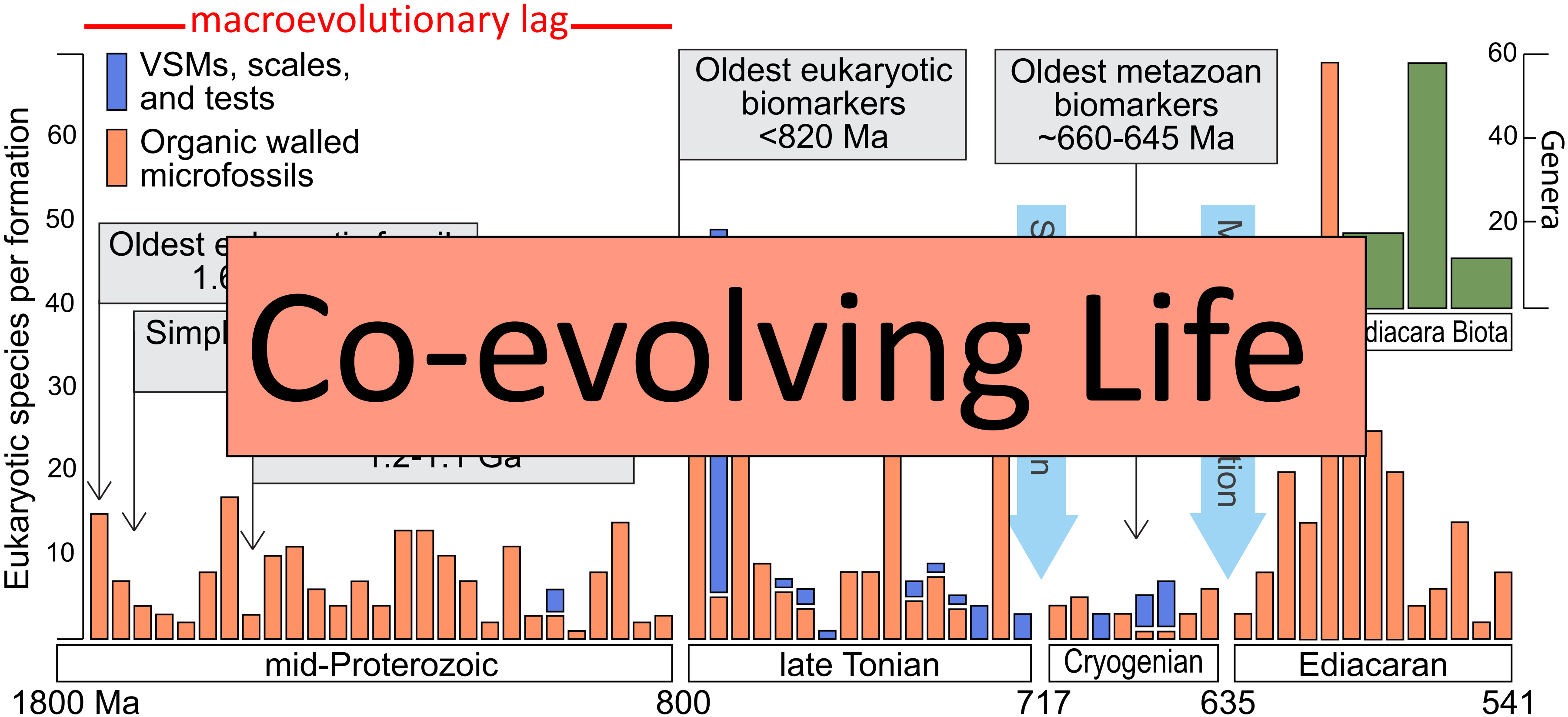


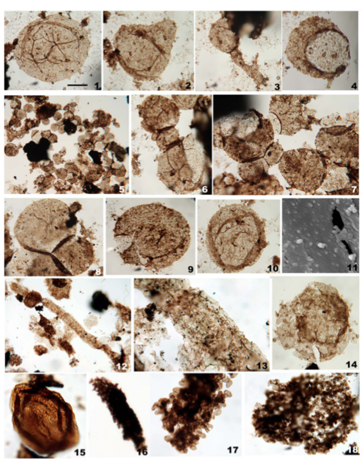
data from many sources

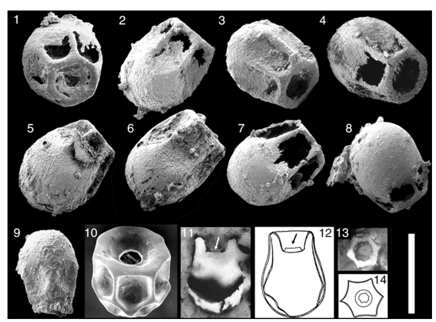
atmosphere to the deep ocean

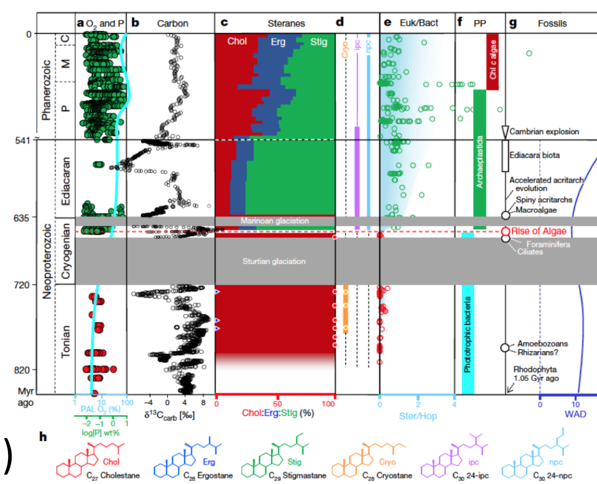
Lyons et al.

Co-evolving Life







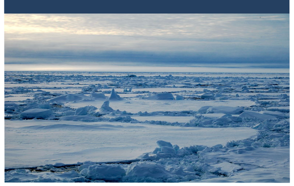


Brocks et al. (2017)

Ediacaran

635 Ma

Cryogenian



720 Ma

nature Vol 457|5 February 2009|doi:10.1038/nature07673

LETTERS

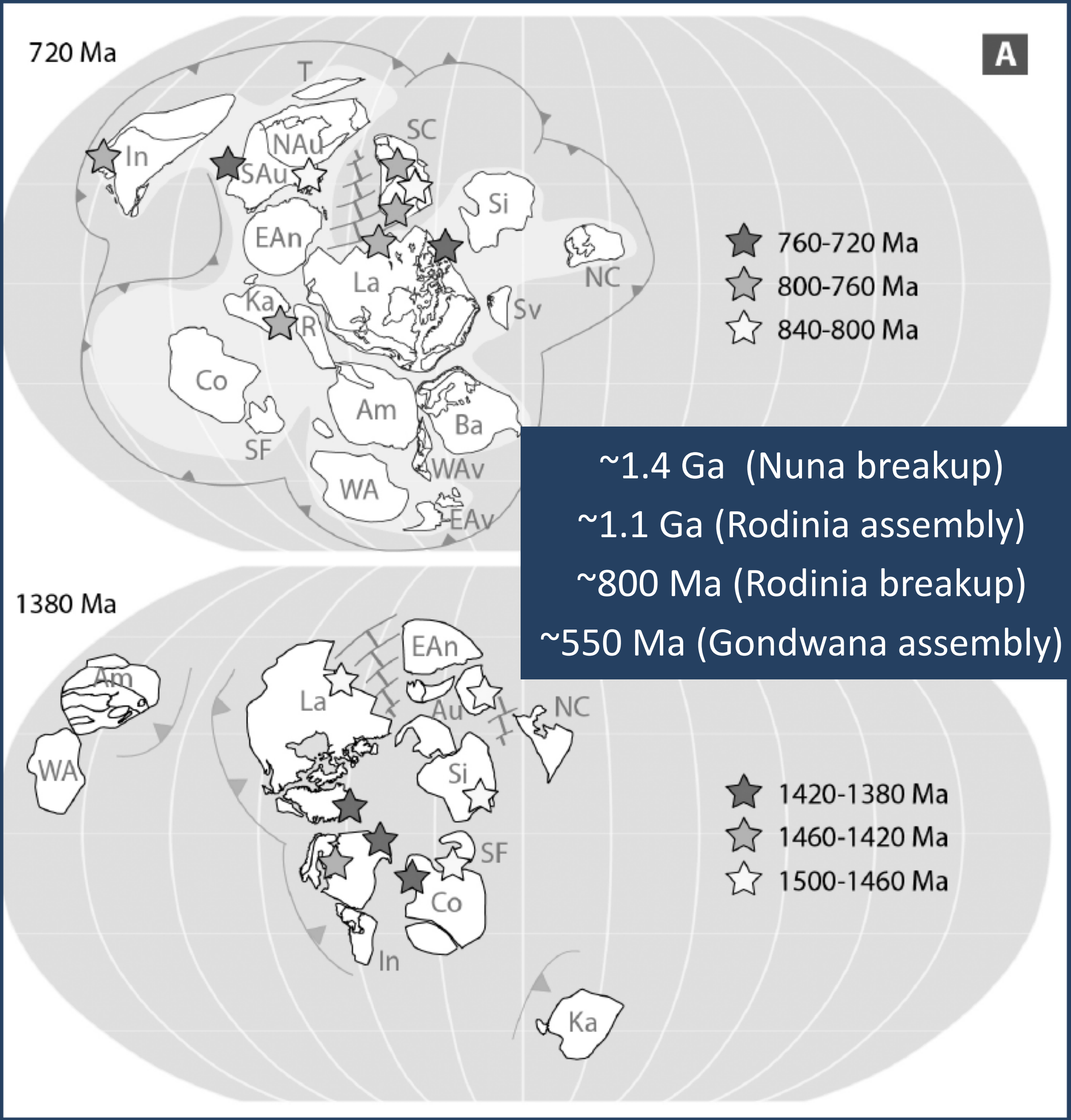
Fossil steroids record the appearance of Demospongiae during the Cryogenian period

Gordon D. Love[1,2], Emmanuelle Grosjean[3], Charlotte Stalvies[4], David A. Fike[5], John P. Grotzinger[5], Alexander S. Bradley[2], Amy E. Kelly[2], Maya Bhatia[2], William Meredith[6], Colin E. Snape[6], Samuel A. Bowring[2], Daniel J. Condon[2]† & Roger E. Summons[2]

Tectonic Drivers

Rodinia
(Neoprot.)

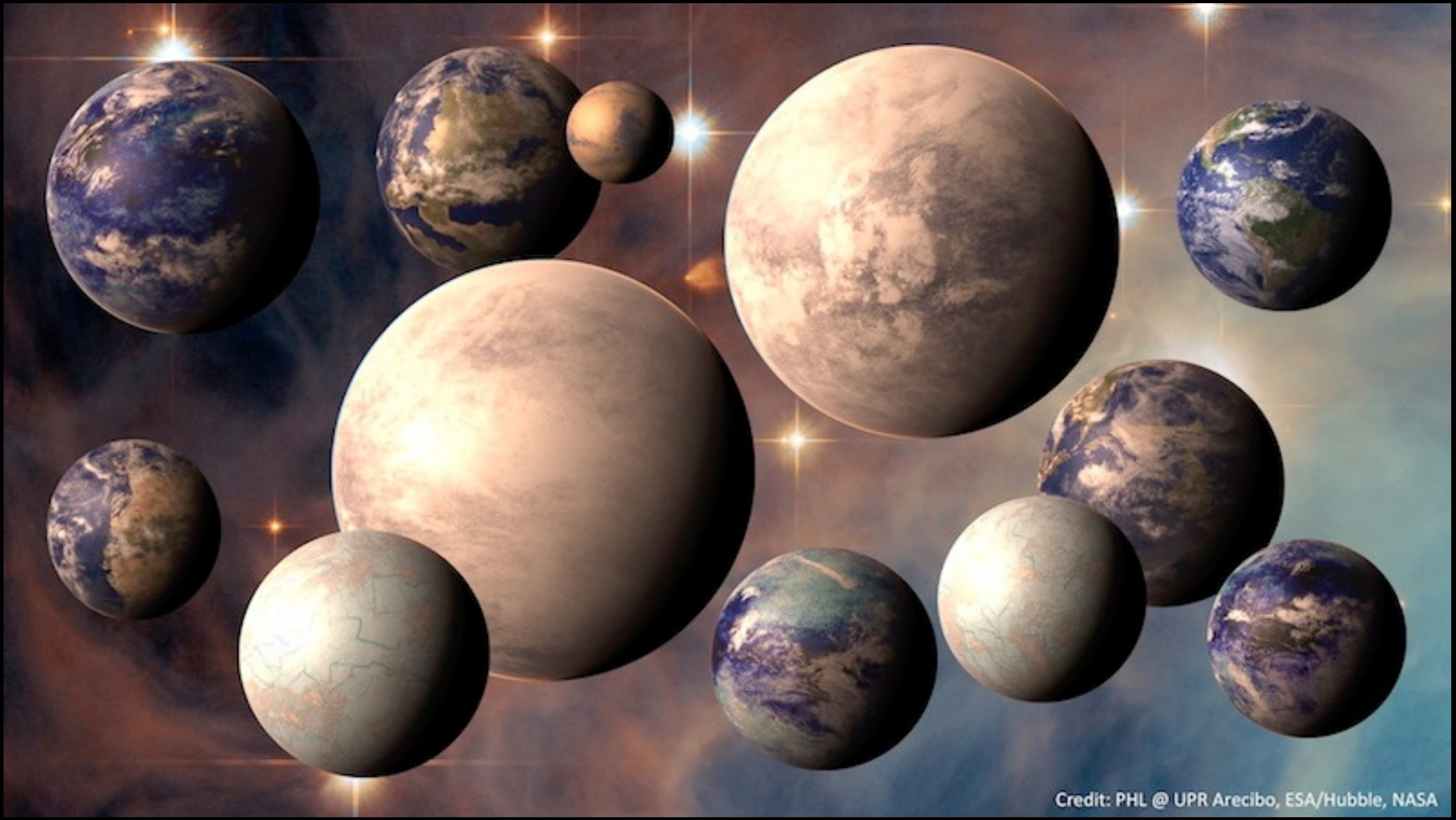
Nuna
(mid-Prot.)
"boring billion"



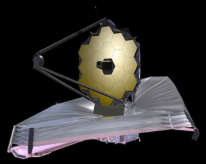
~1.4 Ga (Nuna breakup)
~1.1 Ga (Rodinia assembly)
~800 Ma (Rodinia breakup)
~550 Ma (Gondwana assembly)

Dave Evans in Planavsky et al. (2015)

The Extrapolation



Vertical Integration



Detectability informed by present and future telescopes using instrument simulators.

Synthetic spectra via atmosphere radiative transfer models.

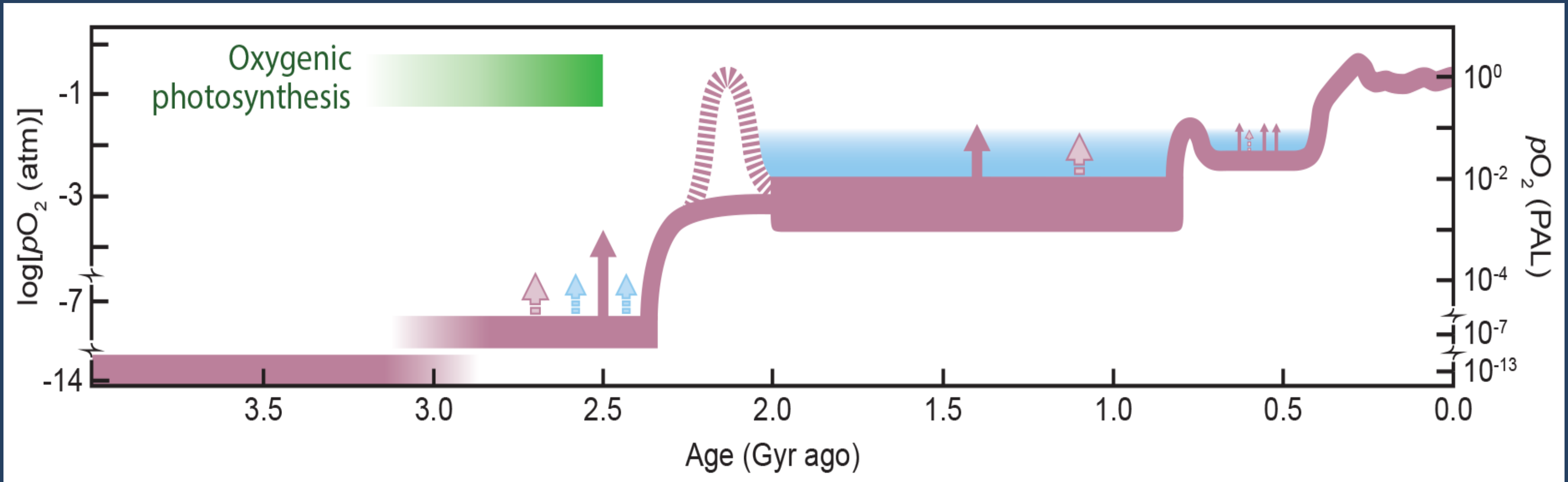
1- and 3-D photochemical climate models.

3-D models define ocean properties and fluxes to atmos.

Proxies developed by us and applied to early Earth to constrain ocean/atmosphere compositions.

Diverse planetary scenarios — in terms of habitability and biosignatures (guided by early ‘alternative’ Earths).

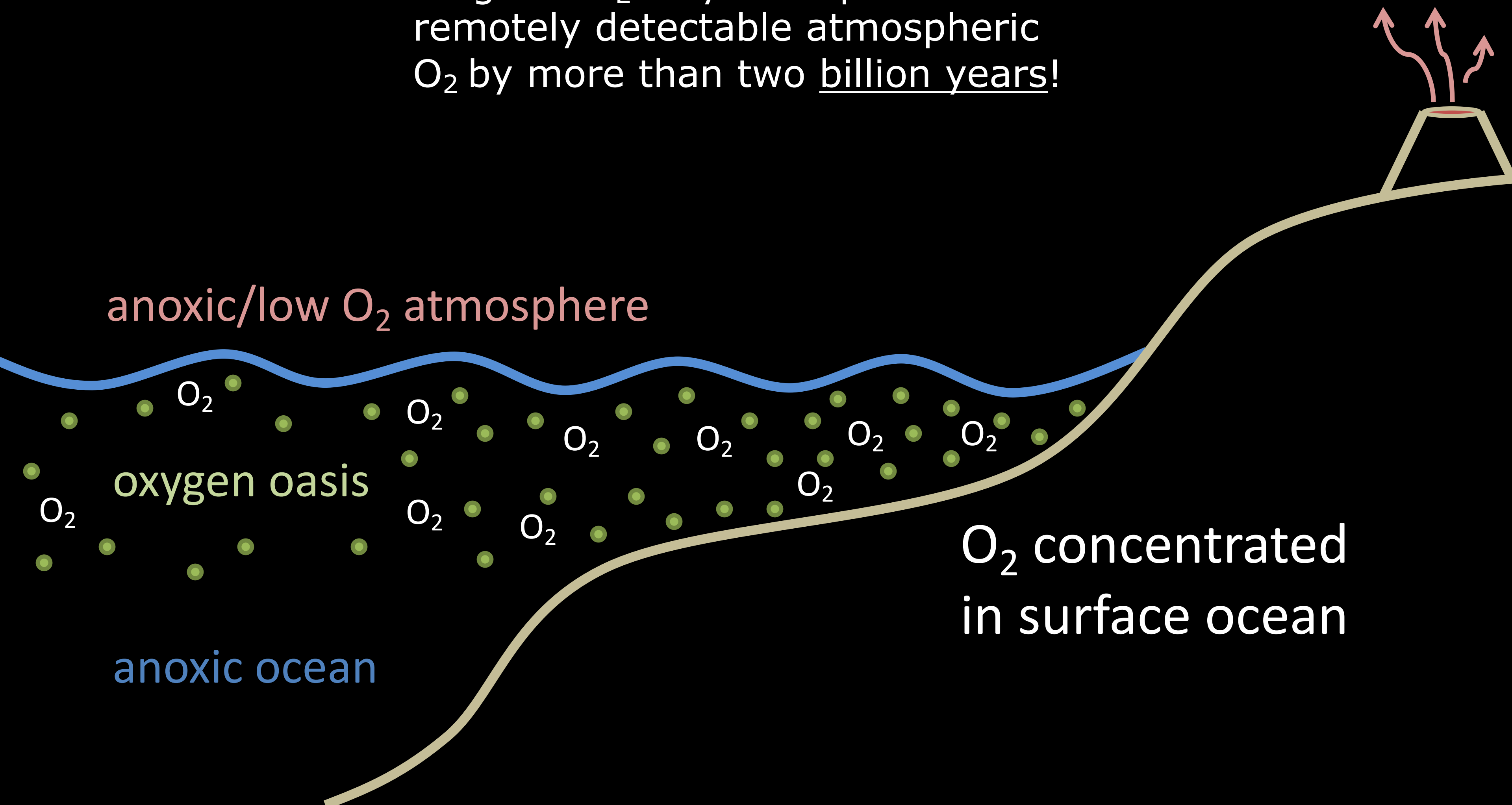
Earth's History of Evolving O_2



after Lyons et al. (2014)

Earth's atmosphere may have been an unfaithful reflection of surface chemistry and biology

✧ Biogenic O_2 may have predated remotely detectable atmospheric O_2 by more than two <u>billion years</u>!



mat-hosted micro-oases

- Chemical conditions that strongly differ from the surrounding environment
- High but extremely localized dissolved O_2 concentrations (**mm scale**)

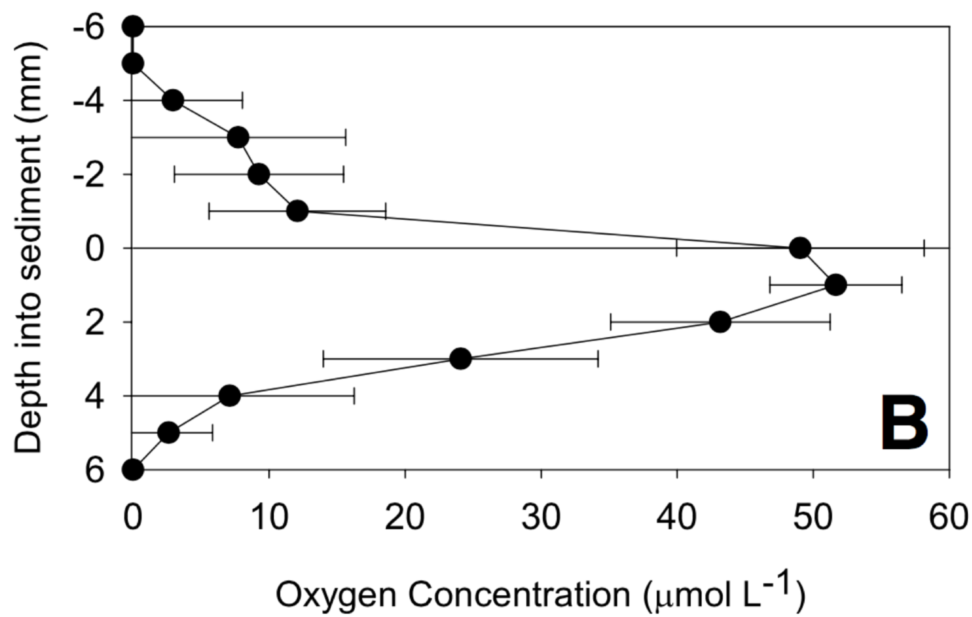
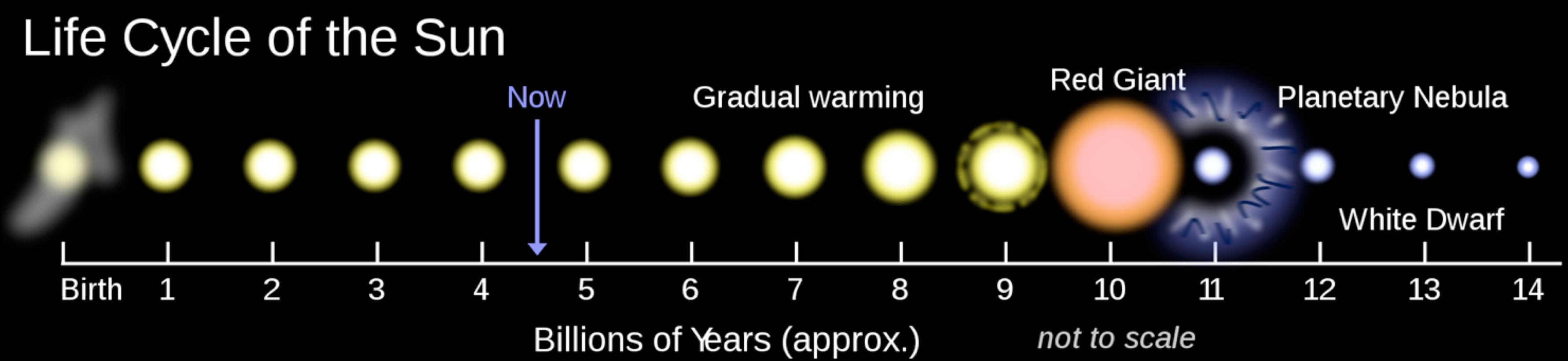


Photo: T. Bosak

Data: Sumner et al. (2015)

Warming Sun


Life Cycle of the Sun
Now
Gradual warming
Red Giant
Planetary Nebula
White Dwarf
Birth
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Billions of Years (approx.)
not to scale


high
CH4

Pathways of respiration (redox)

Aerobic respiration $(CH_2O)_x(NH_3)_y(H_3PO_4) + xO_2 + yH^+$ $\rightarrow xCO_2 + yNH_4^+ + HPO_4^{2-} + 2H^+ + xH_2O$	O_2
Denitrification $(CH_2O)_x(NH_3)_y(H_3PO_4) + \frac{4}{5}xNO_3^- + (\frac{4}{5}x + y)H^+$ $\rightarrow xCO_2 + yNH_4^+ + \frac{2}{5}xN_2 + HPO_4^{2-} + \frac{7}{5}xH_2O$	NO_3^-
Dissimilatory manganese reduction $(CH_2O)_x(NH_3)_y(H_3PO_4) + 2xMnO_2 + (4x + y)H^+$ $\rightarrow xCO_2 + 2xMn^{2+} + yNH_4^+ + HPO_4^{2-} + 2H^+ + 3xH_2O$	Mn(IV)
Dissimilatory iron reduction $(CH_2O)_x(NH_3)_y(H_3PO_4) + 4xFe(OH)_3 + (8x + y)H^+$ $\rightarrow xCO_2 + 4xFe^{2+} + yNH_4^+ + HPO_4^{2-} + 2H^+ + 11xH_2O$	Fe(III)
Sulfate reduction $(CH_2O)_x(NH_3)_y(H_3PO_4) + \frac{1}{2}xSO_4^{2-} + (\frac{1}{2}x + y)H^+$ $\rightarrow xCO_2 + \frac{1}{2}x\Sigma H_2S + yNH_4^+ + HPO_4^{2-} + H^+ + xH_2O$	SO_4^{2-}
Methanogenesis $(CH_2O)_x(NH_3)_y(H_3PO_4) + yH^+$ $\rightarrow \frac{1}{2}xCO_2 + \frac{1}{2}xCH_4 + yNH_4^+ + HPO_4^{2-} + 2H^+$	

AOM: $CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O$

METHANE MUTED

How Did Early Earth Stay Warm?

The Alternative Earths Team of the NASA Astrobiology Institute finds that, contrary to popular climate models for the distant past, methane could not be the gas that kept the oceans liquid and livable.

SO_4^{2-}

For at least a billion years of its early history, planet Earth should have been frozen over but wasn't. The sun was up to 20% dimmer than it is today—too weak to warm the planet on its own. Atmospheric models hype methane, a potent greenhouse gas, as the primary climate warming agent for the first 3.5 billion years of Earth history, because oxygen was absent initially and little more than a whiff later on. … a matter of years.)

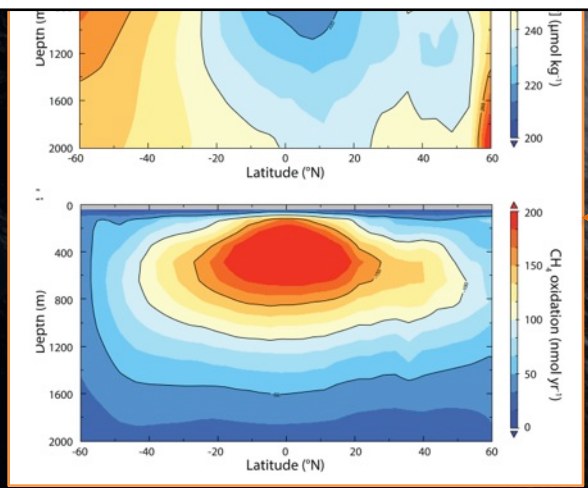
PNAS, Sept. 26, 201

Low methane flux plus weak ozone shielding

Stephanie Olson
UC Riverside

Chris Reinhard
Georgia Tech

Tim Lyons
UC Riverside



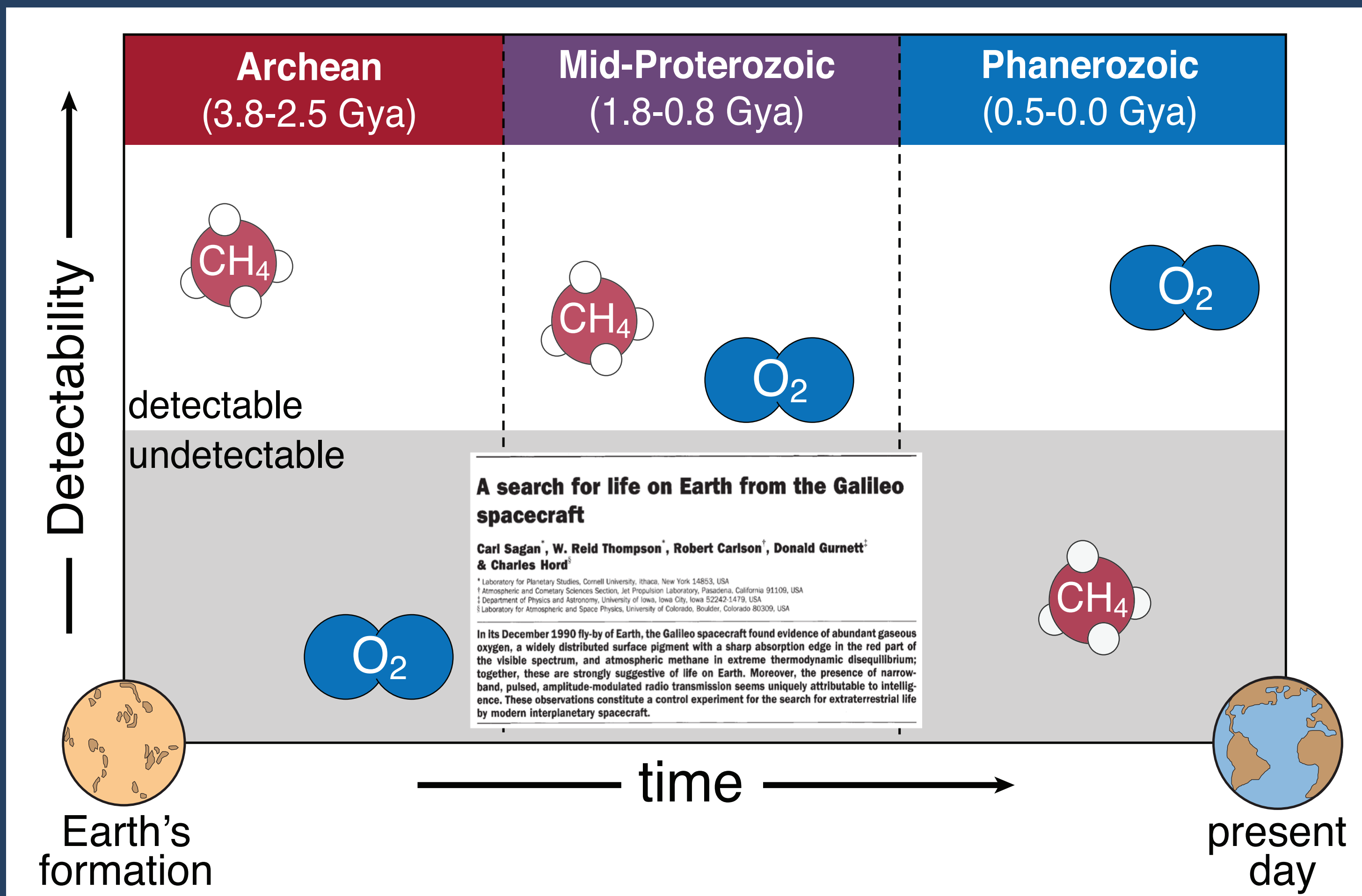
… biogeochemical cycles in …hich is produced in the … ferment organic matter, … oxygen: sulfate. Between …, seawater sulfate limited both the production and accumulation of methane to only 1 to 10 parts per million (ppm) in the atmosphere. That's a fraction of the 300 ppm touted by some previous models—*and well below remote detection limits of current technology*

INNOVATION | The numerical model used in this study, which calculated sulfate reduction (*top*), methane oxidation (*bottom*), and an array of other biogeochemical cycles for nearly 15,000 three-dimensional regions of the ocean, is by far the highest resolution biogeochemical model ever applied to the ancient Earth. Previous models used no more than five regions.

IMPACT | Astrobiologists now face a serious challenge to explain our planet's early habitability. Identifying early Earth's precise greenhouse cocktail, probably including water vapor, nitrous oxide, and carbon dioxide, is essential for spectroscopic efforts to assess the habitability of other planets in our galaxy.

BACKGROUND IMAGE This artist's depiction of an ice-covered planet in a distant solar system resembles what early Earth might have looked like if a mysterious mix of greenhouse gases had not warmed the climate. **CREDIT: EUROPEAN SOUTHERN OBSERVATORY (ESO) VIA WIKIMEDIA COMMONS**

Alternative Earth Biosignatures: The Paradigm



A search for life on Earth from the Galileo spacecraft

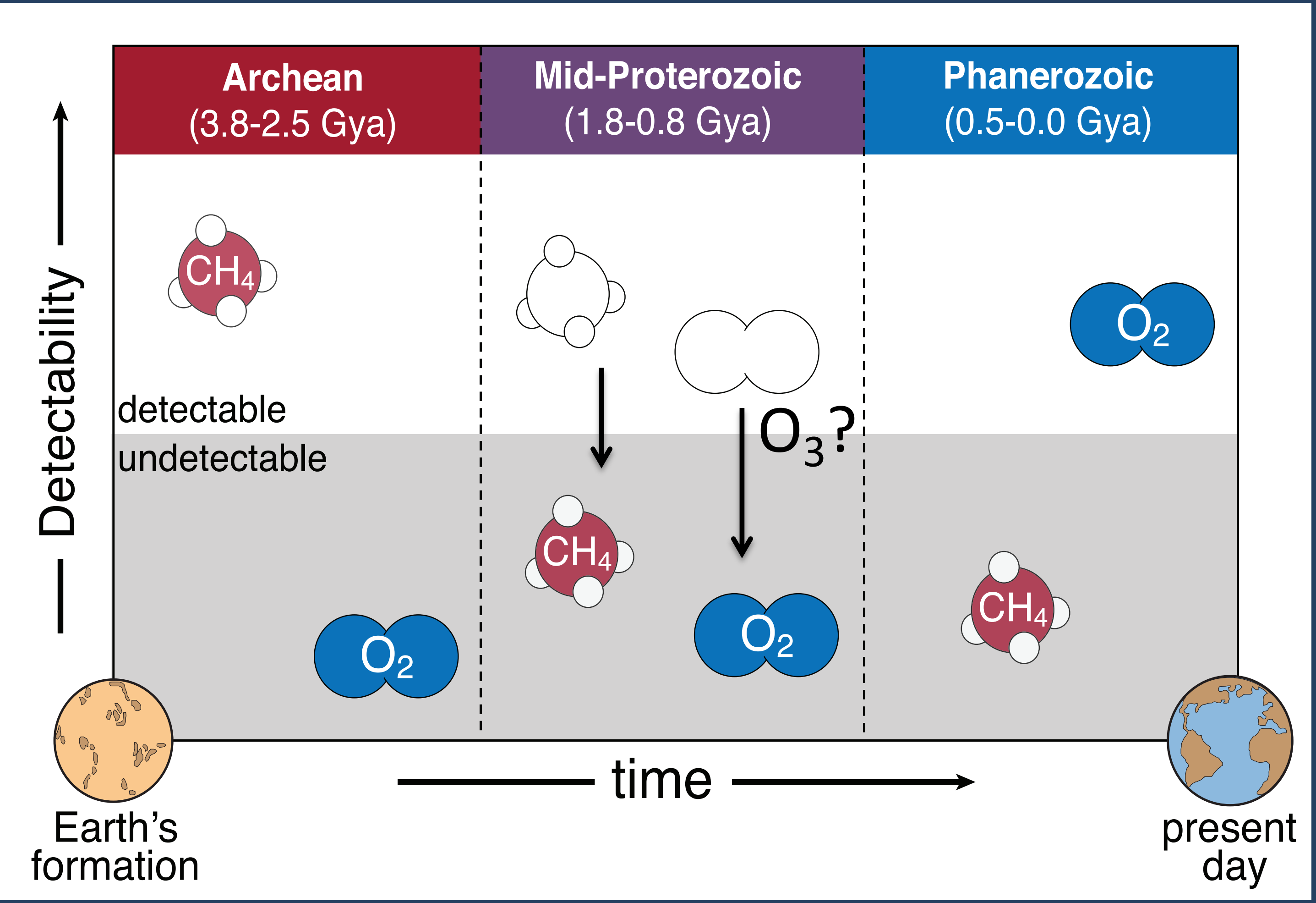
Carl Sagan*, W. Reid Thompson*, Robert Carlson†, Donald Gurnett‡ & Charles Hord§

* Laboratory for Planetary Studies, Cornell University, Ithaca, New York 14853, USA
† Atmospheric and Cometary Sciences Section, Jet Propulsion Laboratory, Pasadena, California 91109, USA
‡ Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242-1479, USA
§ Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado 80309, USA

In its December 1990 fly-by of Earth, the Galileo spacecraft found evidence of abundant gaseous oxygen, a widely distributed surface pigment with a sharp absorption edge in the red part of the visible spectrum, and atmospheric methane in extreme thermodynamic disequilibrium; together, these are strongly suggestive of life on Earth. Moreover, the presence of narrow-band, pulsed, amplitude-modulated radio transmission seems uniquely attributable to intelligence. These observations constitute a control experiment for the search for extraterrestrial life by modern interplanetary spacecraft.

after Des Marais et al. (2002)

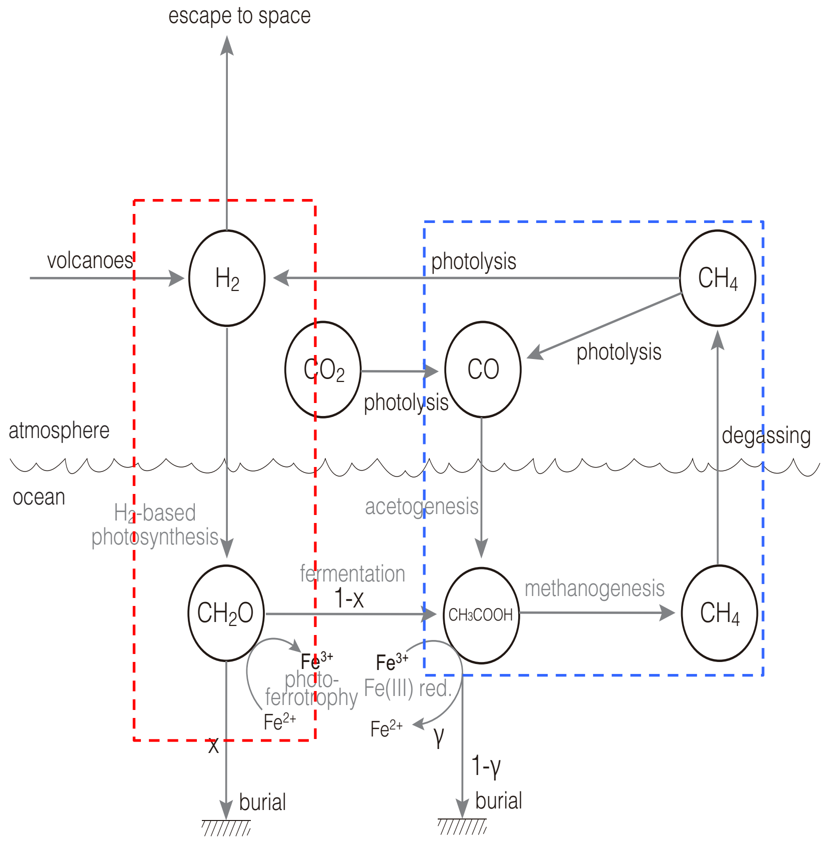
Alternative Earth Biosignatures: An Updated View and False Negatives



modified from Schwieterman et al. (Astrobiology, 2018)

Rethinking CO 'Anti-Biosignatures' in the Search For Life Beyond Earth

Schwieterman et al. (2019)



We demonstrate using a 1-D ecosphere-atmosphere model that anoxic biospheres can easily sustain CO levels exceeding 100 ppmv even at low H_2 fluxes, due to the impact of hybrid photosynthetic ecosystems.

For some exoplanets, remotely detectable carbon monoxide may actually be diagnostic of a robust microbial biosphere.

$$CO_2 + H_2O \underset{\text{Respiration}}{\overset{\text{Photosynthesis}}{\rightleftharpoons}} CH_2O + O_2$$

solubility highest when production is highest (muted)

solubility lowest when production is highest (O_3)

Insolation Temperature Gas solubility

The Astrophysical Journal Letters, 858:L14 (7pp), 2018 May 10 https://doi.org/10.3847/2041-8213/aac171

CrossMark

Atmospheric Seasonality as an Exoplanet Biosignature

Stephanie L. Olson[1,2], Edward W. Schwieterman[1,2,3,4], Christopher T. Reinhard[1,5], Andy Ridgwell[1,2], Stephen R. Kane[1,2], Victoria S. Meadows[1,6], and Timothy W. Lyons[1,2]
[1] NASA Astrobiology Institute Alternative Earths and Virtual Planetary Laboratory Teams
[2] Department of Earth Science, University of California, Riverside, CA, USA
[3] NASA Postdoctoral Program, Universities Space Research Association, Columbia, MD, USA
[4] Blue Marble Space Institute of Science, Seattle, WA, USA
[5] School of Earth and Atmospheric Science, Georgia Institute of Technology, Atlanta, GA, USA
[6] Department of Astronomy, University of Washington, Seattle, WA, USA
Received 2018 January 14; revised 2018 April 30; accepted 2018 April 30; published 2018 May 9

O_2 flux CO_2 flux

Importance of direct imaging

Thanks

Received: 6 July 2018 | Accepted: 27 August 2018

DOI: 10.1111/gbi.12317

ORIGINAL ARTICLE

WILEY geobiology

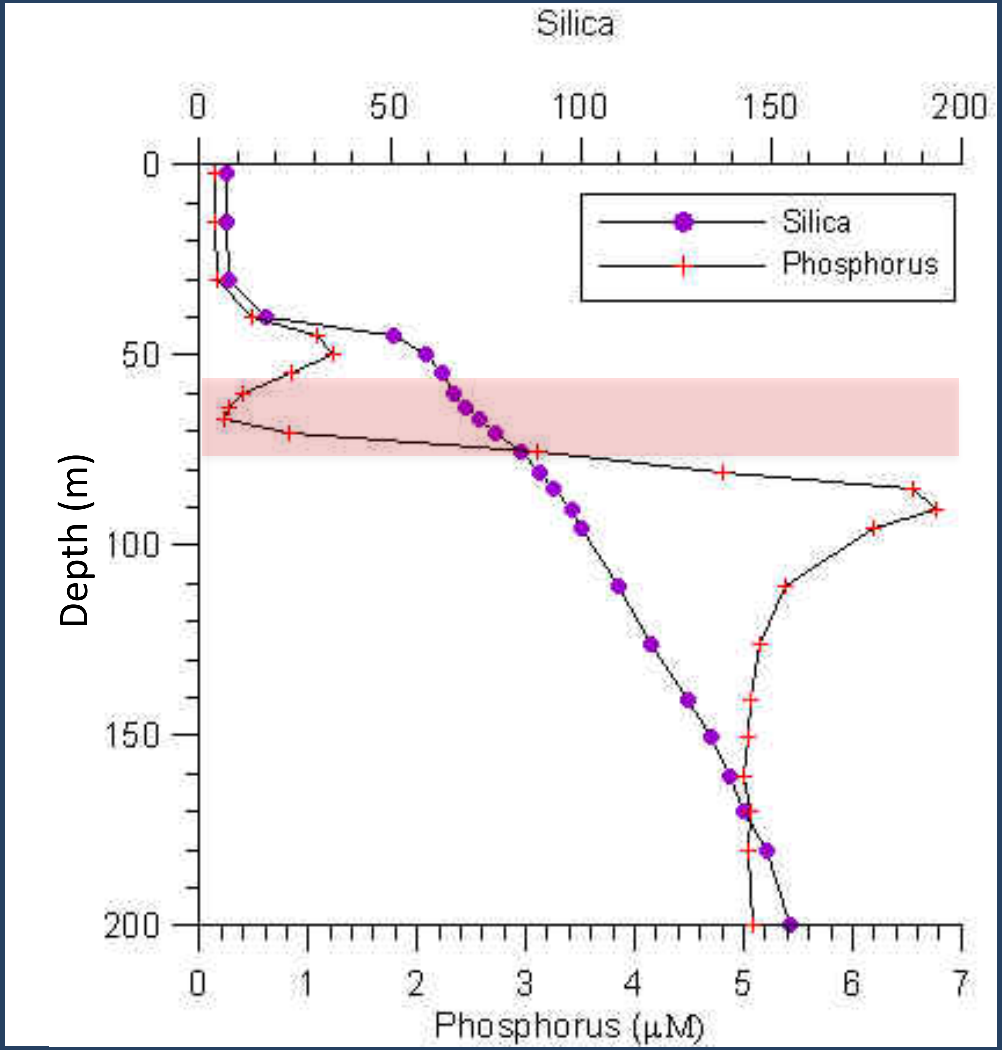
A sluggish mid-Proterozoic biosphere and its effect on Earth's redox balance

Kazumi Ozaki[1,2,3] | Christopher T. Reinhard[1,2] | Eiichi Tajika[4]

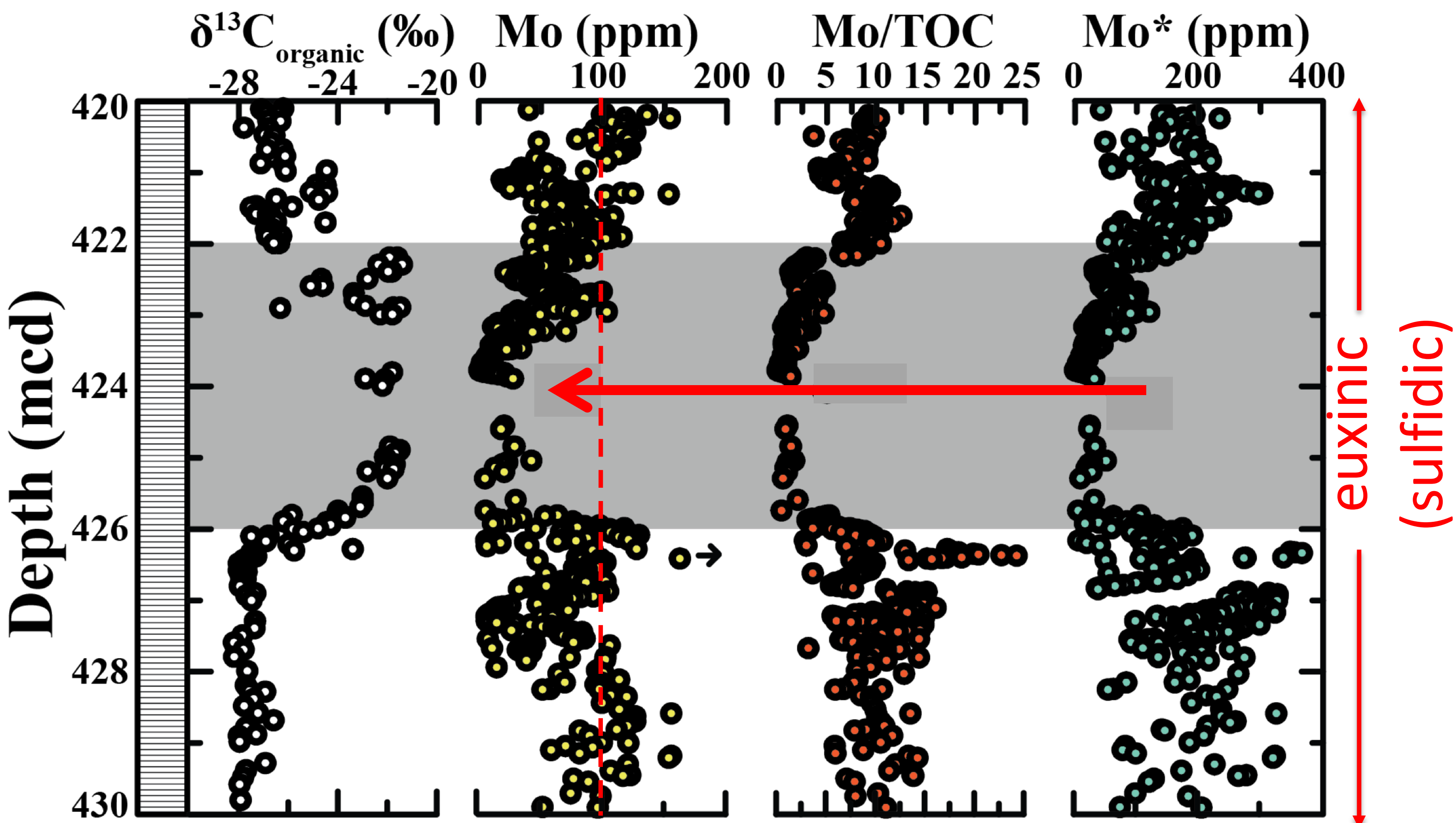
By employing a Monte Carlo approach bounded by observations from the geologic record, we infer that the rate of net biospheric O_2 production was ~25% of today's value, owing largely to phosphorus scarcity in the ocean interior.

Iron trap?

Black Sea

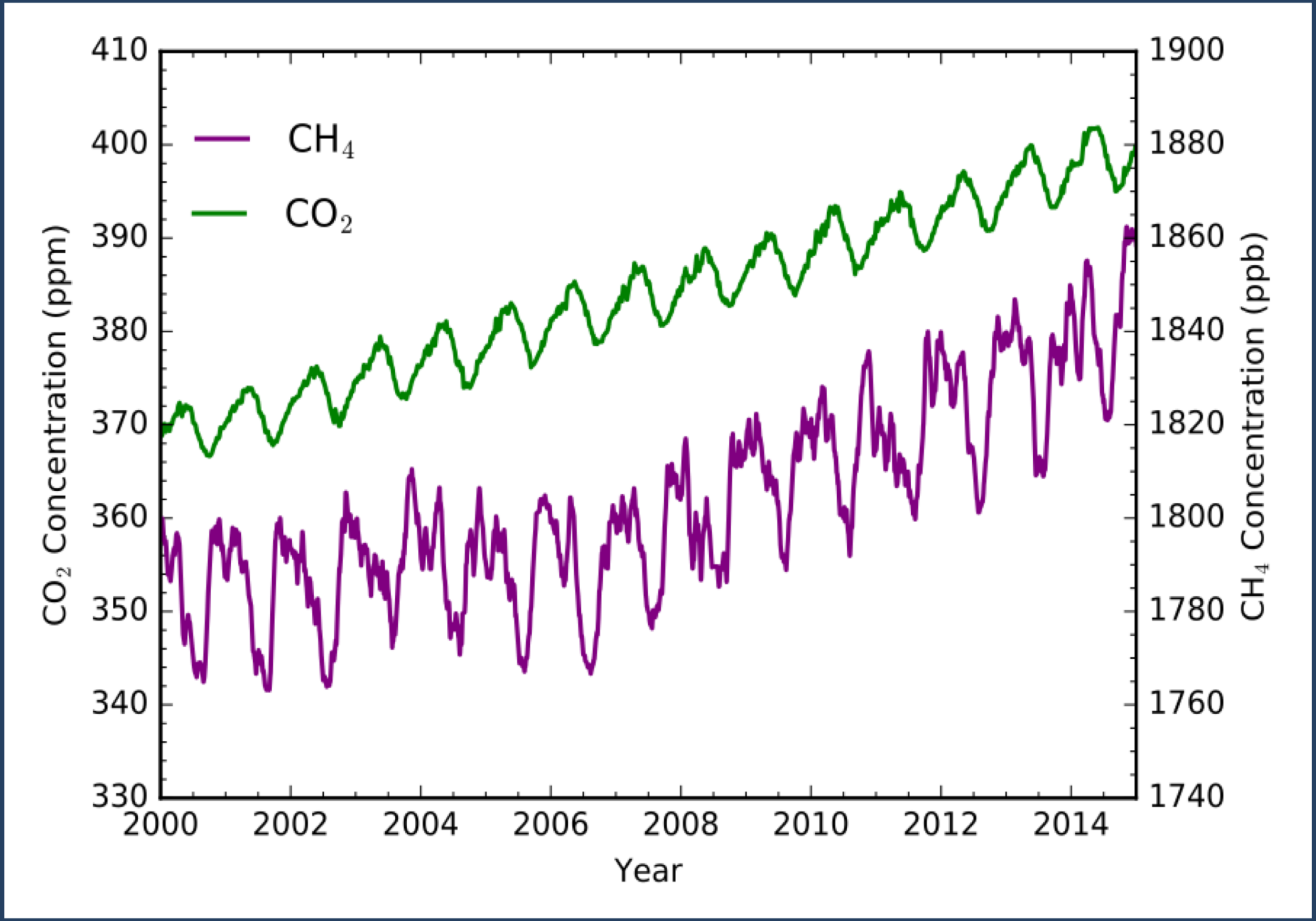


Proof of Concept:
Cretaceous OAE 2, Demerara Rise

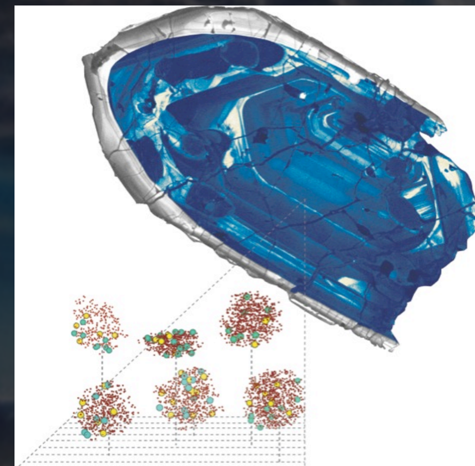


Owens et al. (2016)

The seasonal variations in both gases are partially reflective of the seasonal change in the productivity of the biosphere in the northern hemisphere (The secular increase in both gases is attributable to industrial emissions)



Cooled Quickly, Early Oceans



Valley et al. (2014)

Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago

Simon A. Wilde*, John W. Valley†, William H. Peck†‡ & Colin M. Graham§

(Nature, 2001)

Got Life?

^{13}C-Depleted Carbon Microparticles in >3700-Ma Sea-Floor Sedimentary Rocks from West Greenland

Minik T. Rosing

(Science, 1999)

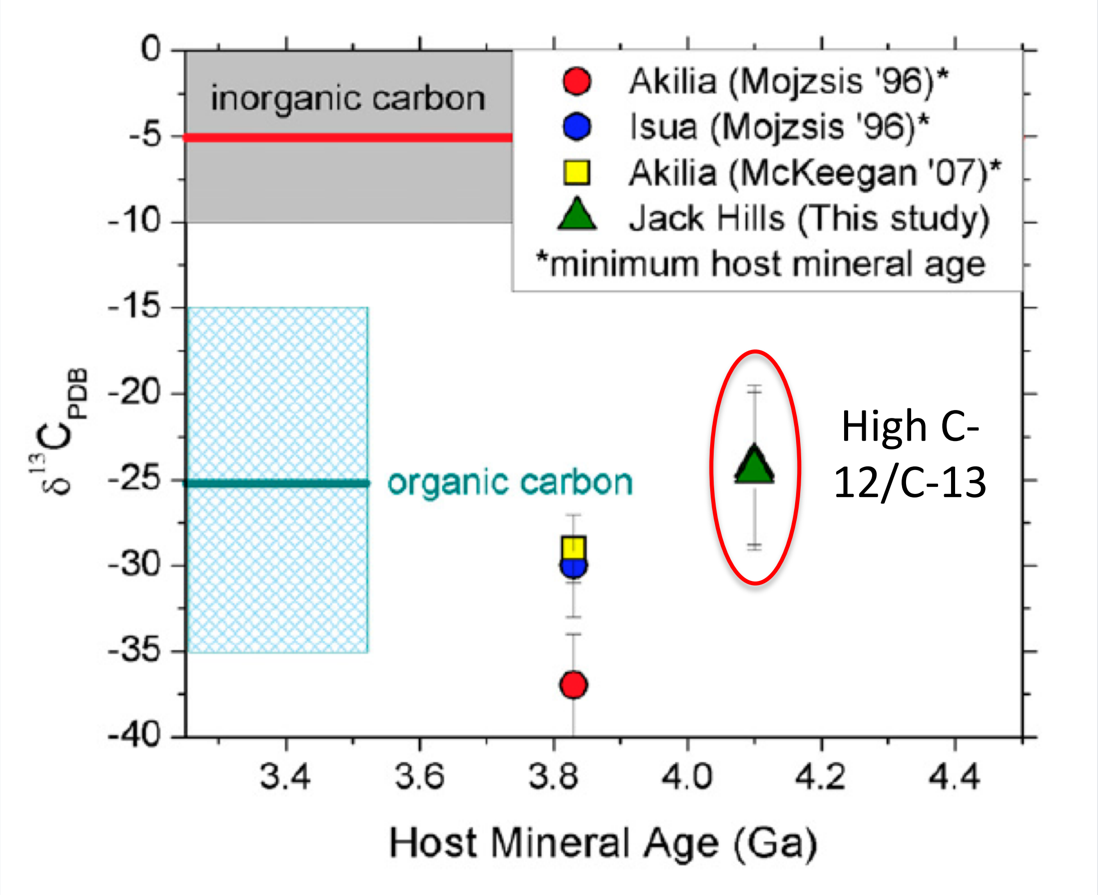
$$^{(12,13)}CO_2 + H_2O \xrightarrow{\text{light}} {}^{(12,13)}CH_2O + O_2$$

Isotopes: two or more forms of the same element that contain equal numbers of protons but different numbers of neutrons in their nuclei.

Potentially biogenic carbon preserved in a 4.1 billion-year-old zircon

Elizabeth A. Bell[a,1], Patrick Boehnke[a], T. Mark Harrison[a,1], and Wendy L. Mao[b]

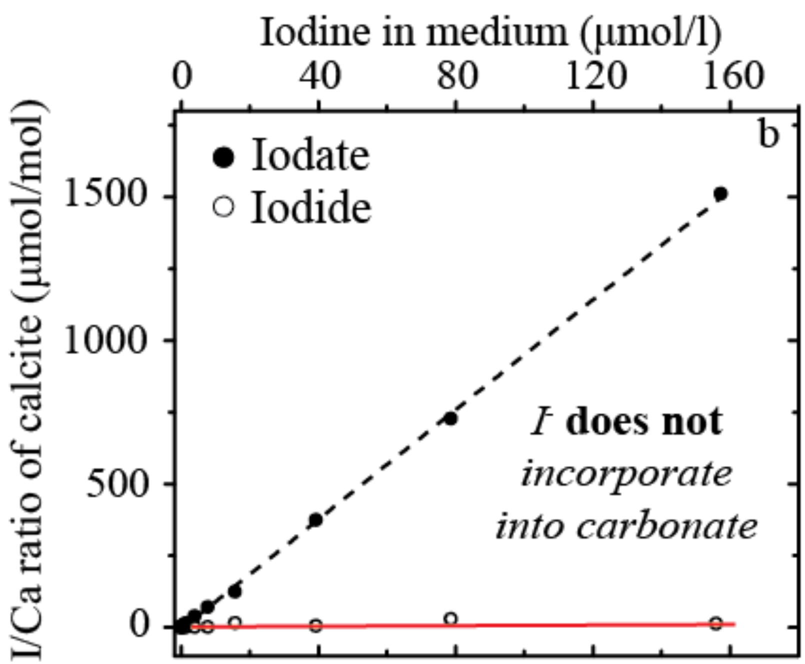
(PNAS, 2015)



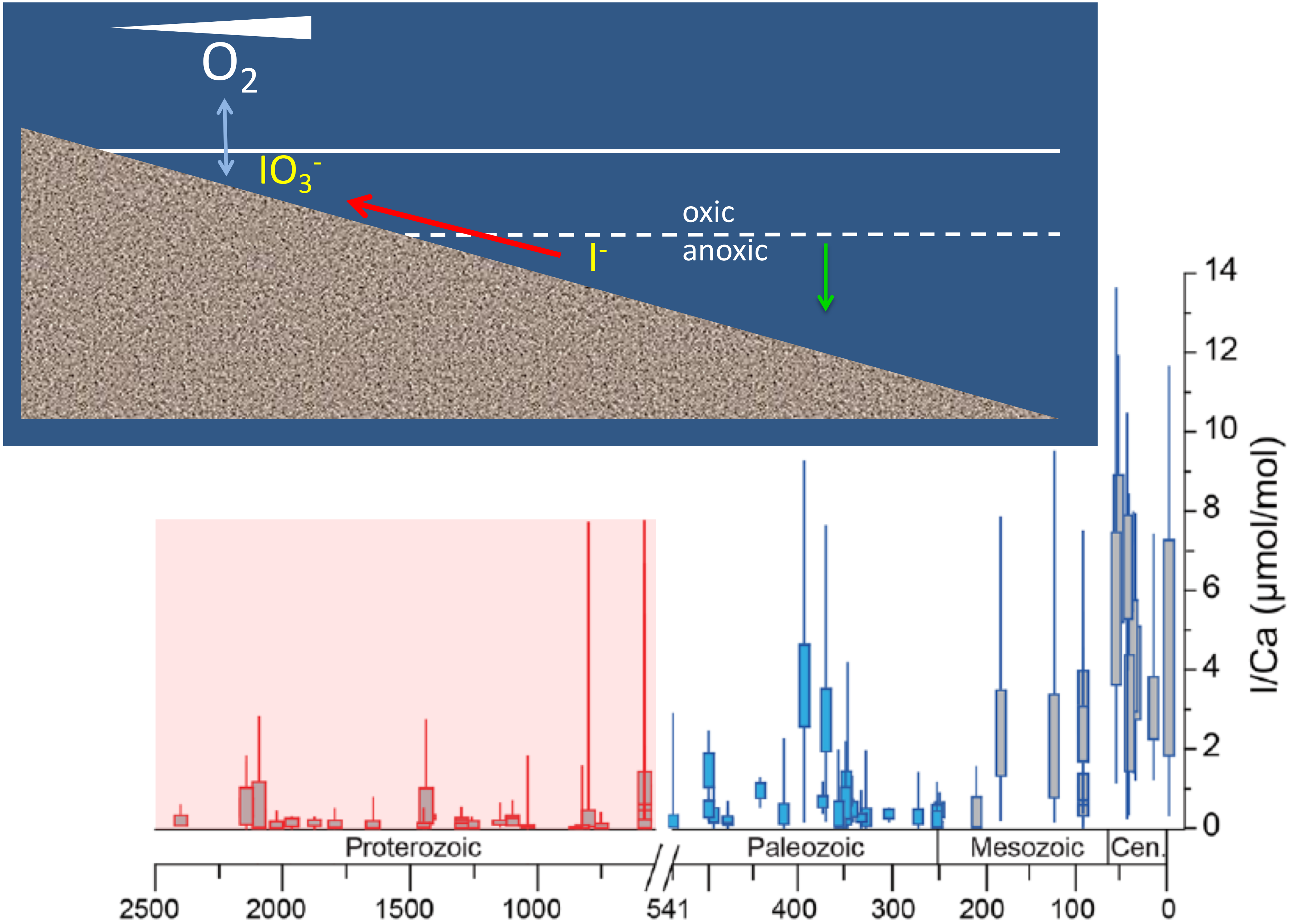
The shallow ocean: carbonate-associated iodine

iodide (I^-) → iodate (IO_3^-)

$O_2 \geq 1\text{-}3\ \mu M$ (>200 µM in the surface mixed layer today)



adapted from Lu et al. (2010)

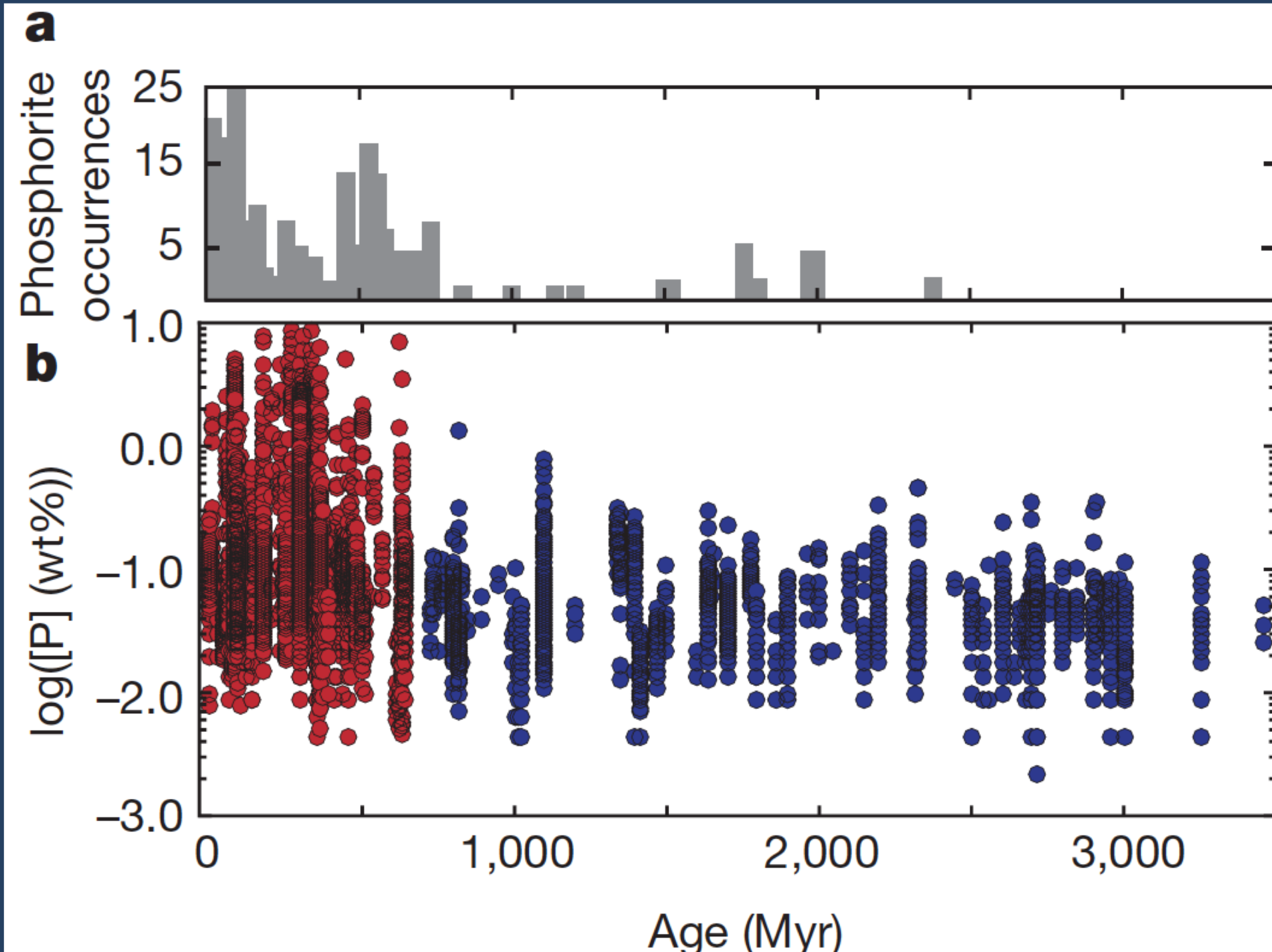


O2
IO3-
oxic
anoxic
I-
14
12
10
8
6
4
2
0
I/Ca (μmol/mol)
Proterozoic
Paleozoic
Mesozoic
Cen.
2500
2000
1500
1000
541
400
300
200
100
0
Age (Ma)

Lu et al. (2018)

Evolution of the global phosphorus cycle

Christopher T. Reinhard[1*], Noah J. Planavsky[2*], Benjamin C. Gill[3], Kazumi Ozaki[1,4], Leslie J. Robbins[5], Timothy W. Lyons[6], Woodward W. Fischer[7], Chunjiang Wang[8], Devon B. Cole[2] & Kurt O. Konhauser[5]



(2017)

P limitation?

Low rates of organic remineralization (high burial efficiency?)

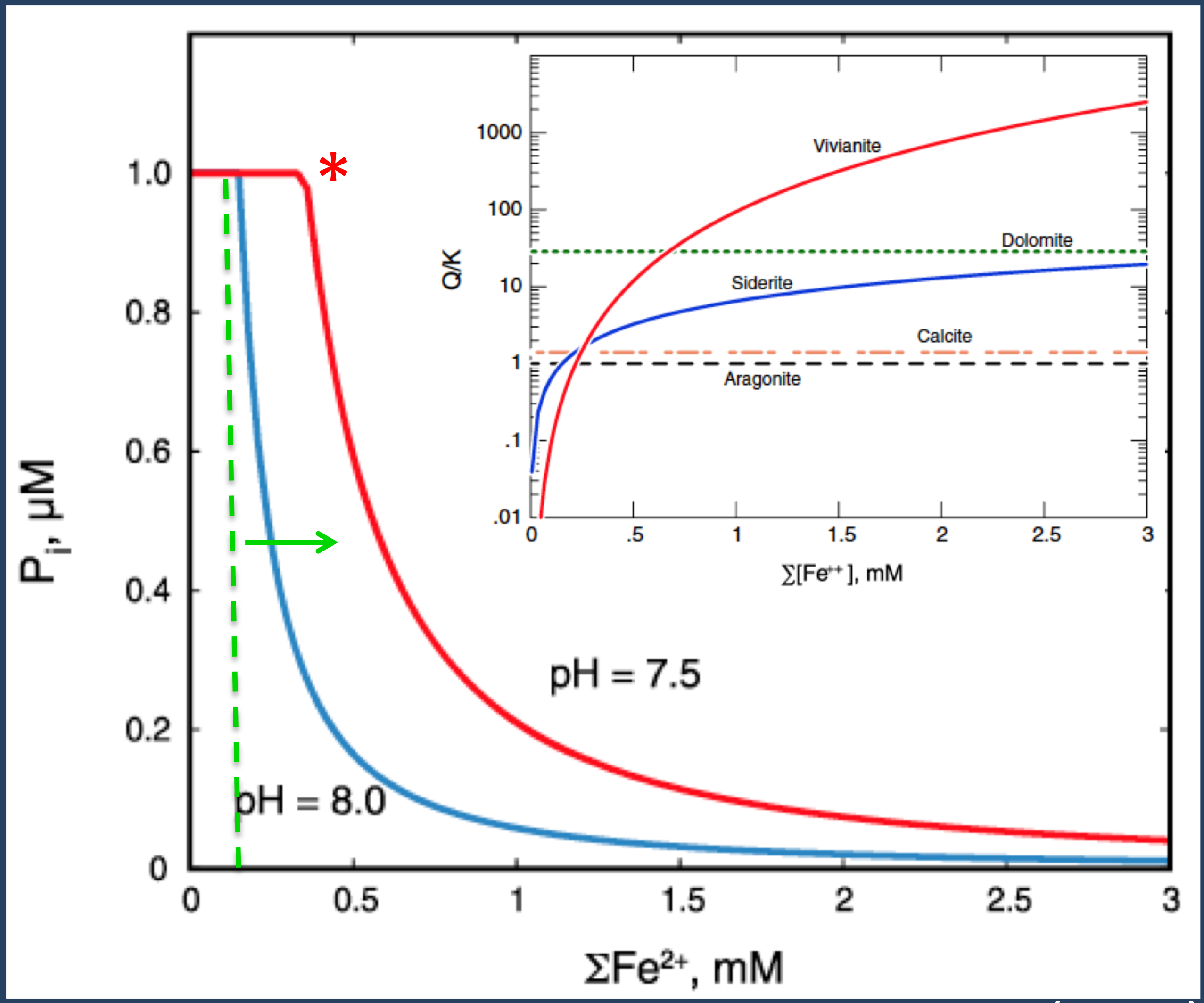
$$P_\mathrm{d} = P_\mathrm{s} + P_\mathrm{r}$$

$$P_\mathrm{d} = P_\mathrm{s} + \frac{[O_{2\mathrm{s}} - O_{2\mathrm{d}}]}{r_{\mathrm{O_2}}} + \frac{[\mathrm{NO_{3s}} - \mathrm{NO_{3d}}]}{r_{\mathrm{NO_3}}} + \frac{[\mathrm{Mn}O_{2\mathrm{s}} - \mathrm{Mn}O_{2\mathrm{d}}]}{r_{\mathrm{MnO_2}}} + \frac{[\mathrm{FeOOH_s} - \mathrm{FeOOH_d}]}{r_{\mathrm{FeOOH}}} + \frac{[\mathrm{SO_{4s}} - \mathrm{SO_{4d}}]}{r_{\mathrm{SO_4}}} + \mathrm{P_{CH_4}}$$

Kipp and Stüeken (2017)

Vivianite precipitation: P buffer?

$$3Fe^{2+} + 2HPO_4{}^{2-} + 8H_2O \Leftrightarrow Fe_3(PO_4)_2 \bullet 8H_2O + 2H^+$$



Derry (2015)

Iron trap?

Regulation of atmospheric oxygen during the Proterozoic

Thomas A. Laakso *, Daniel P. Schrag (2014)

"Low oxygen conditions are stable in our model if the flux of phosphorus to the oceans was greatly reduced during the Proterozoic. We propose a mechanism to reduce this flux through the scavenging of phosphate ions with an "iron trap" driven by greater surface mobility of ferrous iron in a low pO_2 world."

"In a low oxygen atmosphere, rivers would carry more ferrous iron because the kinetics of iron oxidation are slower. Slow oxidation of iron in solution in rivers and estuaries efficiently scavenges phosphorus."

soil crusts

Soil colonization places O_2 production within the weathering environment

Photos: USGS