The Co-Evolution of Life and Biosignatures: A Geochemical Perspective on an Ecological Problem

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NASA's Astrobiology Strategy

- Identifying abiotic sources of organic compounds
- Synthesis and function of macromolecules in the origin of life
- Early life and increasing complexity
- **Co-evolution of life and the physical environment**
- **Identifying, exploring, and characterizing environments for habitability and biosignatures**
- Constructing habitable worlds

Take-away messages

- Planetary chemistry and processes are required to under understand life processes
- Ecosystem-scale biological rates must be placed in context with geochemical rates
- Broadest interpretation of biosignatures possible
- A systems-science approach is best

Outline

- **Geobiochemistry**
  - links between geochemical and biochemical systems
- **Ecology**
  - integrated planetary-scale patterns
- **A biosignature example from geobiochemistry**
- **Implications for Exoplanets**

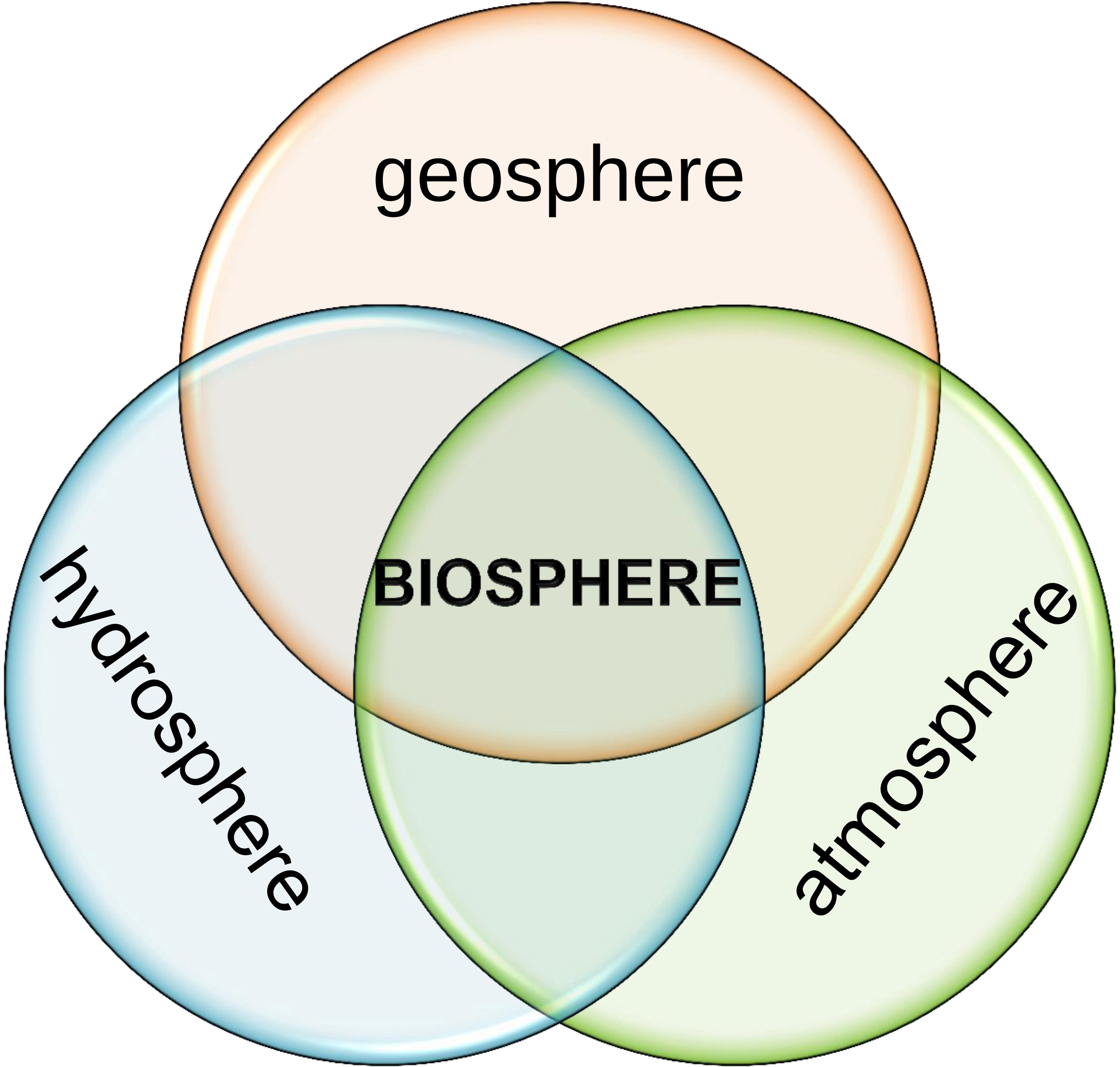
Geobiochemistry

Aims to explain how geology influences biochemistry

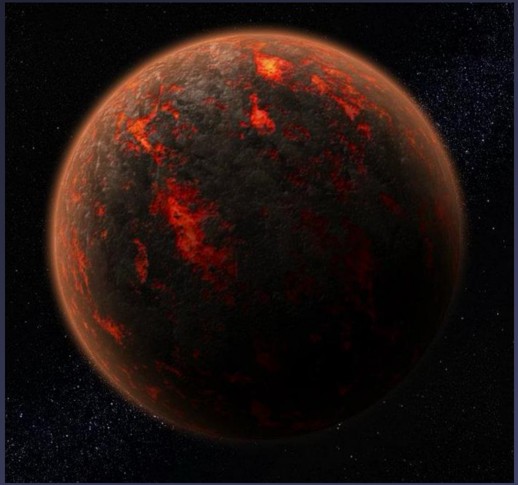
(Shock & Boyd, 2015)

Five Principles

1. **Life emerges as a planetary response**
2. **Biochemical processes have geochemical origins**
3. Enzymatic processes recapitulate mineral catalysis
4. Biological innovations occur near to where first needed
5. “Things that burst into flame are not good to eat”


geosphere
BIOSPHERE
hydrosphere
atmosphere

Life is a planetary response to energy availability

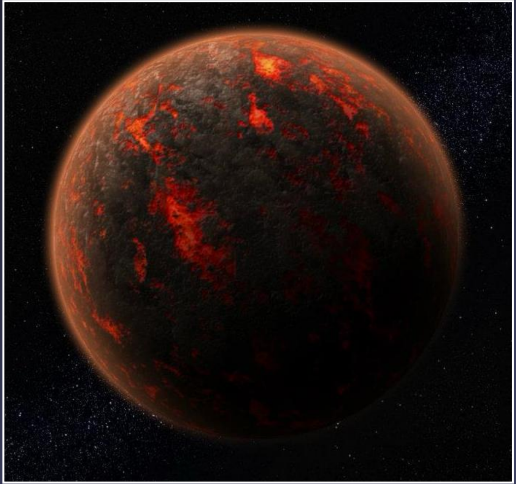


‘Hot, melty’ Earth

Anoxic Earth

Modern Earth

Life is a planetary response to energy availability



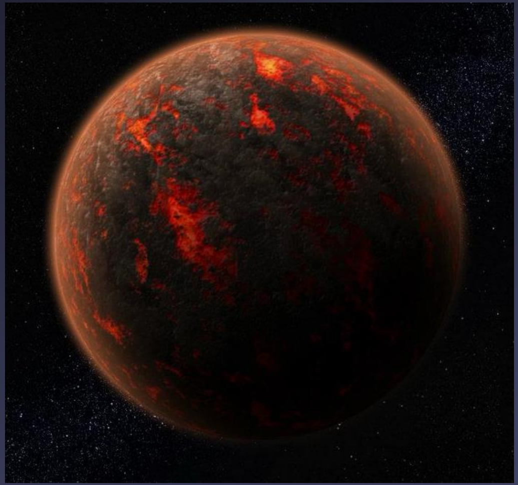
‘Hot, melty’ Earth

Anoxic Earth

Modern Earth

- Cooling Earth → slower water-rock-organic reactions
- Life catalyzes slow reactions and captures the energy released

Life is a planetary response to energy availability



'Hot, melty' Earth

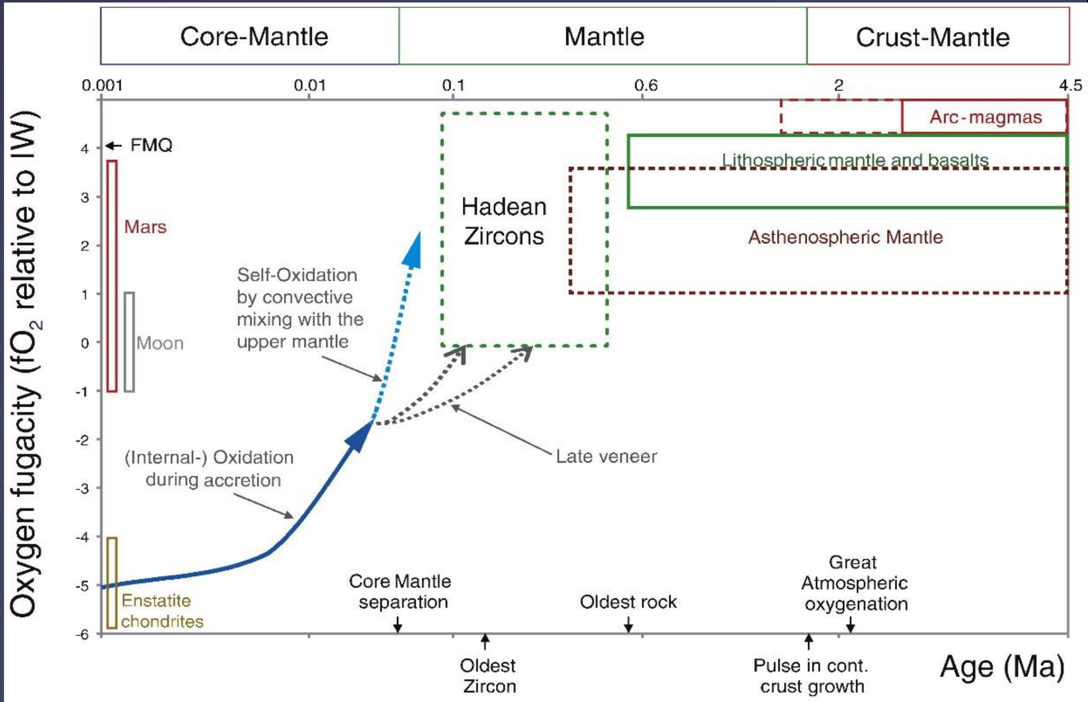
Anoxic Earth

Modern Earth

- **But we study modern organisms in modern ecosystems**
  - How do they inform past processes or what happens elsewhere?

Redox changes over time

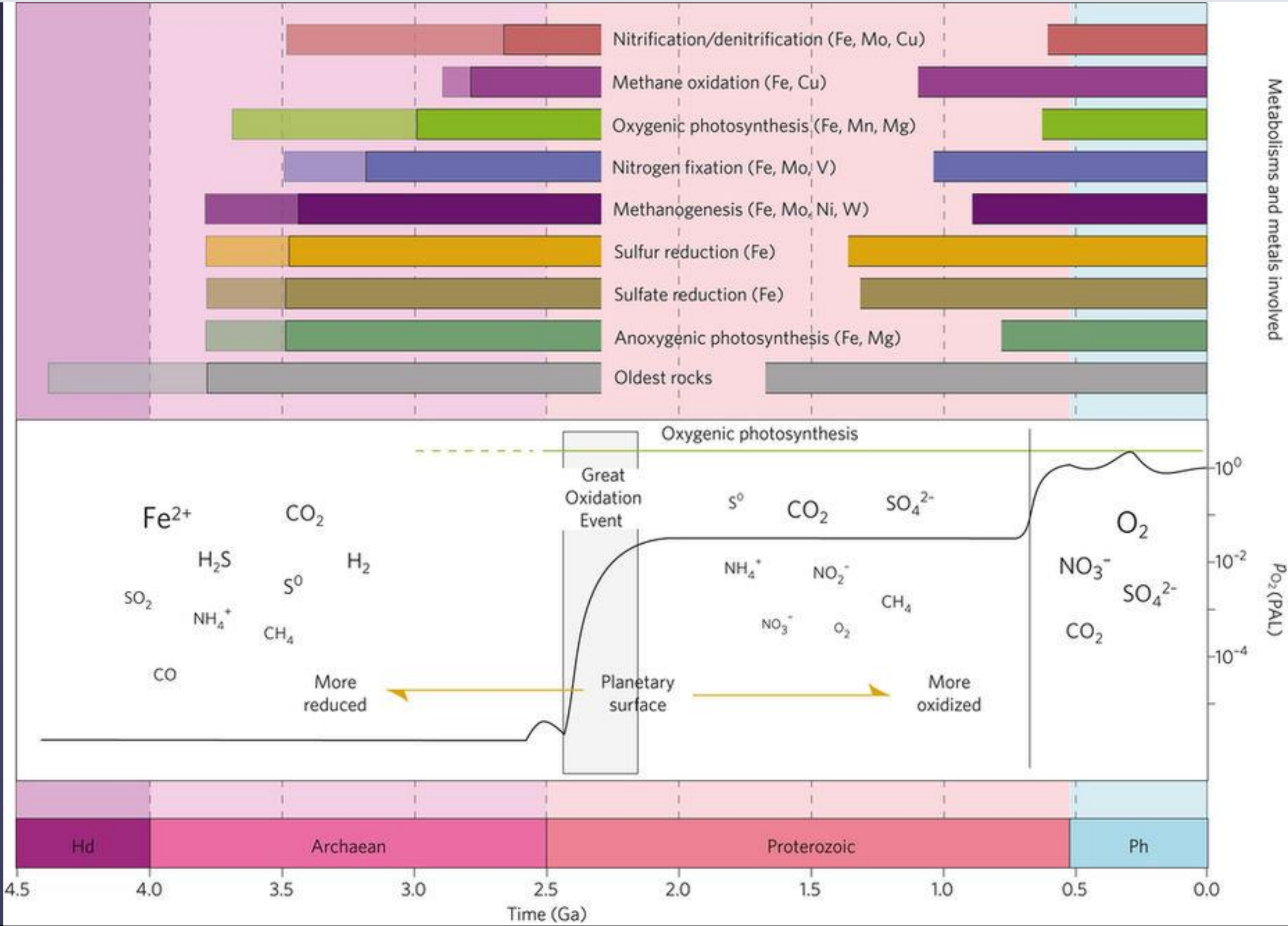
- **Mantle evolution**
  - Cooling and continent formation (Hawkesworth et al. 2017)
  - H_2 loss (Zahnle et al. 2013)
- **Biological evolution**
  - Metabolisms of all sorts (Moore et al. 2017)



Gaillard et al. 2015

Life is part of Earth's early history

- **Remarkable correspondence among emergence of metabolisms, elemental distributions, and major Earth transitions**



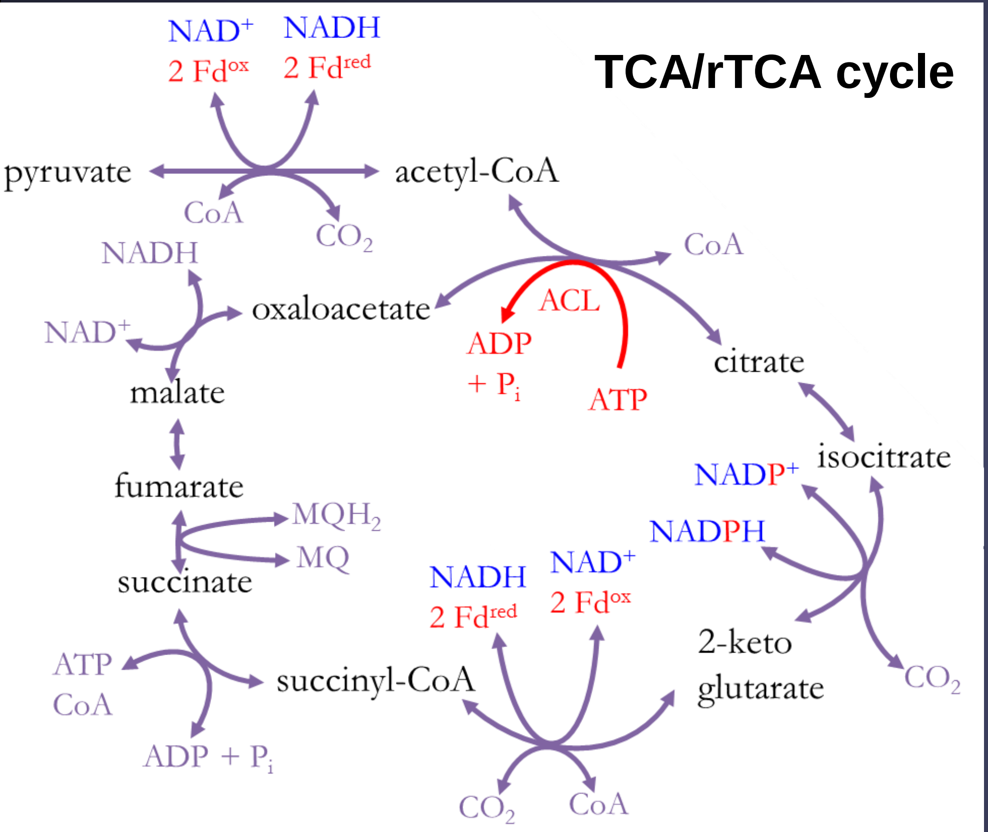
Moore et al. 2017

Biochemical processes have geochemical origins

The biochemistry we have is one that the Earth allows.

− C. Manning

Biochemical processes have geochemical origins



Carbon oxidation – a core metabolism

Reversibility abounds!

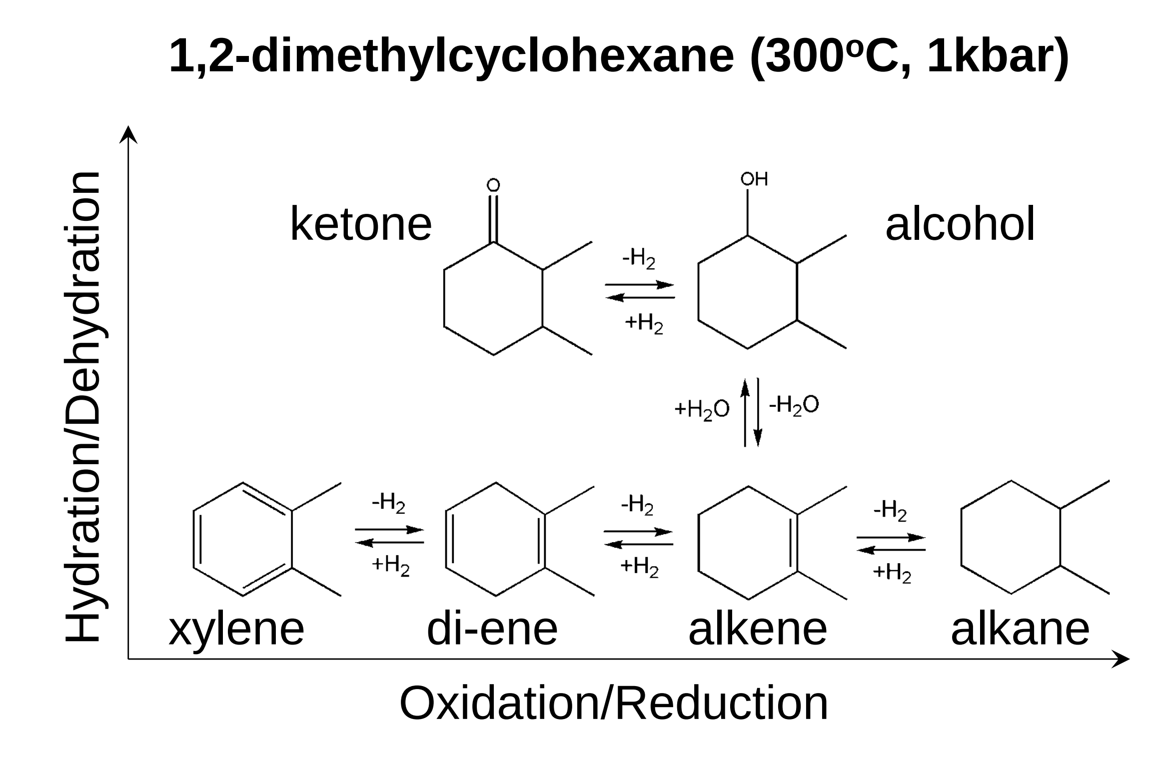
- Hydrogenation/ Dehydrogenation
- Hydration/Dehydration
- Coupled redox/ Decarboxylation reactions

Biochemical processes have geochemical origins

Abiotic hydrothermal organic reactions

Reversibility abounds!

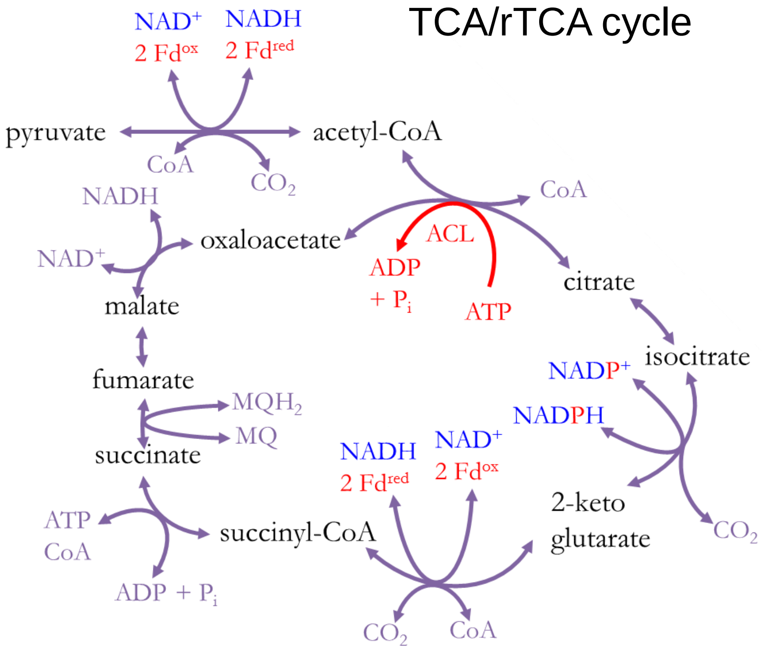
- Hydrogenation/ Dehydrogenation
- Hydration/Dehydration
- Coupled redox/ Decarboxylation reactions



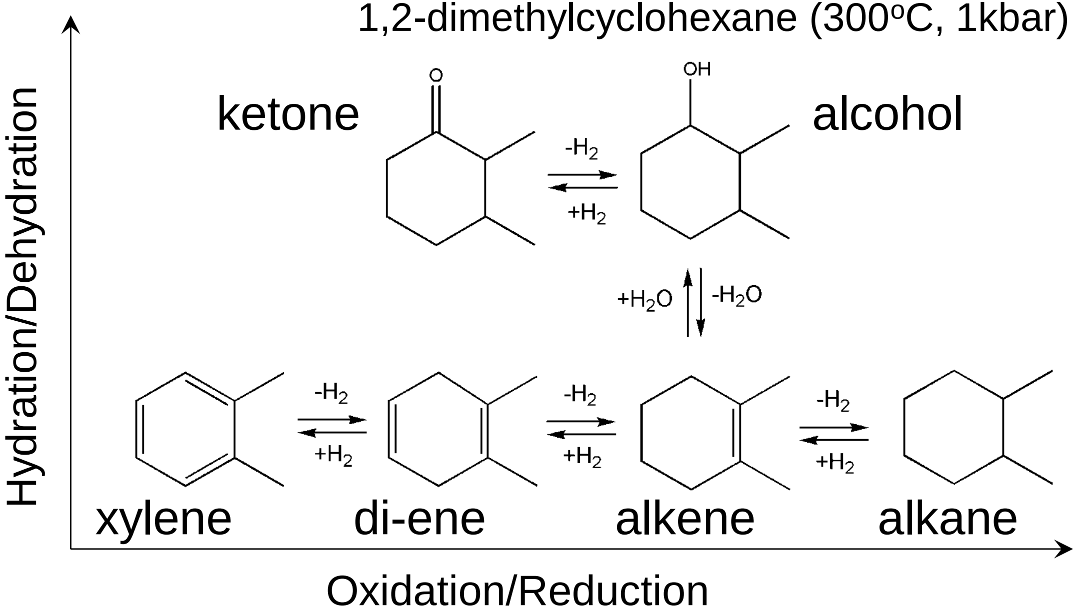
Shipp et al. 2013

Biochemical processes have geochemical origins

TCA/rTCA cycle



1,2-dimethylcyclohexane (300ºC, 1kbar)



Shipp et al. 2013

- Enzymes in this metabolic cycle catalyze thermodynamically favorable organic reactions that are slow at low temperatures

Take-away messages

- **Planetary chemistry and processes are required to under understand life processes**

An ecosystems perspective

- **Multiple metabolisms co-occur everywhere**

  We should assume this for other planets.

- **On Earth, biology dominates cycles of CHNOPS and we forget (or ignore) geochemical production and consumption.**

  We cannot assume this for other planets.

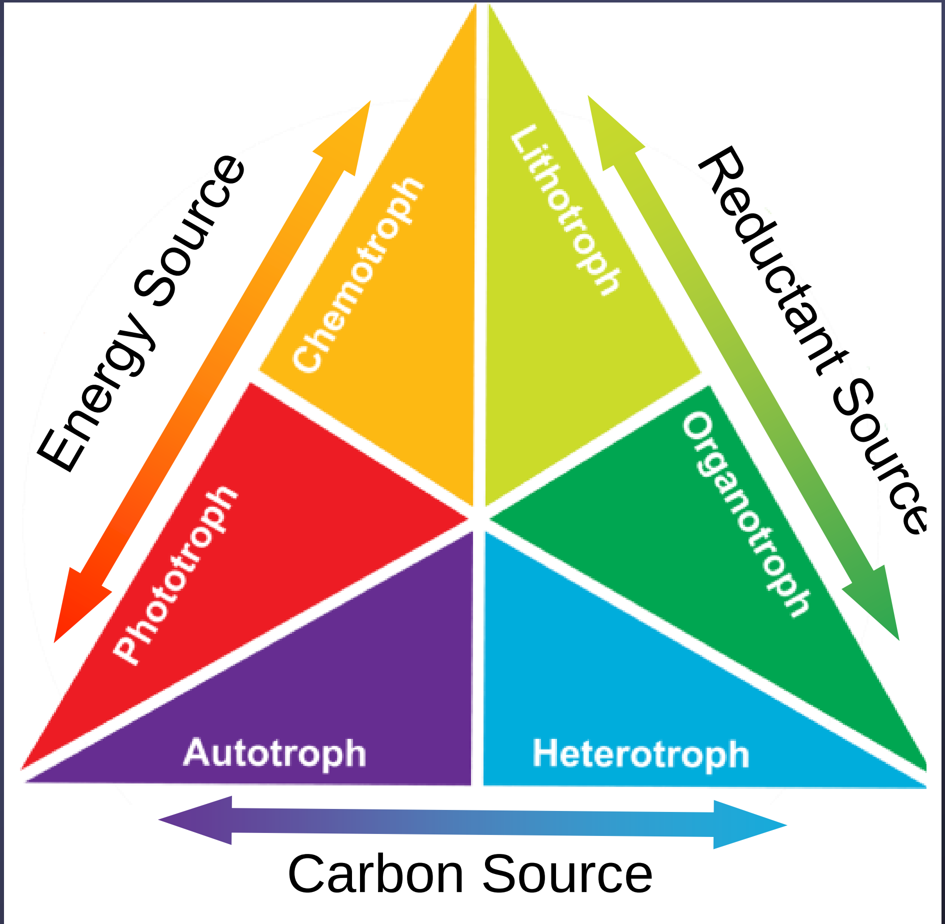
An ecosystems perspective

Energy

Reductants

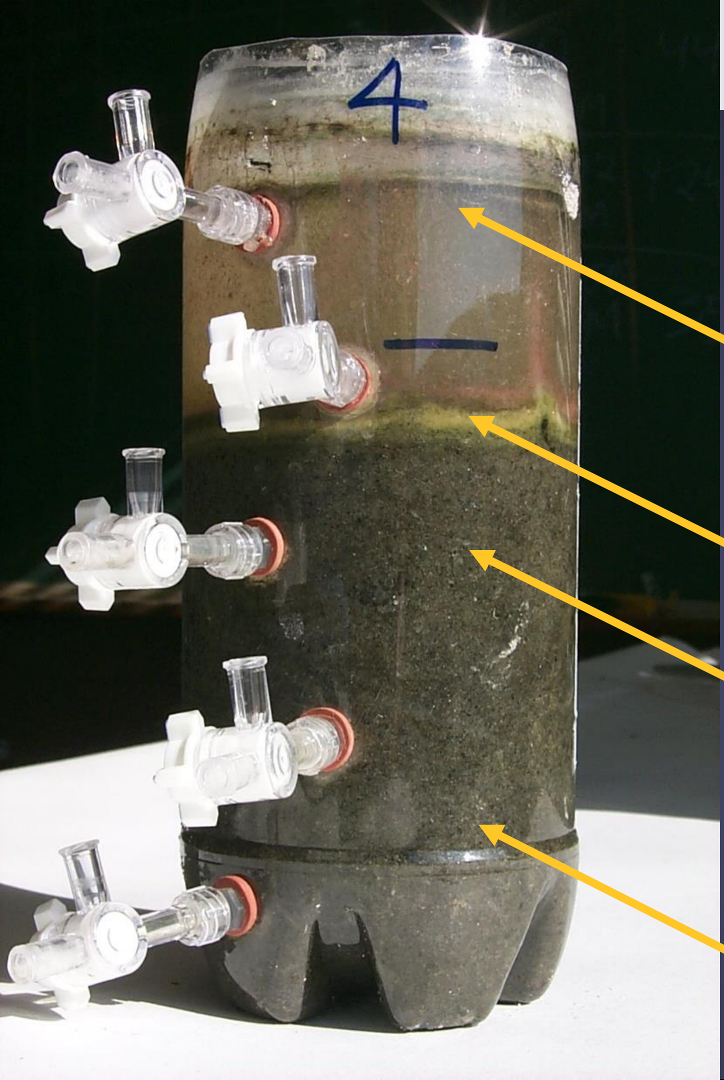
Carbon

- **Metabolism names reflect this**
  - chemoorganoheterotroph
  - chemolithoautotroph
  - Photolithoautotroph



Modified from Garcia-Pichel, 2005

A Winogradsky analogy



Many metabolisms in one system

photoautrophs

aerobic heterotrophs

denitrifiers

sulfate reducers

An O_2 or CO_2 flux will integrate all the active metabolisms in the bottle (as well as any abiotic processes)

An ecosystems perspective

Net Planetary Biological Production (NPBP) =

$$\sum(\text{Production} - \text{Consumption})_{\text{biology}} - \sum(\text{Production} - \text{Consumption})_{\text{geochemistry}}$$

- **If biological rates exceed abiotic rates then you have a biosignature**
  - But, give consideration to other sorts of biosignatures

Take-away messages

- Planetary chemistry and processes are required to under understand life processes

- Ecosystem-scale biological rates must be placed in context with geochemical rates

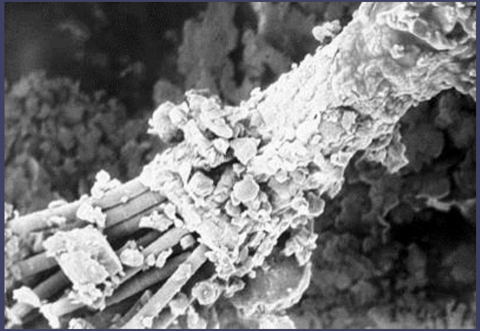
Geobiochemistry and Biosignatures

- **Biological Soil Crusts as a geobiochemical system**
  - Environmental context
  - Metabolic rates
  - Preservable biosignatures

Biological Soil Crusts

- soil particles bound by microbial filaments and organic material
- a consortia of bacteria, fungi, & algae
- they fix N_2 & CO_2

“dark” cyanobacterial crust (early developmental stage)

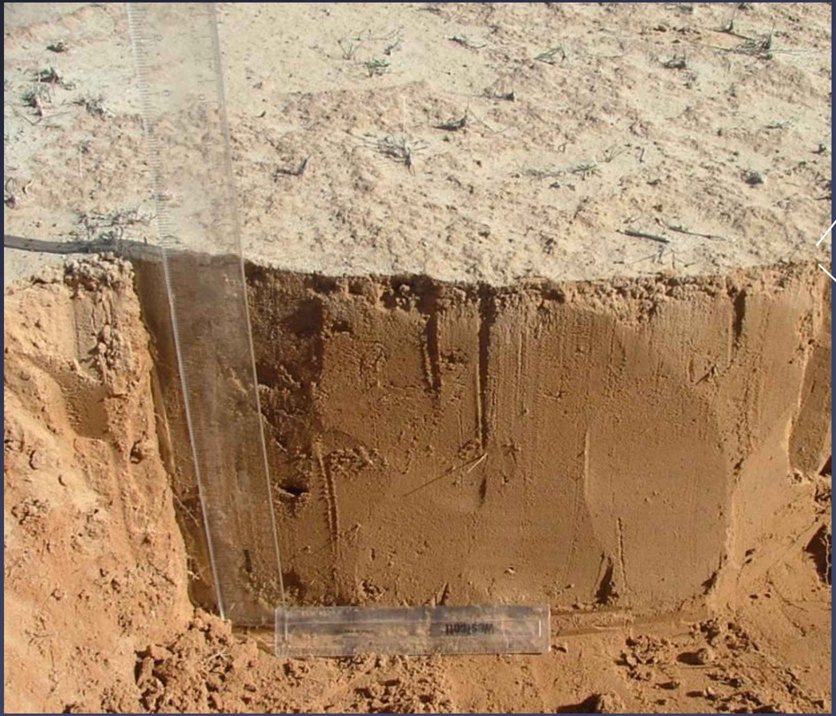


A bundle of cyanobacterial filaments

Soils less than 6" deep, held in place by crusts.

- Highly adapted to their “harsh environment”

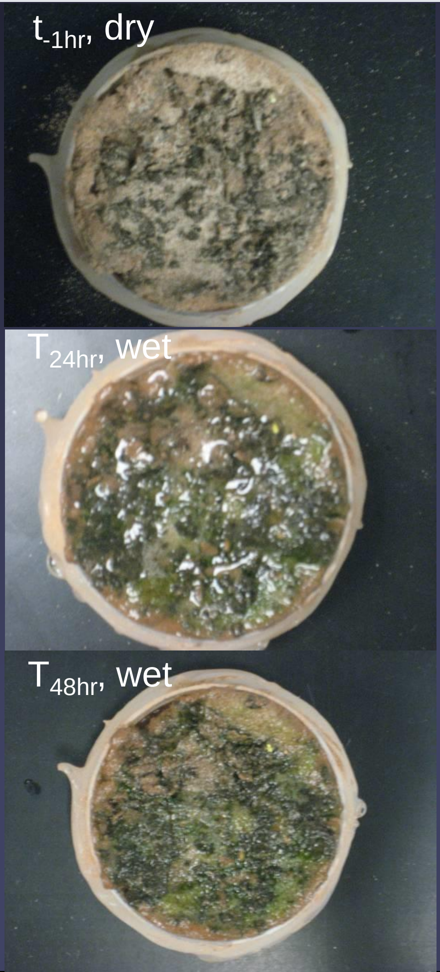
Biological Soil Crusts: a layered ecosystem



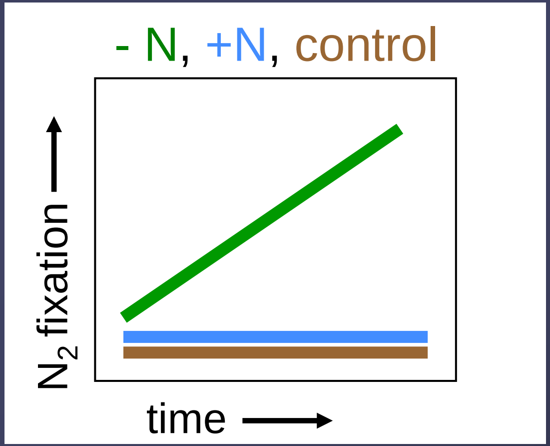
- the crust-former (*Microcoleus vaginatus*) does not fix N_2
  - it has a heterotrophic N_2-fixing microbiome
- Absolute metal requirements!

Garcia-Pichel et al., 2003, Giraldo-Silva et al, 2017

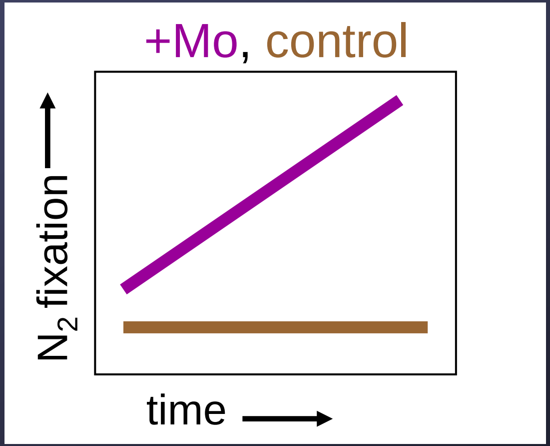
Hypotheses



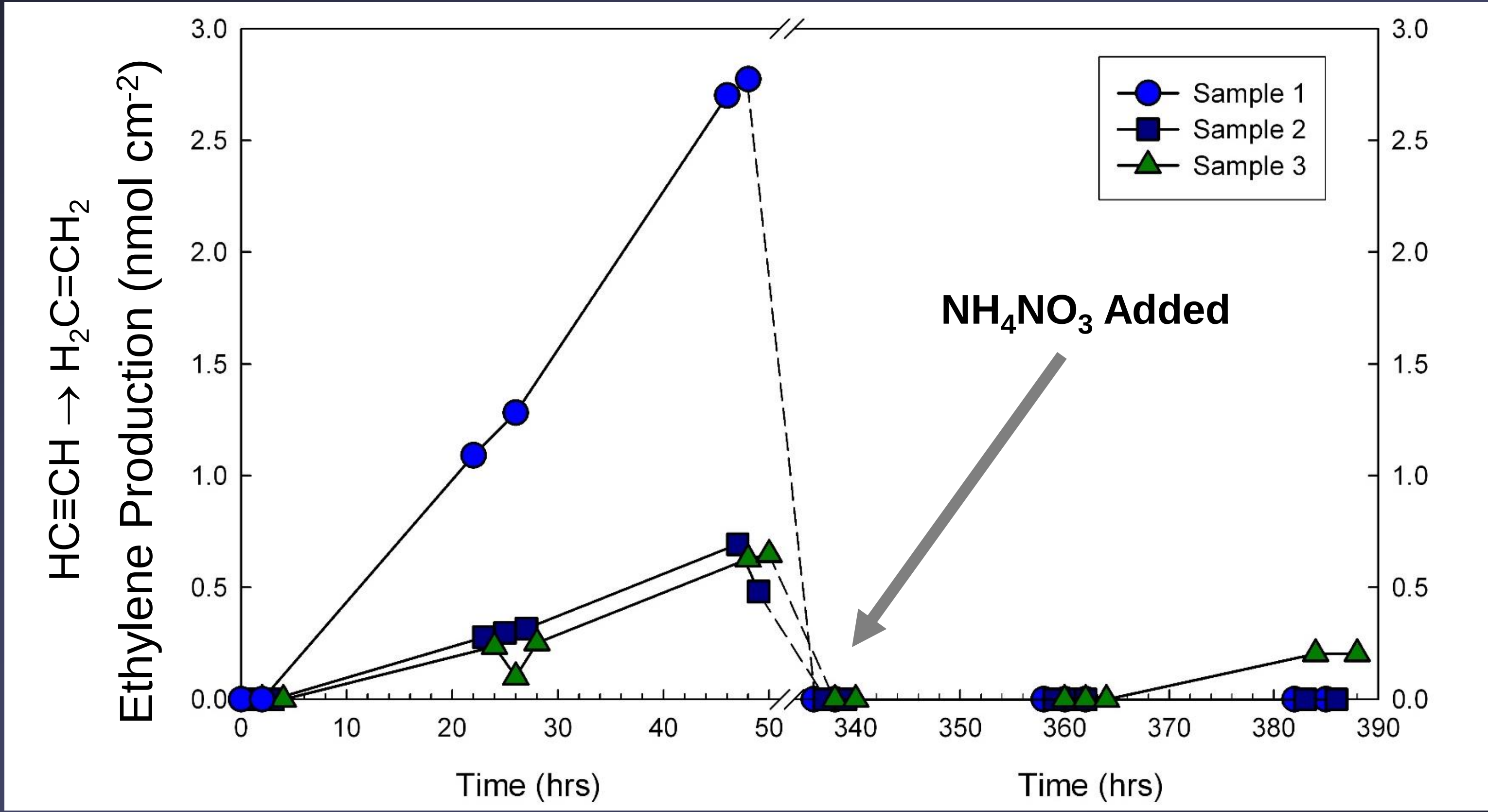
N limitation:
Crusts fix N only when it is needed



Metal limitation:
Metal addition will enhance N_2-fixation

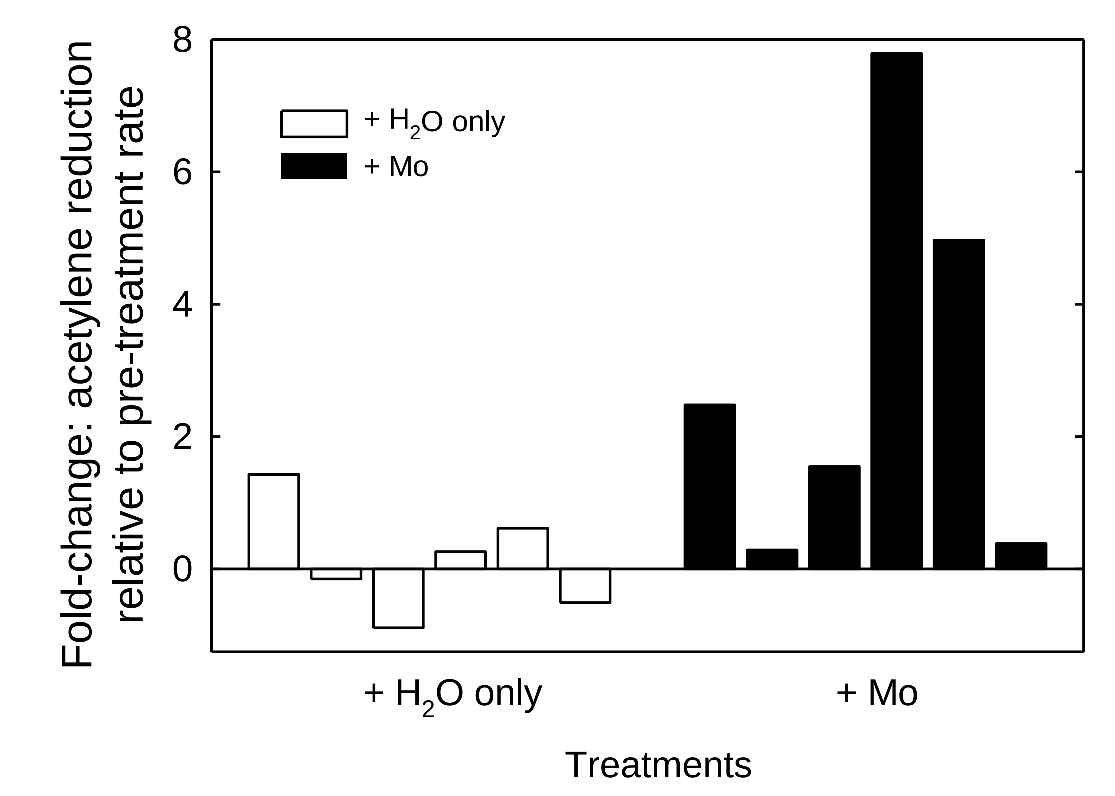


N_2-fixation stops when nitrogen is added



Hartnett et al., submitted.

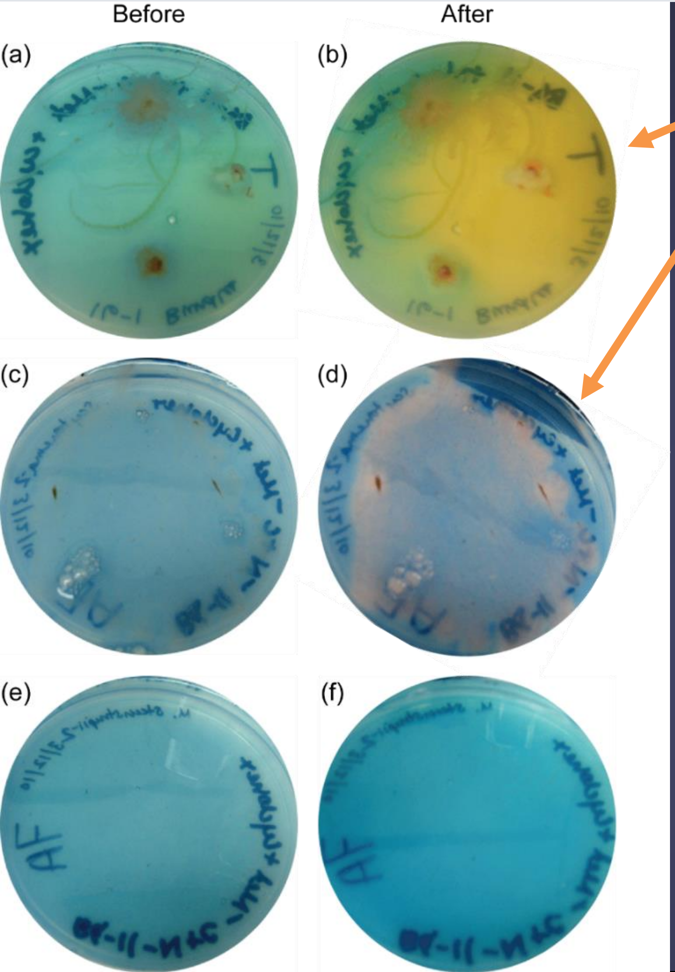
Crusts are molybdenum limited



Hartnett et al., submitted.

- **2-8 fold increase in N_2-fixation with added Molybdenum**
- **How do they acquire metals?**

Crusts make siderophores (metal-binding ligands)



- **CAS assay, isolation, and 16S rRNA sequencing to identify siderophore producers**

Isolates	Closest Sequence	% Similarity
Cyanobacteria		
203	Leptolyngbya sp.	96.5
259	Leptolyngbya sp.	92.4
Firmicutes		
128	Bacillus subtilis, B. vallismortis	99.3
150	B. licheniformis, B. mojavensis, and B. subtilis	99.1
247	Paenibacillus polymyxa	90.8
α-Proteobacteria		
39	uncultured Methylobacteriaceae	92.2
244	Methylobacterium radiotolerans	99.8
β-Proteobacteria		
265	Janthinobacterium sp.	95.9

Low similarity implies many of these are novel organisms

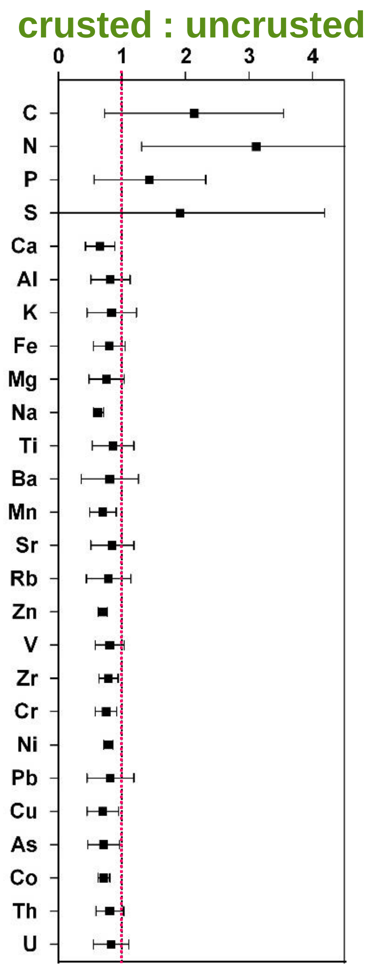
What about a crust biosignature?

- **Net biological production and consumption (CO_2 fluxes) exceed background fluxes, but rates are relatively low**
  - Problem for arid ecosystems in general

- **Minor parts of the community are important for understanding how crusts work**

What other record do crusts leave?

Crust communities alter soil metal content



- **Crusts are enriched in C, N, P, and depleted in metals**

This is a record that could be preserved in paleosols and detected with rover-type instrumentation

Beraldi-Campesi et al. 2009

Take-away messages

- Planetary chemistry and processes are required to under understand life processes
- Ecosystem-scale biological rates must be placed in context with geochemical rates
- Broadest interpretation of biosignatures possible

What about exoplanets?

What about exoplanets

- **Exoplanets are common**
  - >5000 candidates exoplanets
  - 3,726 confirmed planets
  - 10-30 fall into some definition of ‘habitable zone’

- **How many of them are going to look like our Earth?**

- **What if they don’t look like Earth?**

What about exoplanets?

- **We need planetary-scale ecosystem ecology**
  - We will never see proteins, genomes, or even microbes
  - What we may see is the influence of microbes (possibly many microbes) at the scale of a planet

Net Planetary Biological Production (NPBP) =

$$\sum(\text{Production} - \text{Consumption})_{\text{biology}} - \sum(\text{Production} - \text{Consumption})_{\text{geochemistry}}$$

Anoxic Worlds could be common

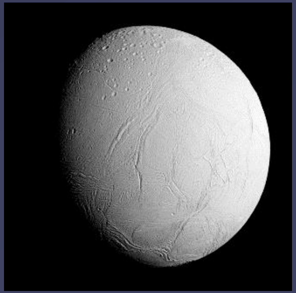
Early Earth

Earth was anoxic for ~2.4 Ga; even post-GOE O_2 levels may be difficult to detect on exoplanets.

Mars

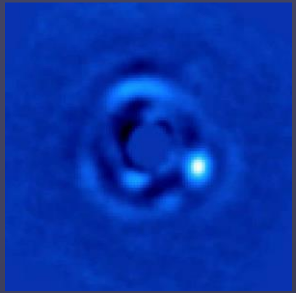
Mars was warm and wet for ~1 Ga; it might have evolved life, but likely not oxygenic photosynthesis.

Icy Worlds



Deep hydrothermal vents, could host life but, again, not oxygenic photosynthesis.

Exoplanets



How many exoplanets will be anoxic?

What are the signatures of life on these planets?

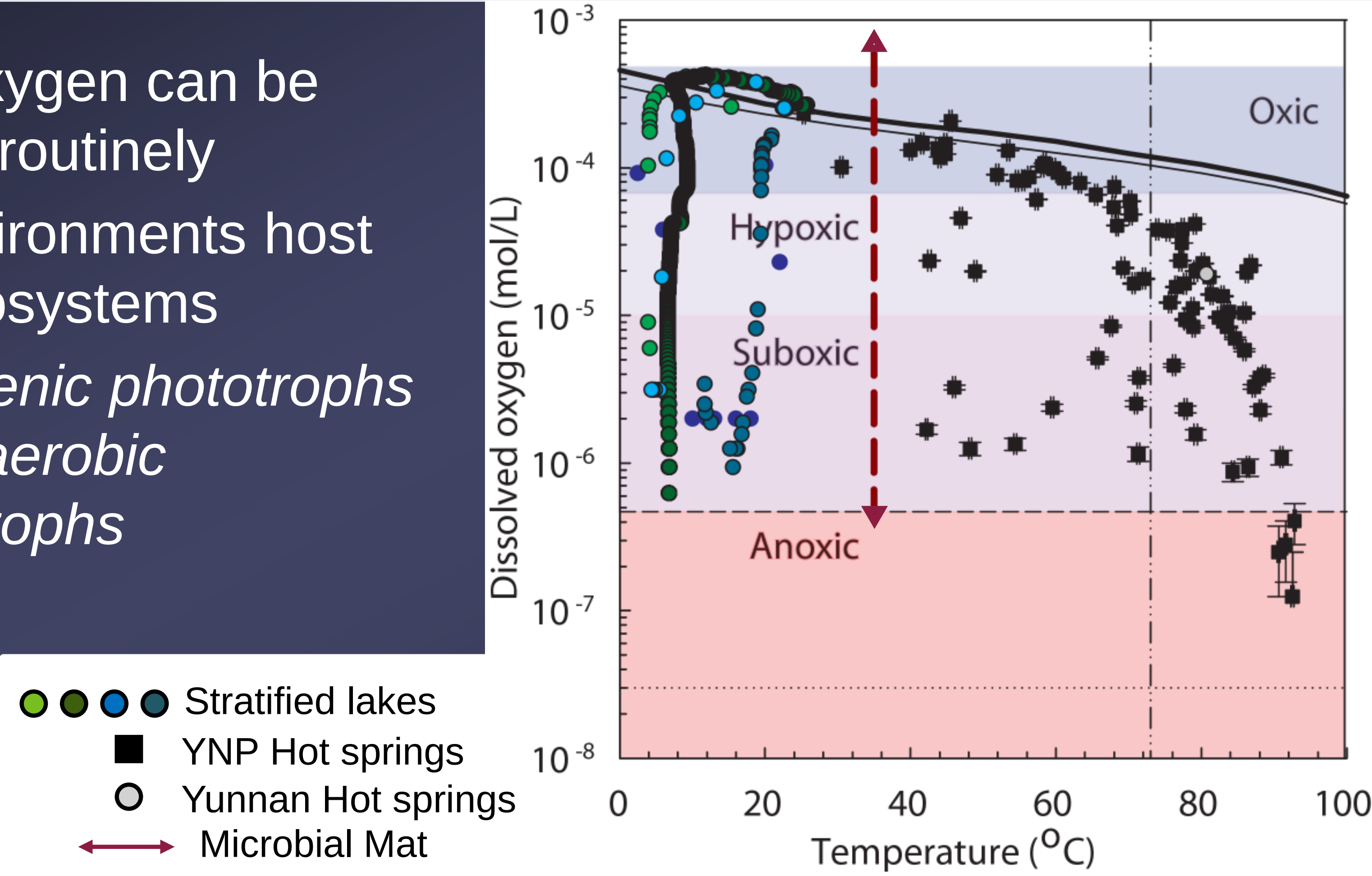
Mostly what we have are questions…

- How are anoxic worlds different from the Earth today?
- How will we recognize them?
- How long do habitable planets remain anoxic?
- What are the best analog systems to explore?

…what we need is data

Earth still has Anoxic Ecosystems

- Sub-µM oxygen can be measured routinely
- These environments host unique ecosystems
  - *anoxygenic phototrophs and anaerobic heterotrophs*



What can we do?

How can we optimize our search for biosignatures that the biology, biogeochemistry, and sedimentology of anoxic worlds?

Assessing biosignatures requires a systems approach

- Planetary and Environmental Constraints
  - Geophysical, geochemical, and geobiological patterns and **process rates**
- Biological Capabilities
  - Determine energetic limits and evolution of processes
  - **Production and consumption rates** for anoxygenic and anaerobic metabolisms
  - Molecular, isotopic, structural, mineralogical signatures
- Preservation and Detection of Biosignatures
  - Examine preservation and degradation processes and rates
  - Optimize detection techniques for biosignatures

Ideally all three approaches applied in the same analog sites, with integrated assessment and modelling!

Take-away messages

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- Ecosystem-scale biological rates must be placed in context with geochemical rates
- Broadest interpretation of biosignatures possible
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Summary

- **Life on Earth reflects the chemistry allowed by Earth; we have no reason to think exoplanets will be different**
  - We need to a systems-based geobiochemical perspective
- **The search for life elsewhere requires understanding planetary-scale ecosystems and biosignatures**
  - Integrated biological rates
  - Emergent properties exist at many scales (isotopic, elemental, molecular, structural, etc.)

Thanks!

Take-away messages

- **Life on Earth reflects the chemistry our planet allows**
  - explore life from a systems-based, geobiochemical perspective
- **The search for life elsewhere requires understanding planetary-scale biosignatures**
  - relative rates of biological and geochemical processes
- **Broadest possible menu of biosignatures**
  - Multiple metabolisms and chemistries
  - evaluate biosignatures across many scales (isotopic, elemental, molecular, structural, etc.)