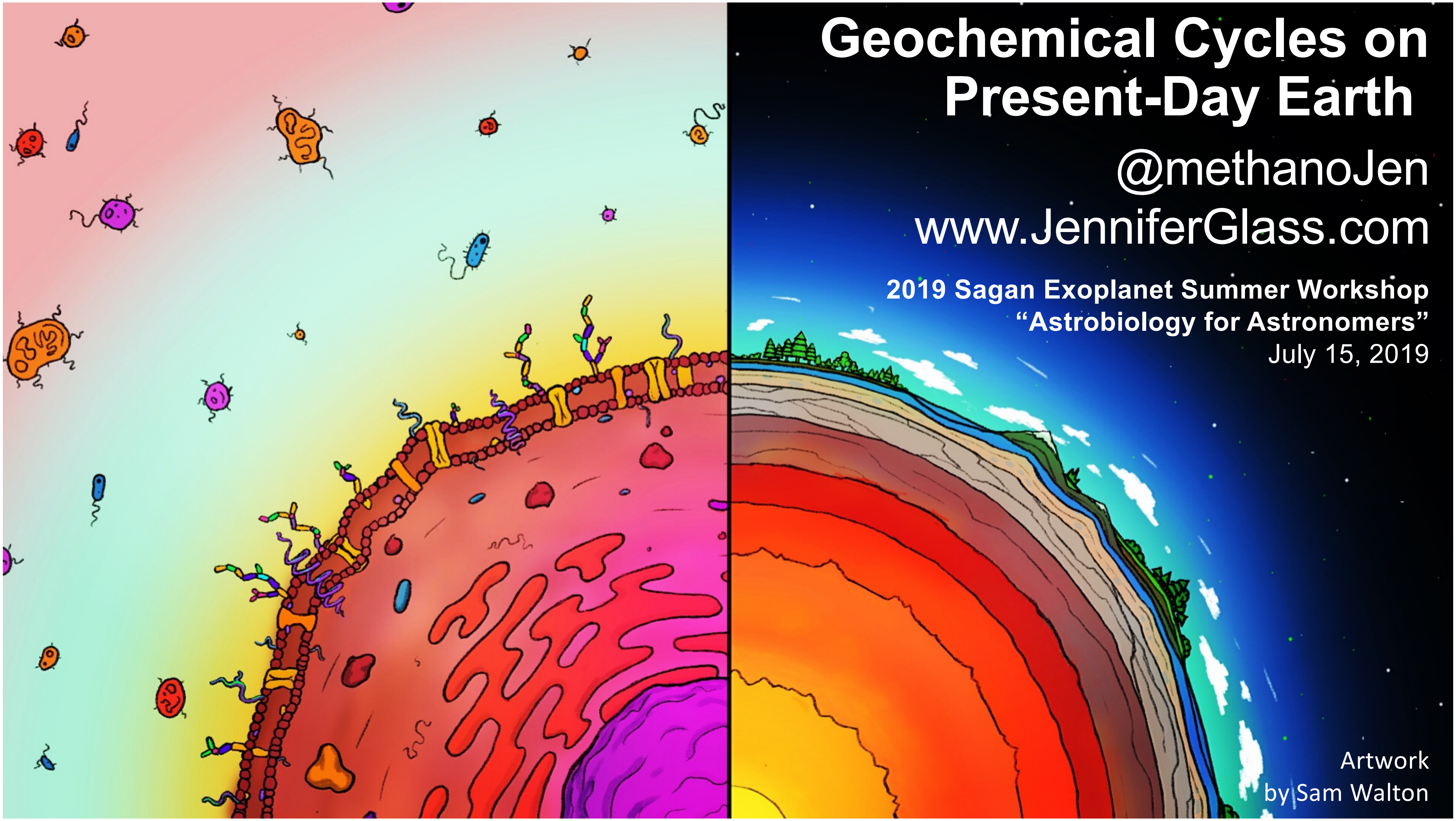


Geochemical Cycles on Present-Day Earth

@methanoJen

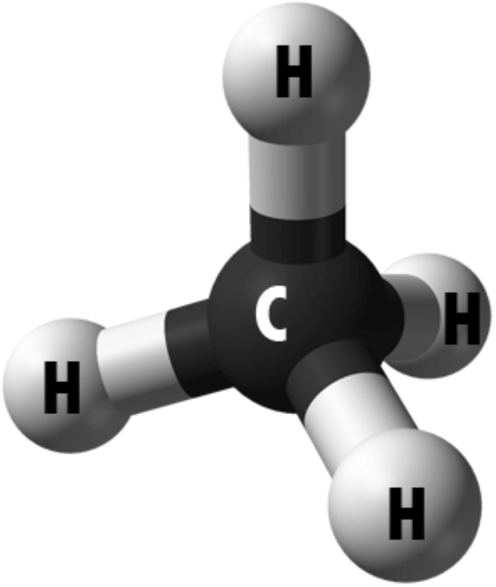
www.JenniferGlass.com

2019 Sagan Exoplanet Summer Workshop
“Astrobiology for Astronomers”
July 15, 2019

Artwork
by Sam Walton

On Earth, O_2 and CH_4 have *no significant abiotic sources*

N_2	78.08%
O_2	20.95%
Ar	0.93%
CO_2	0.0407%
Ne	0.0018%
He	0.000524%
CH_4	0.00018%

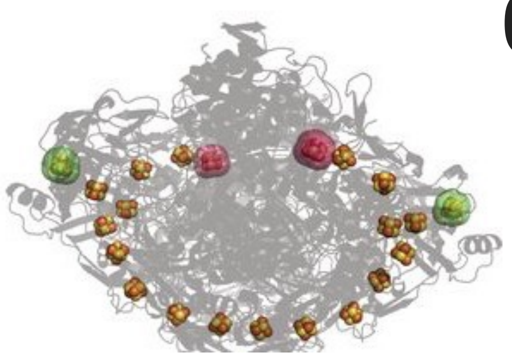
I. Modern  Cycle

Biological Methanogenesis

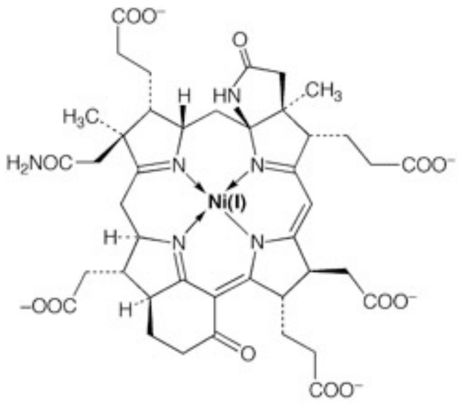
$$4H_2 + CO_2 \longrightarrow CH_4 + 2H_2O$$

0-120°C

no O_2



46 Fe-S clusters in first enzyme: FWD
Wagner et al., 2016, *Science*



Nickel cofactor F_{430} in last enzyme (MCR)

Abiotic Methane Production

$$4H_2 + CO_2 \longrightarrow CH_4 + 2H_2O$$

“Fischer-Tropsch Process”

$$3H_2 + CO \longrightarrow CH_4 + H_2O$$

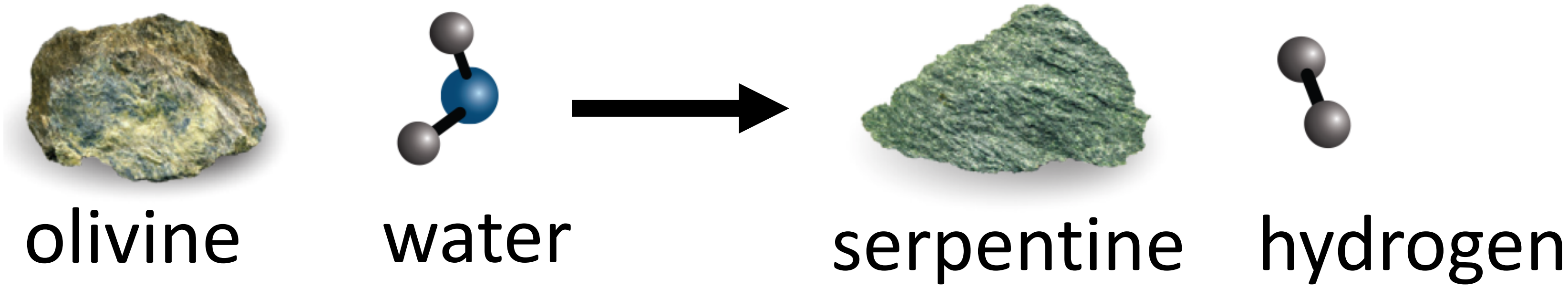
150–300 °C

Abiotic reactions are sluggish at low temperatures without mineral catalysts (Seewald et al. 2006, McCollom 2016)

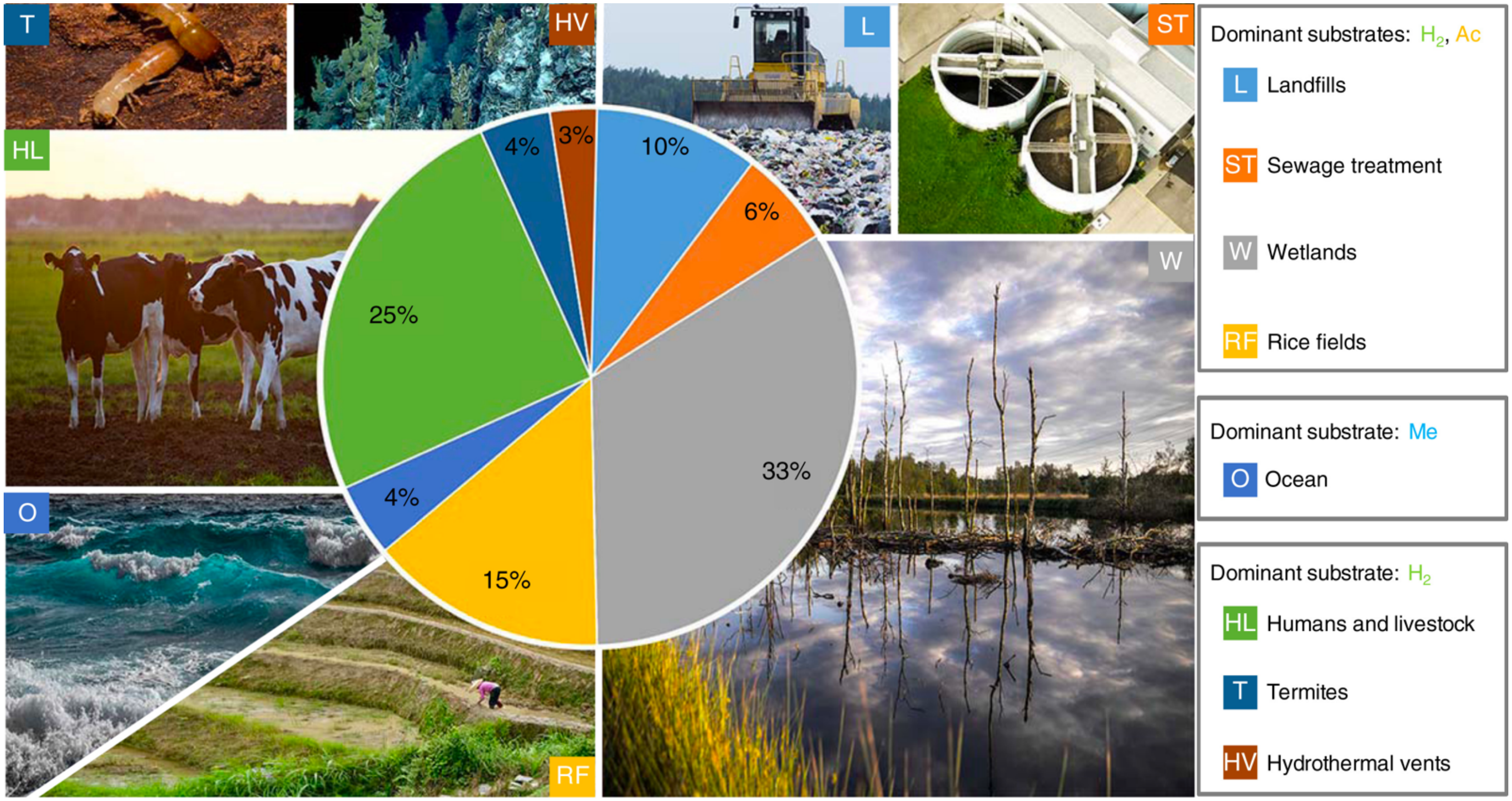
Methane production is overwhelmingly biological

"Abiotic methane production estimates from serpentinization ranging between approximately 1/30th and 1/150th the present biotic flux appear reasonable for modern Earth." - Arney et al., 2018, Astrobiology

Serpentinization: Source of Hydrogen



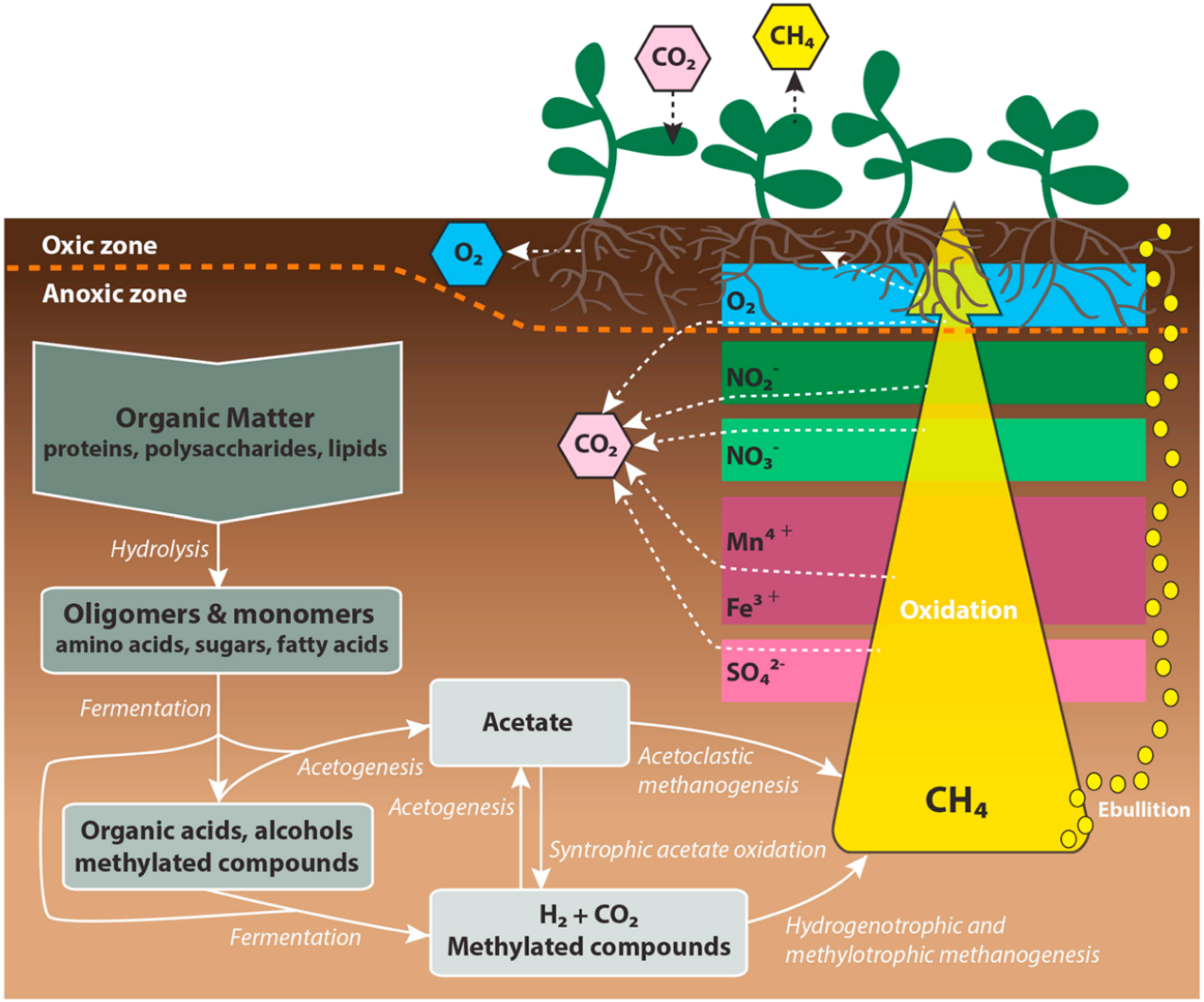
Biological methane emissions to the atmosphere



Current Biology

Lyu Z, Shao N, Akinyemi T, Whitman WB (2018) Methanogenesis. Current Biology 28: R727-R732

Methane cycling prior to release to atmosphere

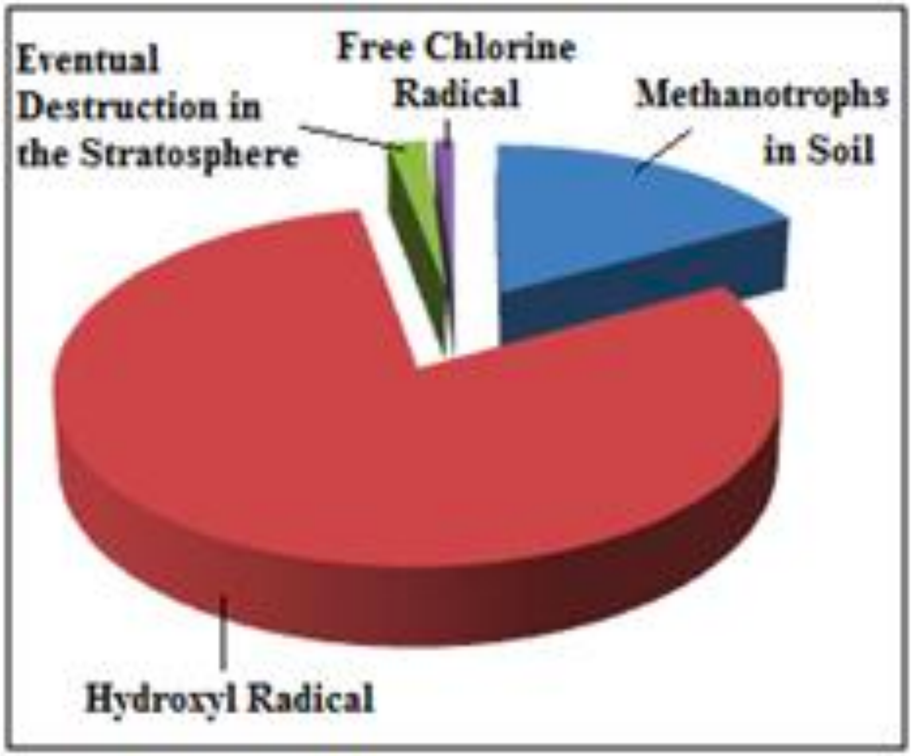


Dean JF, Middelburg JJ, Röckmann T., Aerts R, Blauw LG, Egger M, et al (2018). Methane feedbacks to the global climate system in a warmer world. Reviews of Geophysics, 56, 207–250.

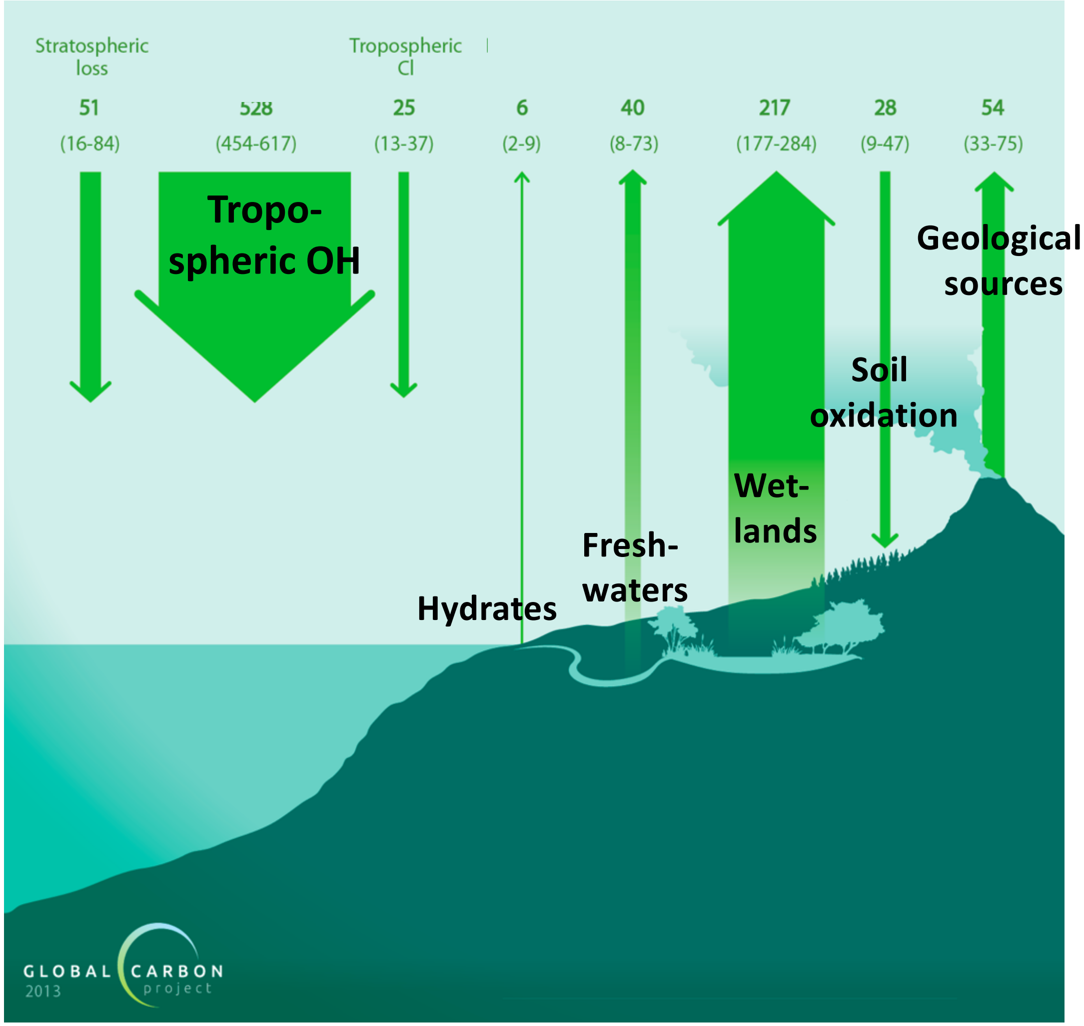
The major sinks for atmospheric methane is photolytic destruction, which depends on OH radicals

Modern methane’s atmospheric lifetime is ~10 years

May not go quite as fast in atmosphere without oxygen



Natural Methane Sources and Sinks (Tg yr^{-1})



Tropo-spheric OH

Geological sources

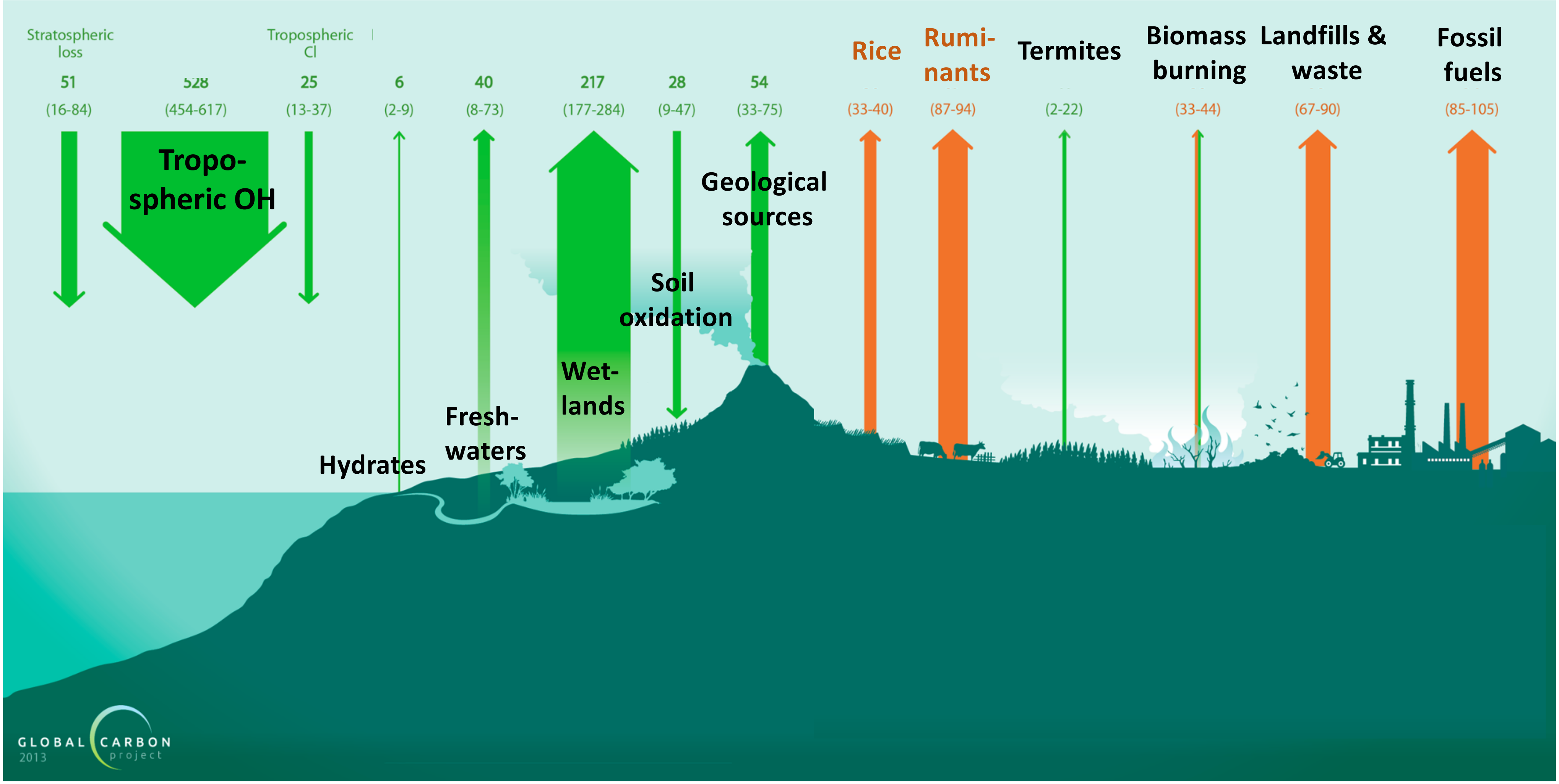
Soil oxidation

Wet-lands

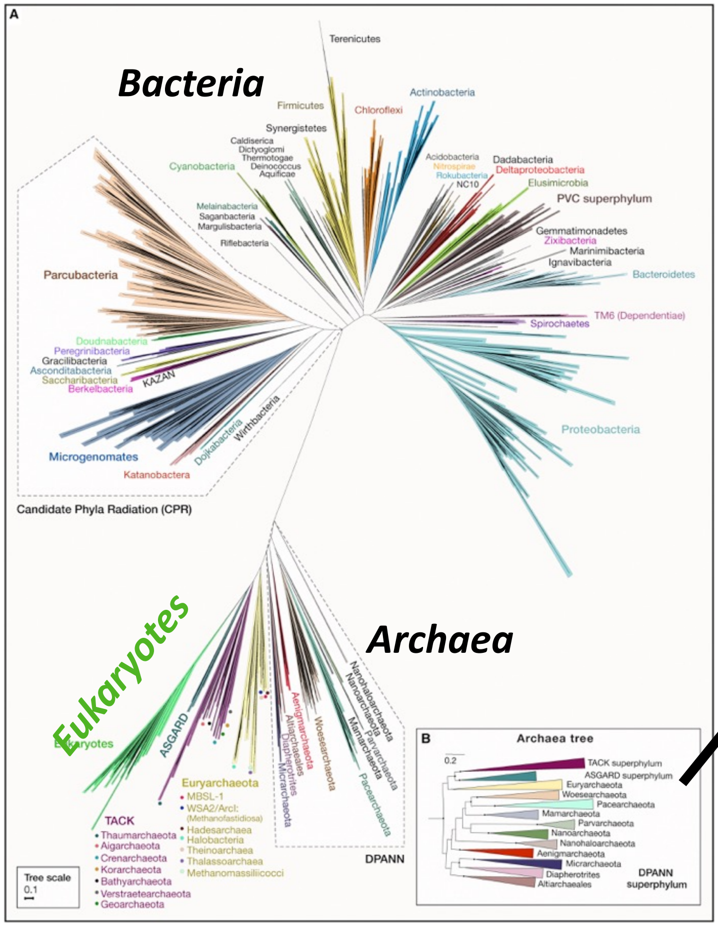
Fresh-waters

Hydrates

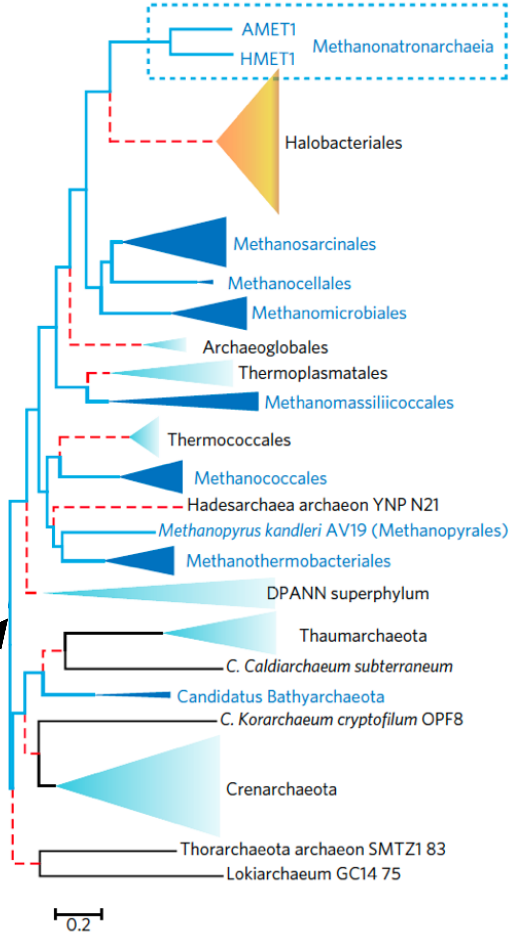
Anthropogenic Methane Sources and Sinks (Tg yr^{-1})



Microbial methane makers: Euryarchaeota

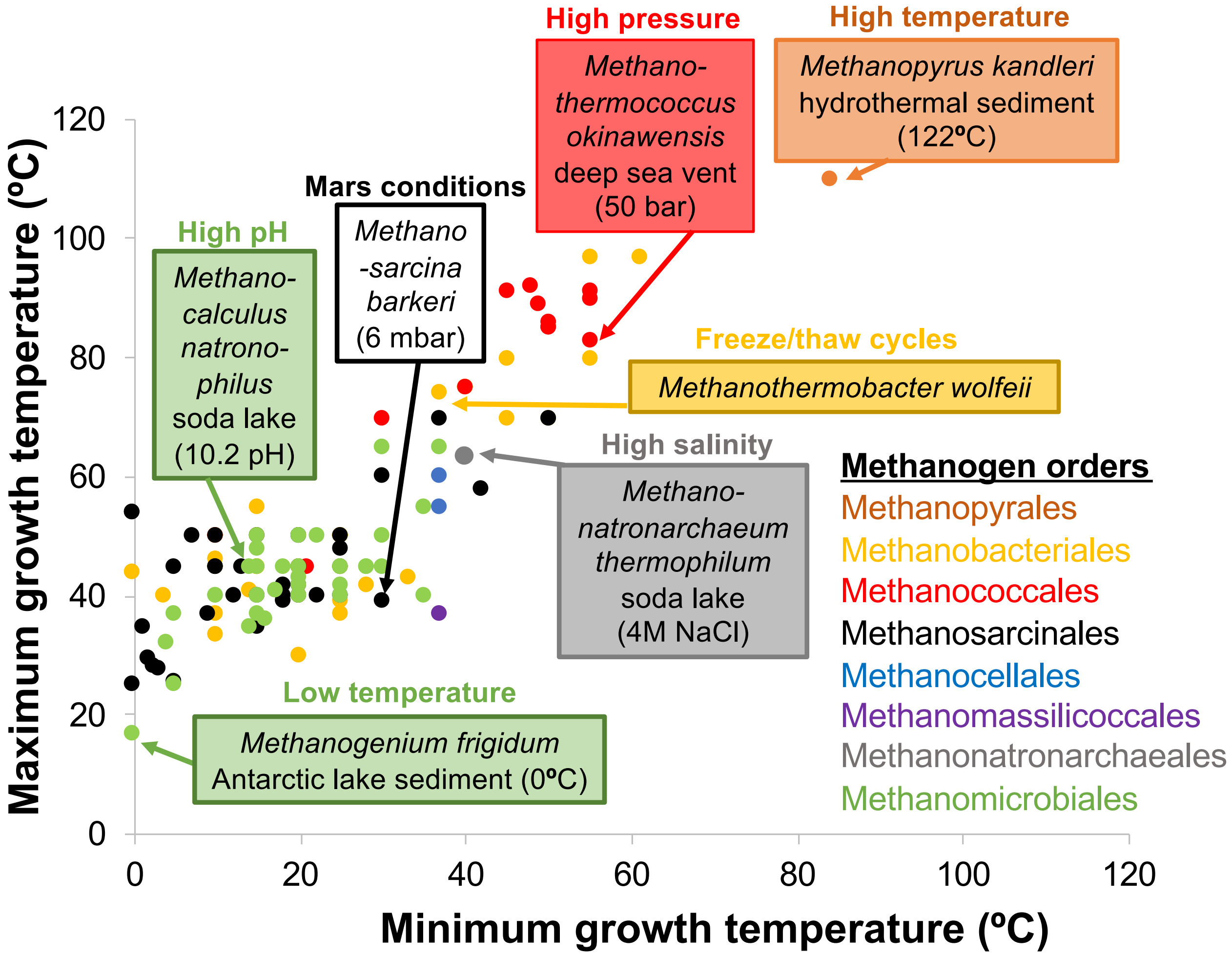


Castelle & Banfield 2018 *Cell*



Sorokin et al. 2017 Nature Microbiol

Methanogens grow at extreme environmental conditions



High pressure

Methano-thermococcus okinawensis deep sea vent (50 bar)

High temperature

Methanopyrus kandleri hydrothermal sediment (122ºC)

Mars conditions

Methano-sarcina barkeri (6 mbar)

High pH

Methano-calculus natrono-philus soda lake (10.2 pH)

Freeze/thaw cycles

Methanothermobacter wolfeii

High salinity

Methano-natronarchaeum thermophilum soda lake (4M NaCl)

Low temperature

Methanogenium frigidum Antarctic lake sediment (0ºC)

Glass & Whitman, 2019, in press, Methanogenesis, Encyclopedia of Astrobiology

nature COMMUNICATIONS

ARTICLE

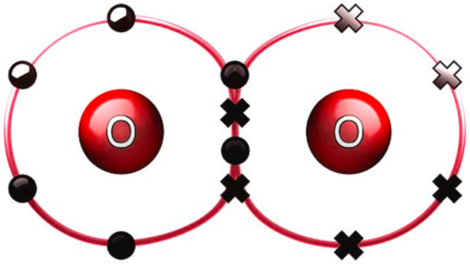
DOI: 10.1038/s41467-018-02876-y

Biological methane production under putative Enceladus-like conditions

Ruth-Sophie Taubner[1,2], Patricia Pappenreiter[3], Jennifer Zwicker[4], Daniel Smrzka[4], Christian Pruckner[1], Philipp Kolar[1], Sébastien Bernacchi[5], Arne H. Seifert[5], Alexander Krajete[5], Wolfgang Bach[6], Jörn Peckmann[4,7], Christian Paulik[3], Maria G. Firneis[2], Christa Schleper[1] & Simon K.-M.R. Rittmann[1]

The detection of silica-rich dust particles, as an indication for ongoing hydrothermal activity, and the presence of water and organic molecules in the plume of Enceladus, have made Saturn's icy moon a hot spot in the search for potential extraterrestrial life. Methanogenic archaea are among the organisms that could potentially thrive under the predicted conditions on Enceladus, considering that both molecular hydrogen (H_2) and methane (CH_4) have been detected in the plume. Here we show that a methanogenic archaeon, *Methanothermococcus okinawensis*, can produce CH_4 under physicochemical conditions extrapolated for Enceladus. Up to 72% carbon dioxide to CH_4 conversion is reached at 50 bar in the presence of potential inhibitors. Furthermore, kinetic and thermodynamic computations of low-temperature serpentinization indicate that there may be sufficient H_2 gas production to serve as a substrate for CH_4 production on Enceladus. We conclude that some of the CH_4 detected in the plume of Enceladus might, in principle, be produced by methanogens.

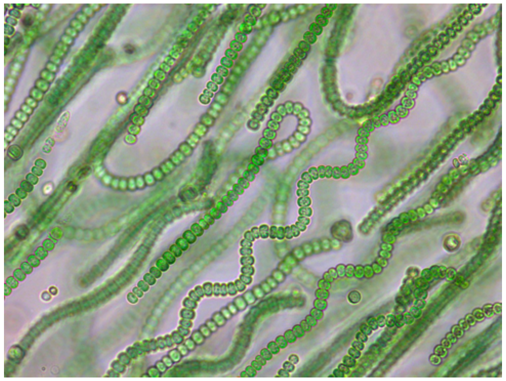
I. Modern



Cycle

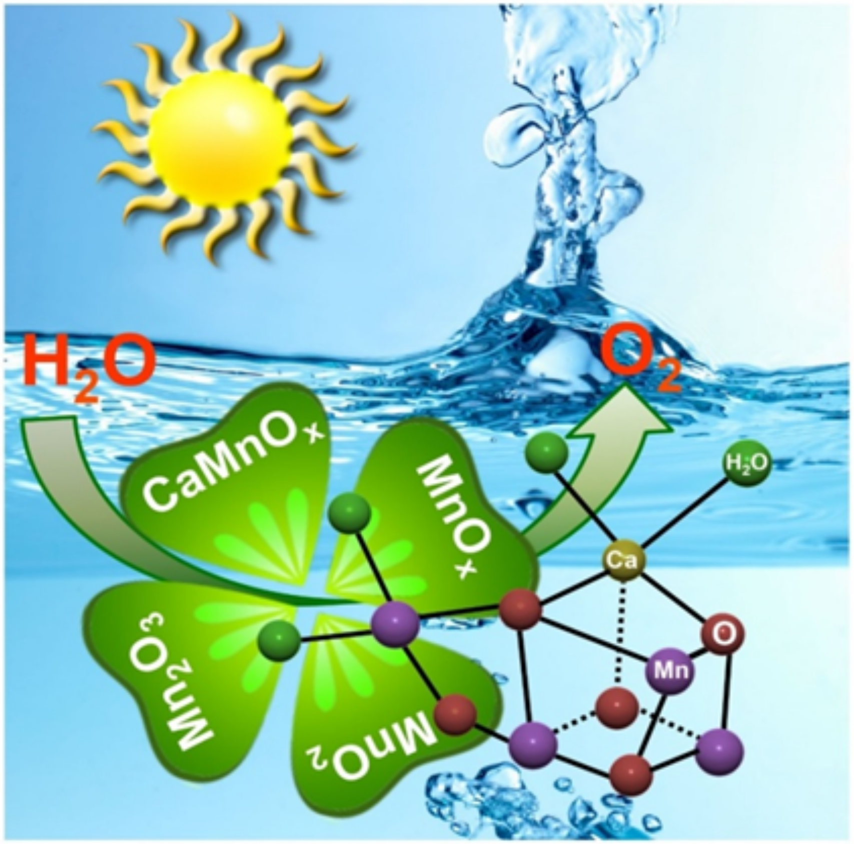
Take another deep breath

… and thank



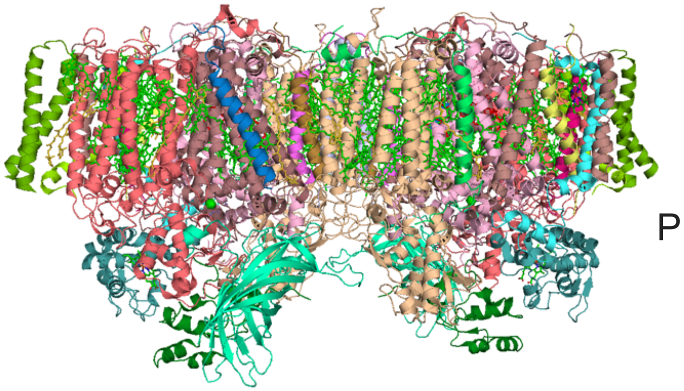
for the O_2
you’re
breathing

Photosystem II: nature's O_2 producer



Manganese-rich oxygen-evolving complex

Originated in **cyanobacteria** at least 2.4 billion years ago, spread to algae and plants by endosymbiosis



PDB 2AXT

Large biological O_2 fluxes are balanced

Photosynthesis:

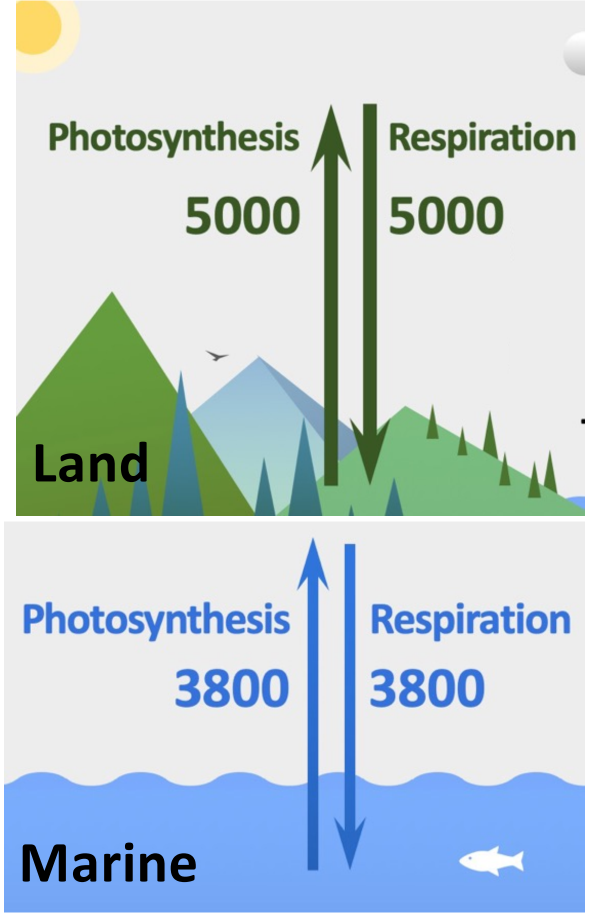
Process by which CO_2 is converted to organic carbon (simplified as CH_2O) using energy from sunlight:

CO_2 + H_2O + sunlight + nutrients → CH_2O + O_2

Aerobic Respiration:

Process by which organic carbon is oxidized to CO_2 with O_2 to fuel ATP production:

CH_2O + O_2 → CO_2 + H_2O + nutrients

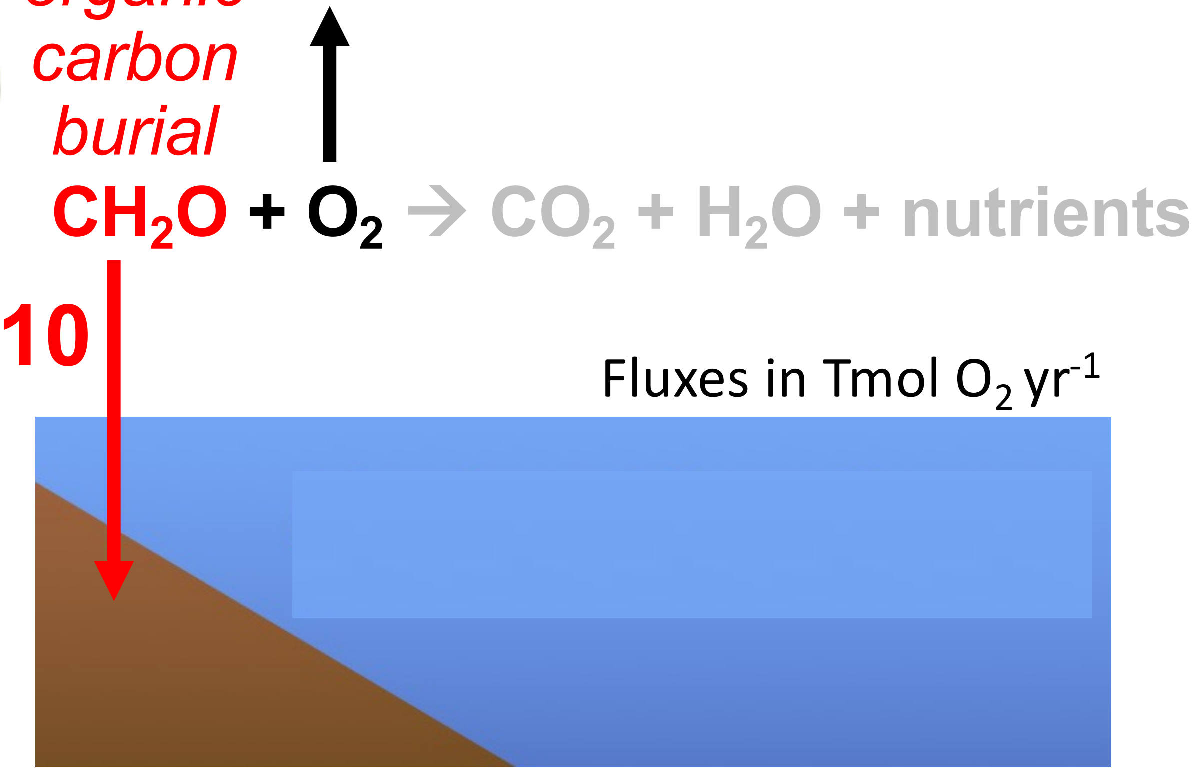


Fluxes in Tmol O_2 yr^{-1}

Artwork by Pengxiao Xu, Georgia Tech

Kasting, JF, Canfield DE (2012) The Global Oxygen Cycle. Chapter 7. Fundamentals of Geobiology, 93-104.

O_2 export to atmosphere requires *burial* of reductants that consume O_2



organic carbon burial

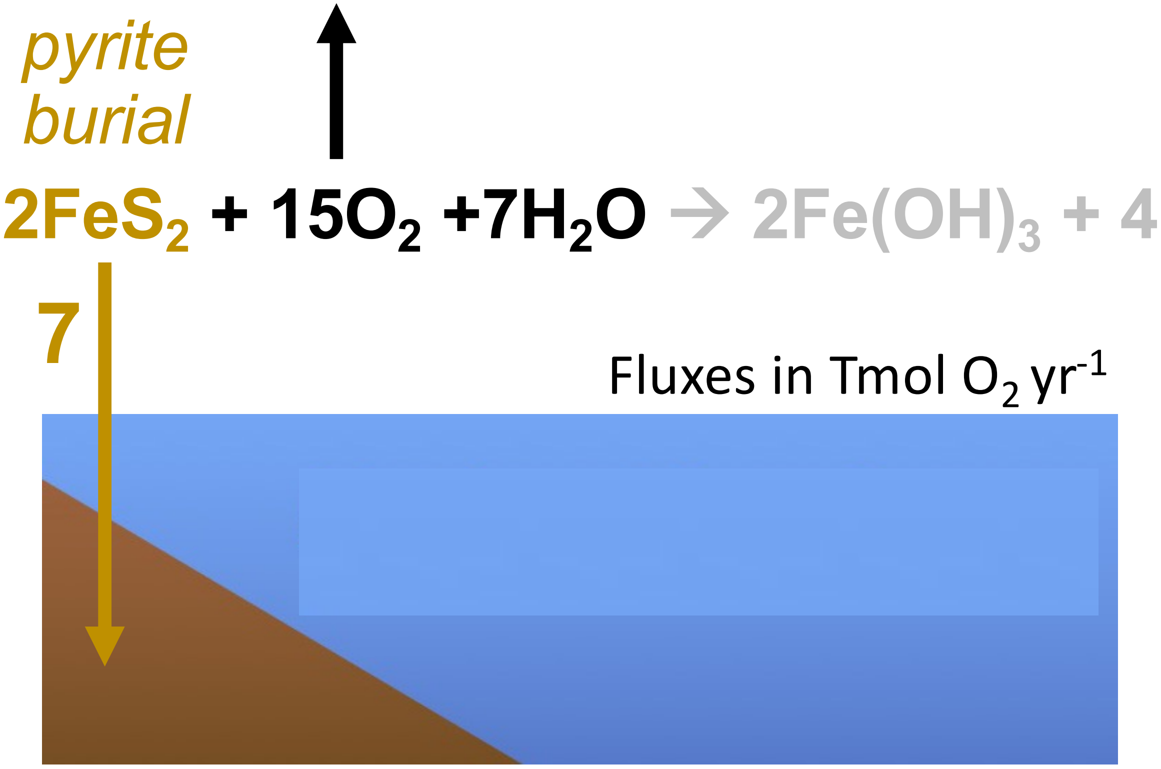
$CH_2O + O_2 \rightarrow CO_2 + H_2O$ + nutrients

10

Fluxes in Tmol O_2 yr^{-1}

Kasting, JF, Canfield DE (2012) The Global Oxygen Cycle. Chapter 7. Fundamentals of Geobiology, 93-104.

O_2 export to atmosphere requires *burial* of reductants that consume O_2



pyrite burial

$2FeS_2 + 15O_2 + 7H_2O \rightarrow 2Fe(OH)_3 + 4H_2SO_4$

Fluxes in Tmol O_2 yr^{-1}

Kasting, JF, Canfield DE (2012) The Global Oxygen Cycle. Chapter 7. Fundamentals of Geobiology, 93-104.

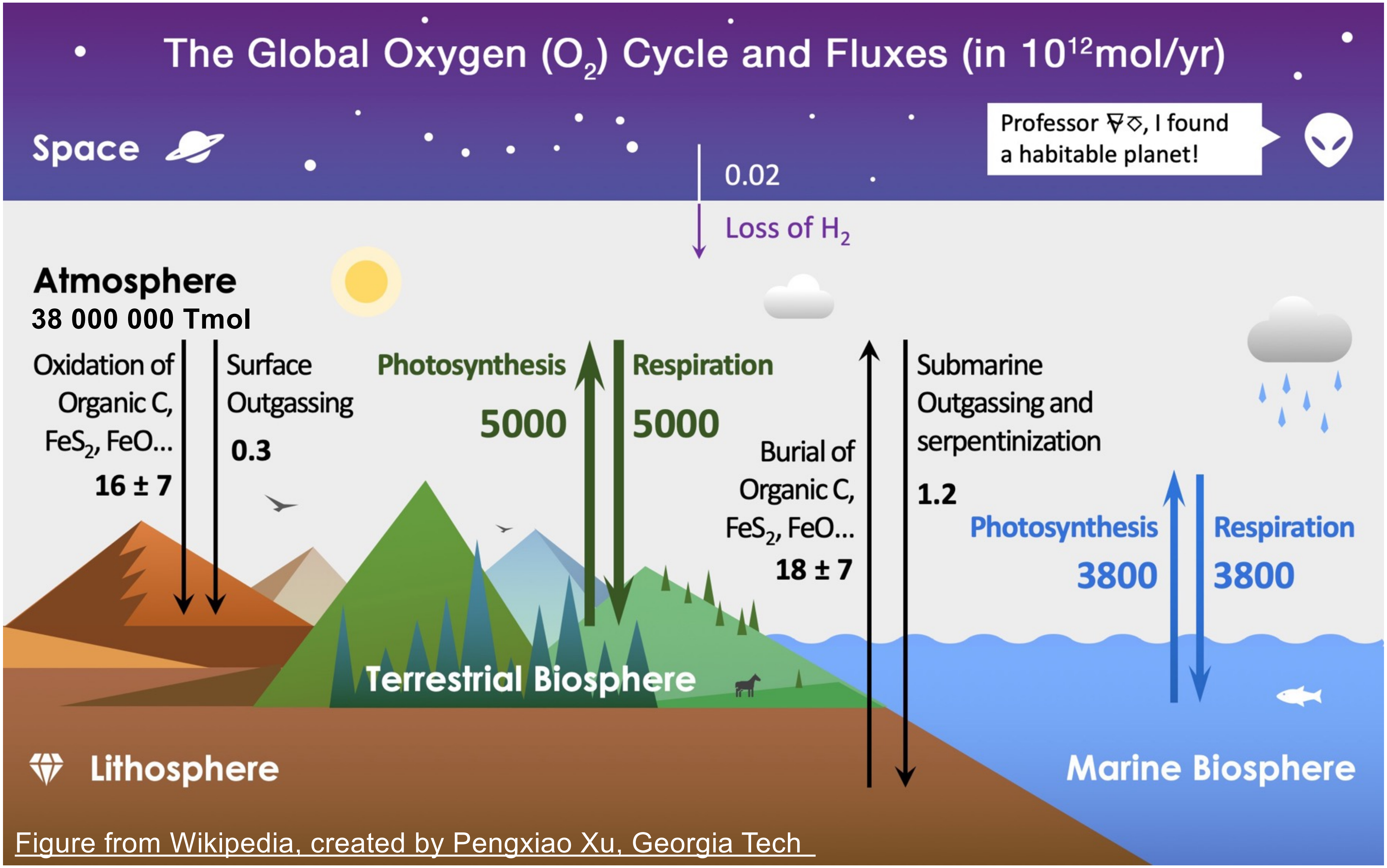
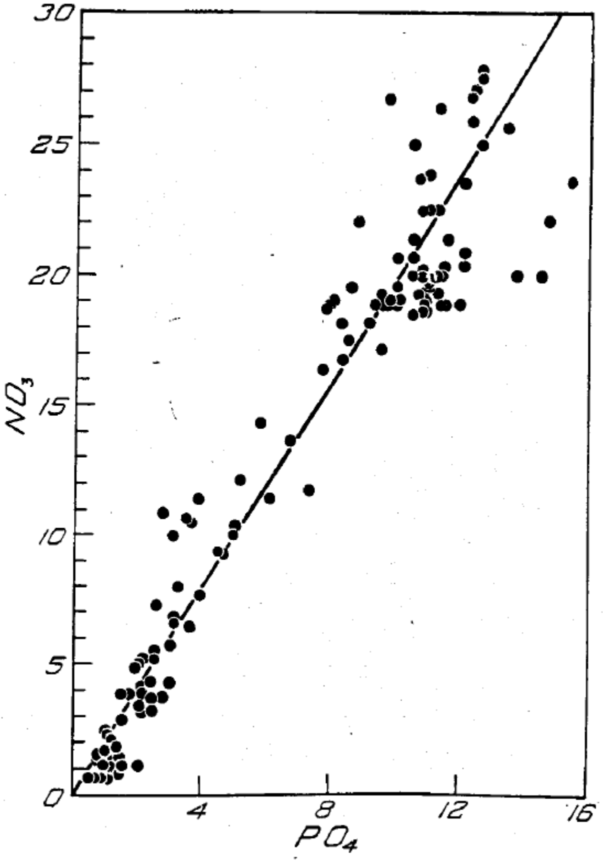


Figure from Wikipedia, created by Pengxiao Xu, Georgia Tech

“Redfield Ratio”

FIG. 1.



Correlation between concentrations of nitrate and phosphate in the waters of western Atlantic Ocean. Ordinate, concentration of nitrate, units 10^{-3} millimols per liter; abscissa, concentration of phosphate, units 10^{-4} millimols per liter. The line represents a ratio of $\triangle N : \triangle P = 20 : 1$ milligram atoms.

Consistent atomic ratio of **106 C: 16 N: 1P** in marine phytoplankton.

Leaves its imprint on ocean chemistry

Now extended to include terrestrial life and trace elements

Redfield, A.C. (1934) **On the Proportions of Organic Derivatives in Sea Water and Their Relation to the Composition of Plankton**. James Johnstone Memorial Volume, University Press of Liverpool, 176-192.

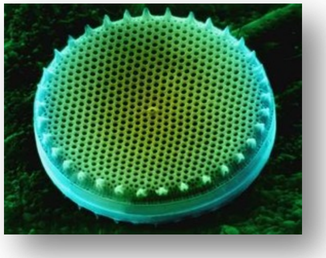
Nutrient limitation

Baking a cake

4 eggs:
3 cups flour:
2 cups sugar
+ (trace butter,
baking powder,
vanilla extract,
salt, etc.)

Making an organism

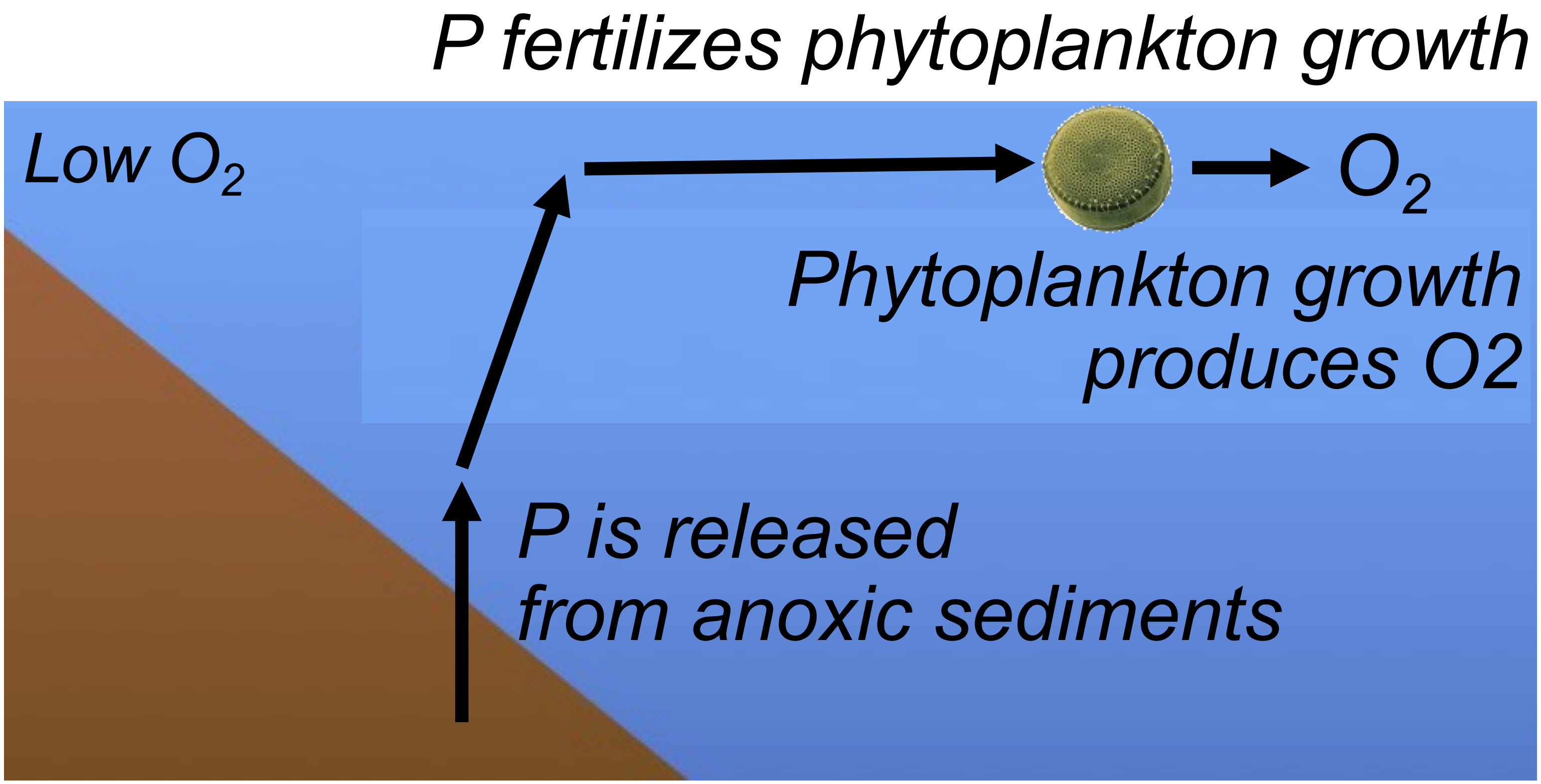
106 moles carbon:
16 moles nitrogen:
1 moles phosphorus
+ (trace iron,
manganese,
molybdenum,
zinc, etc.)



If you only have 4 eggs, even if you have infinite flour and sugar, you can only make 1 cake.

If you only have 1 mol of P, even if you have infinite nitrogen and carbon, you can only make 1 diatom (equivalent).

Phosphorus availability may control long-term O_2



P fertilizes phytoplankton growth

Low O_2

O_2

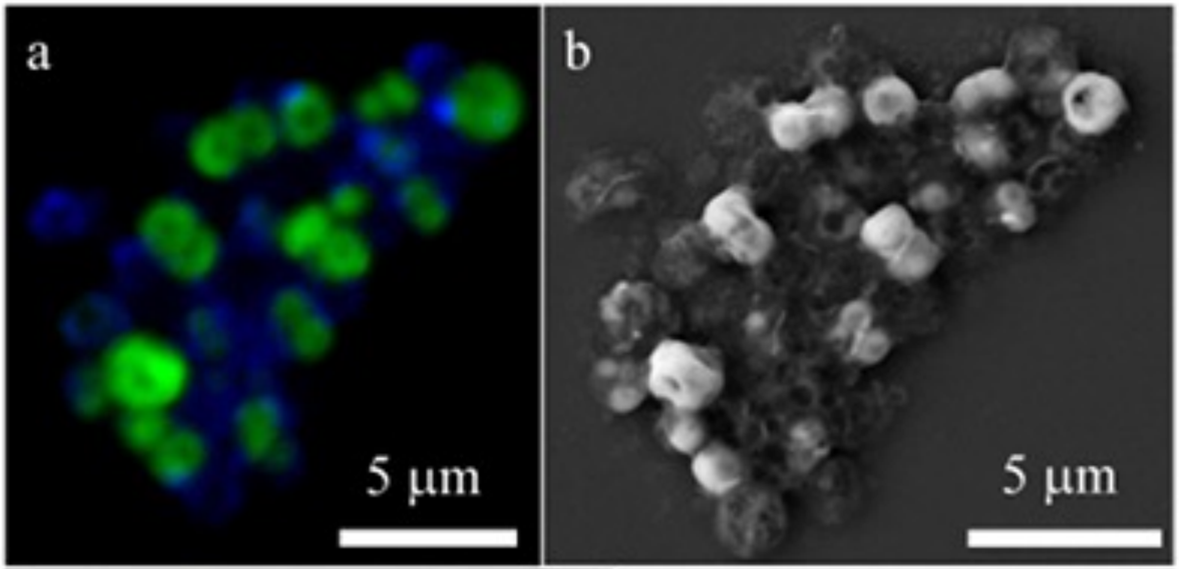
Phytoplankton growth produces O2

P is released from anoxic sediments

Catling D, Zahnle Z (2003). Evolution of Atmospheric Oxygen. Encyclopedia of Atmospheric Sciences, pp. 754-76

Life is extremely good at acquiring scarce bioessential elements

I. Storage



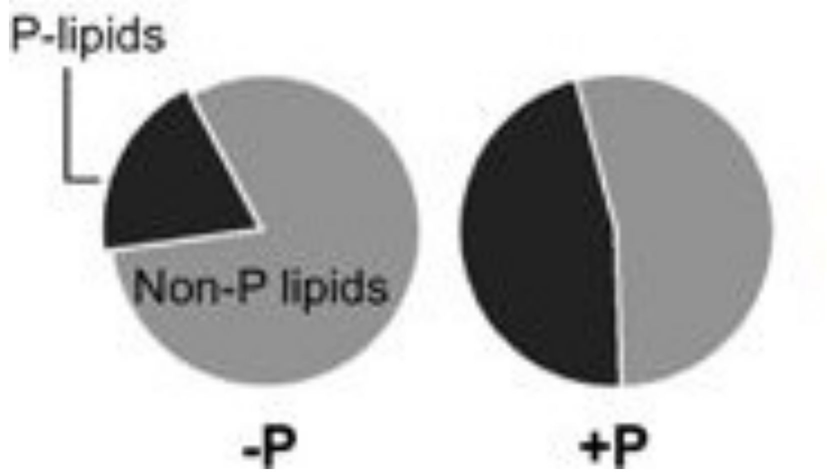
Polyphosphate

Nucleic acid

Rivas-Lamelo et al 2017 Magnetotactic bacteria as a new model for P sequestration in the ferruginous Lake Pavin. *Geochemical Perspectives Letters*

Life is extremely good at acquiring scarce bioessential elements

II. Substitution



Sebastian et al. 2016, Lipid remodelling is a widespread strategy in marine heterotrophic bacteria upon phosphorus deficiency. ISME Journal

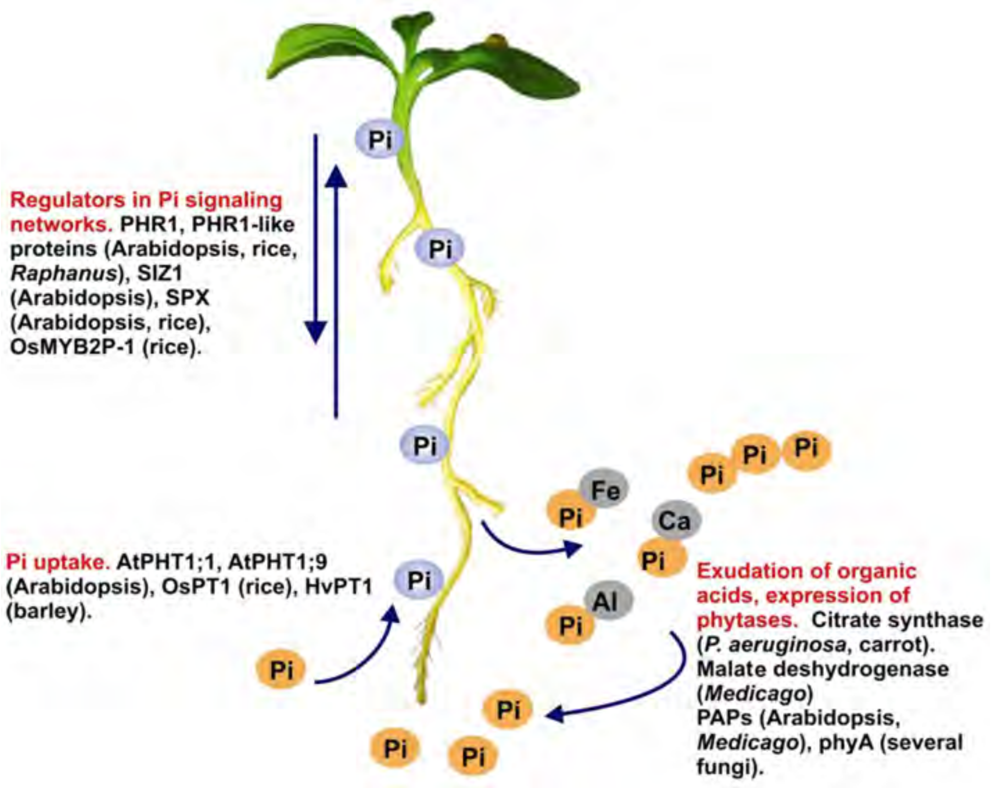
Life is extremely good at acquiring scarce bioessential elements

III. Scavenging

High-affinity phosphate transport

Phosphatase

Exudation of organic acids

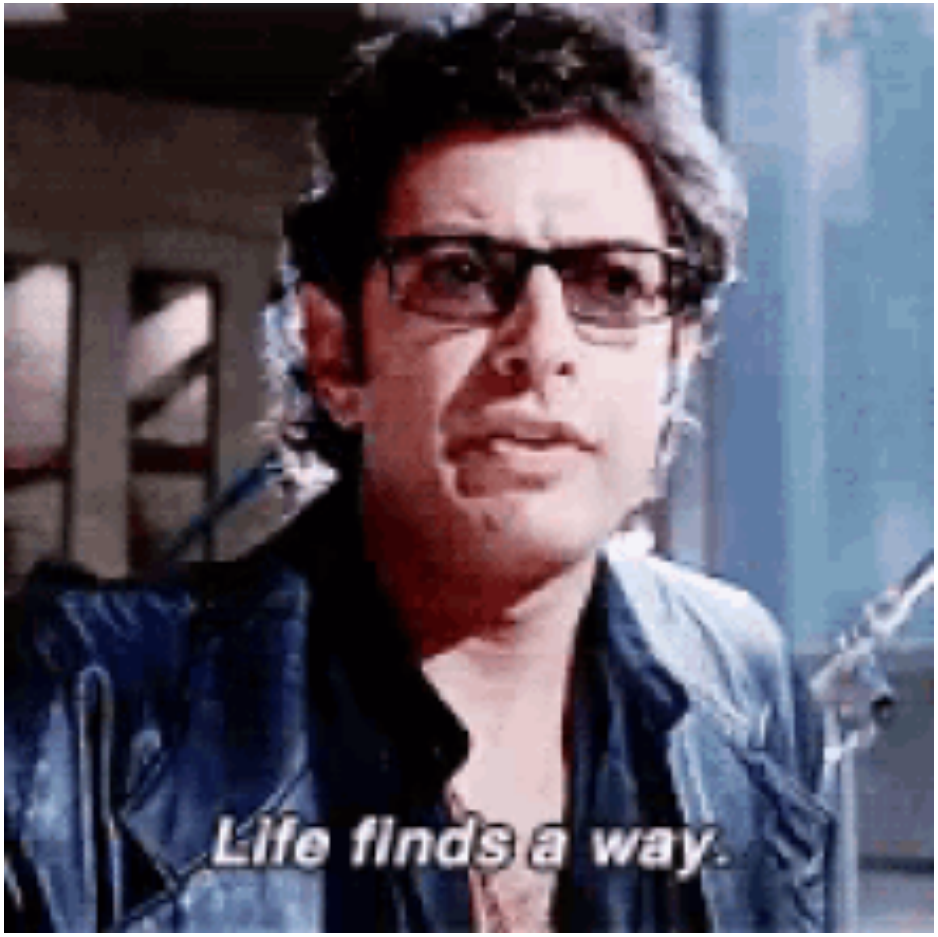


Regulators in Pi signaling networks. PHR1, PHR1-like proteins (Arabidopsis, rice, *Raphanus*), SIZ1 (Arabidopsis), SPX (Arabidopsis, rice), OsMYB2P-1 (rice).

Pi uptake. AtPHT1;1, AtPHT1;9 (Arabidopsis), OsPT1 (rice), HvPT1 (barley).

Exudation of organic acids, expression of phytases. Citrate synthase (*P. aeruginosa*, carrot). Malate deshydrogenase (*Medicago*) PAPs (Arabidopsis, *Medicago*), phyA (several fungi).

Lopez-Arredondo et al. 2013, Biotechnology of nutrient uptake and assimilation in plants. Int. J. of Developmental Biology


Life finds a way.

Recommended References

Modern Methane Cycle

Lyu Z, Shao N, Akinyemi T, Whitman WB (2018) Methanogenesis. Current Biology 28: R727-R732

Dean JF, Middelburg JJ, Röckmann T., Aerts R, Blauw LG, Egger M, et al (2018). Methane feedbacks to the global climate system in a warmer world. Reviews of Geophysics, 56, 207–250.

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Catling D, Zahnle Z (2003). Evolution of Atmospheric Oxygen. Encyclopedia of Atmospheric Sciences, pp. 754-76.

Biosignature Gases

Seager S, M Schrenk, W Brazelton. An Astrophysical View of Earth-Based Biosignature Gases. Astrobiology 12: 61-82