USC *Geobiology* *Astrobiology* CENTER for LIFE DETECTION JPL

Brijuni Conference
Matter Under Extreme Conditions

Searching for Life in the Universe

Learning from the Extremes of Life on Earth

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But First -- Many Thanks

Danko Bosanac for invitation
Many students, postdocs, colleagues
Funding agencies (NSF; DOE; NASA)

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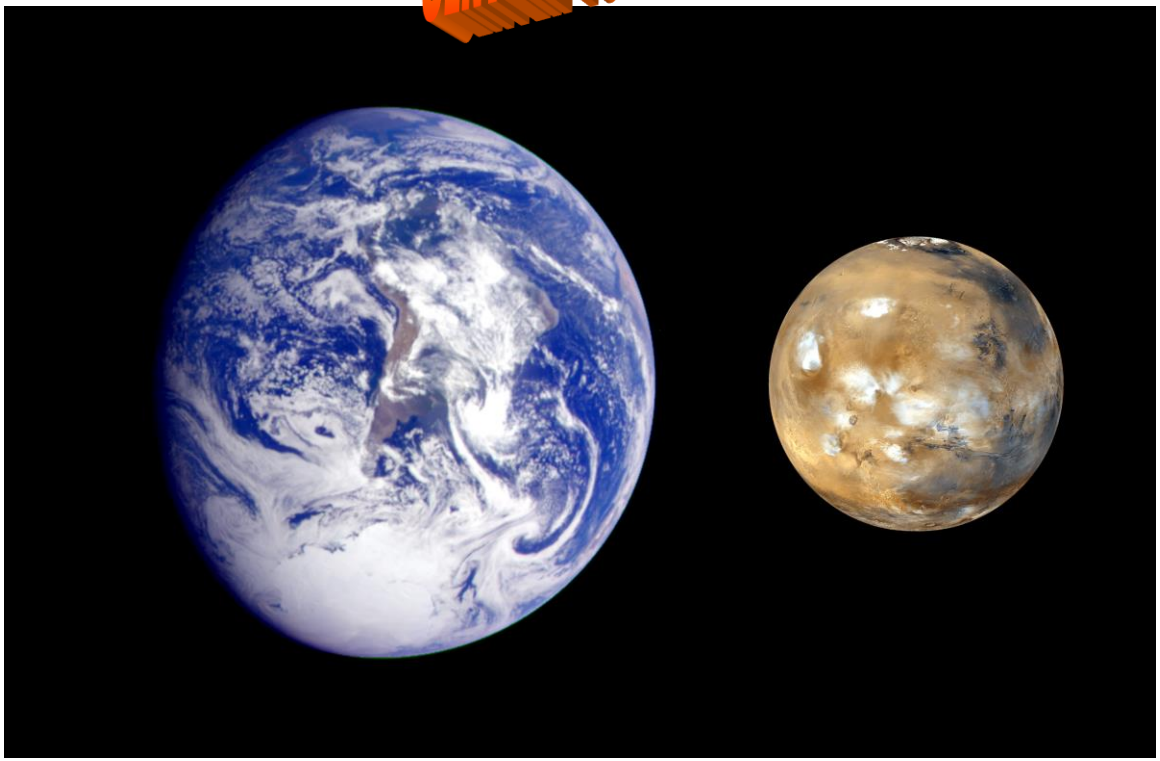
What can we learn by studying the Earth, that will help us in the search for life on elsewhere?



Specifics of earthly life
Details, etc. → General Features (quantifiable, deployable) → Strategy for Life Detection (Missions)

I work with life, not matter!
&, my extremes are not extreme!

To this end, I will attempt to:

(1) Define "Life"

(2) Define its "extremes"

(3) Discuss how such information might impact the search for life

Defining life?

Books are full of definitions.
Most are not particularly useful.

Usually try to distinguish it from non-life
Gives us something to measure

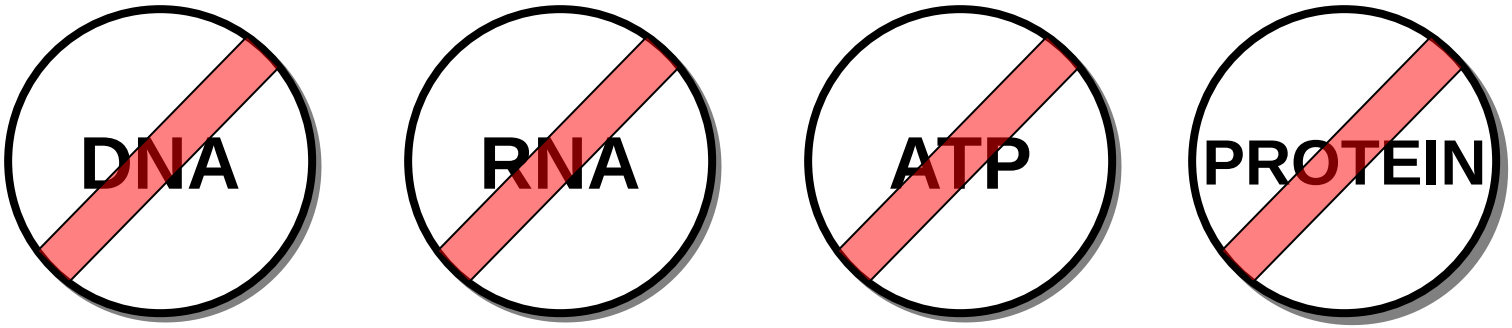
Our rules at CLD:

must be non-Earthcentric
must be measureable

Focus on the general features of life as we imagine them
Avoid the specific molecules of earthly life

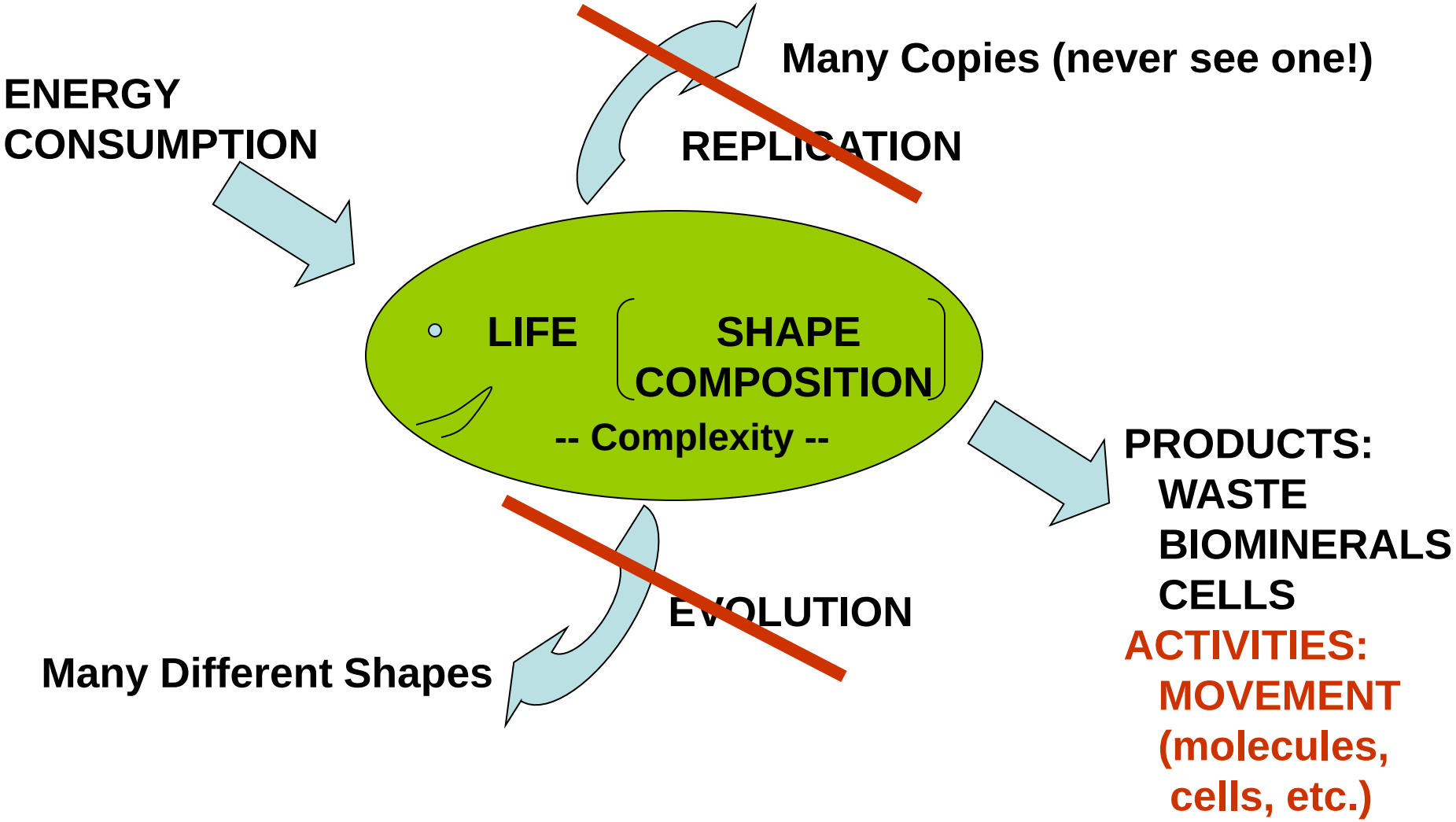
Non-Earth Centric Life Detection

No familiar clues allowed !



(No Lipids, Carbohydrates, LPS, Antibodies, etc.)

Fundamental Features of Life

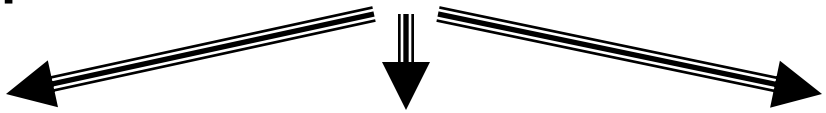


Can we convert this to a few features?

(remembering that we want to be able to measure these features!)

1. Complex materials
   - molecular/cellular topologies, motors, etc.
   - compositions completely out of equilibrium
     - elements/monomers/polymers
2. Catalysts – enzymes
   - Highly specific
   - highly catalytic (6 – 7 orders of magnitude)
3. Non-random movement
   - from molecular to organismal levels

Approaches to Life Detection



Structure and Chemistry

A. Find the structures

B. Determine their Chemistry

- Elemental composition
- Chiral composition
- Isotope fractionation
- Complex molecules

Thermodynamics and Kinetics

A. Define the system

- Energy sources
- Electron donors
- Electron acceptors

B. Identify temporal and spatial extents of energy disequilibria

- Layer formation
- Temporal disruptions

Non-Random Movement

A. Observe Movement

- Spatial scales
- Temporal scales
- Data treatment

To this end, I will attempt to:

(1) Define "Life"

(2) Define its "extremes"

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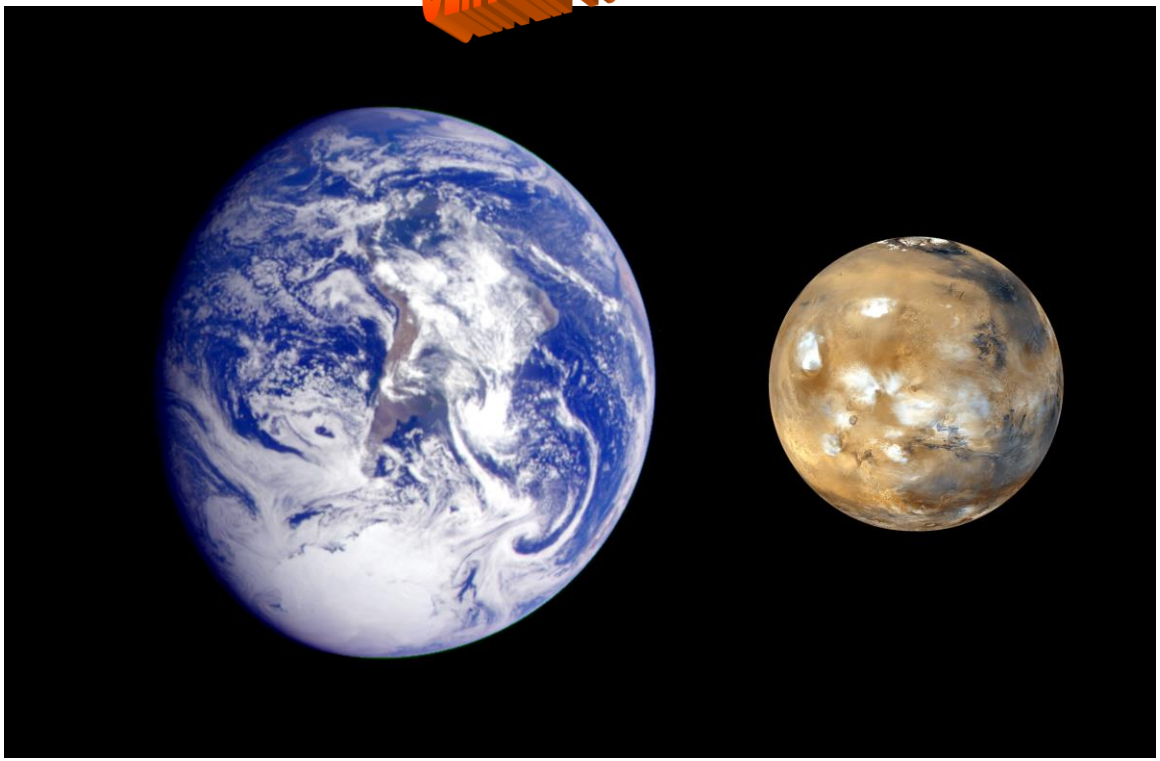
What are the Extremes of Life?

What can we learn by studying the Earth, that will help us in the search for life on Mars?



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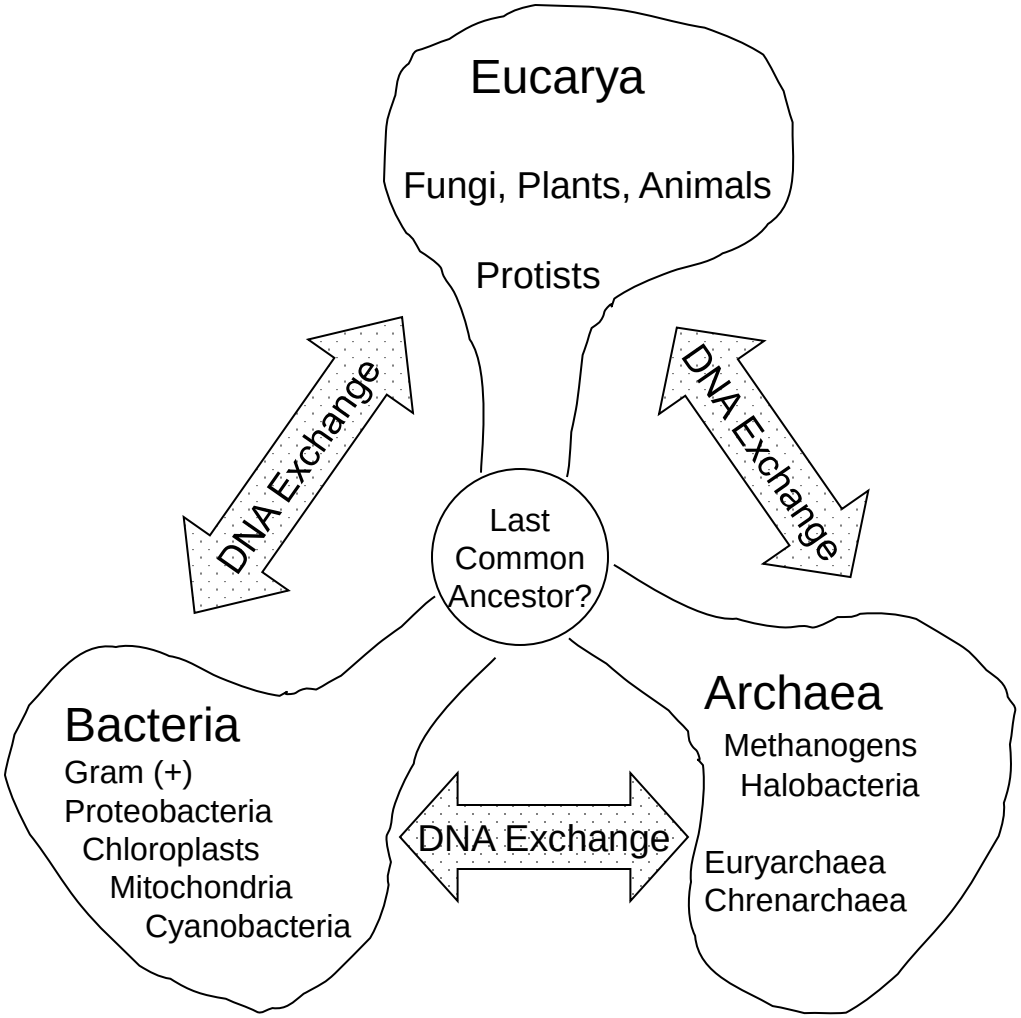


Eukaryotes:

large cells
two chromosomes
nucleus and nuclear membrane
eat other organisms
complex structures
sensitive to extremes
metabolically simple

Prokaryotes

small cells (~ 1 micrometer)
single chromosome
no nucleus or nuclear membrane
do not eat other organisms
simple cellular structure

Extremophiles { very tough and resistant
metabolically diverse !

Extremophiles

In the eyes of the beholders –

usually quite human-centric/too hot for us, it is extreme

Physical extremes – T, P (thermophile, piezophile)

Chemical extremes – aridity, pH, salinity

Resistance to toxic things– radiation, metals, organics, etc.

These are things that are not "needed" *per se*

Things that at extremes are not compatible with "life"

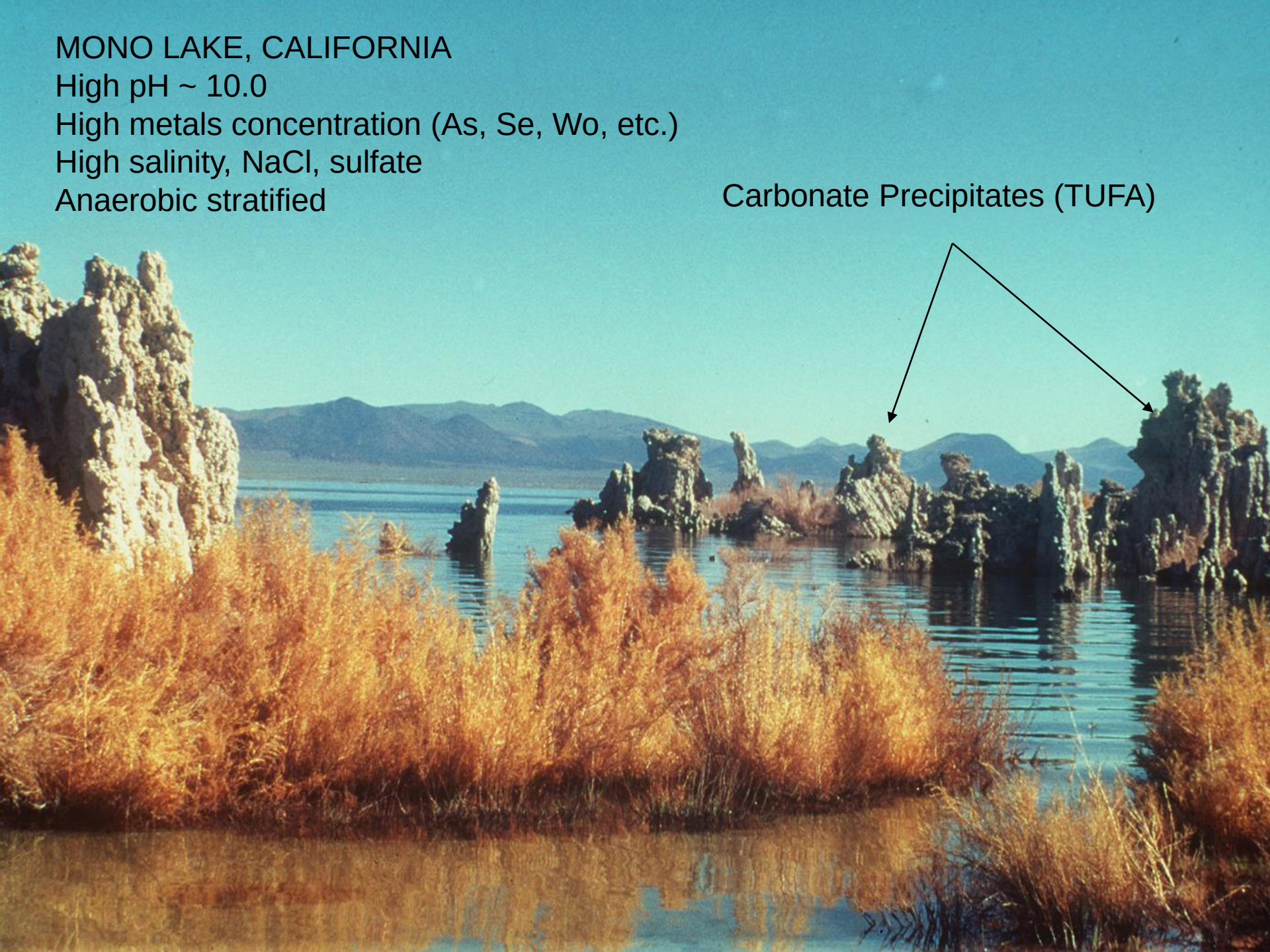
often is involved with availability or quality of water

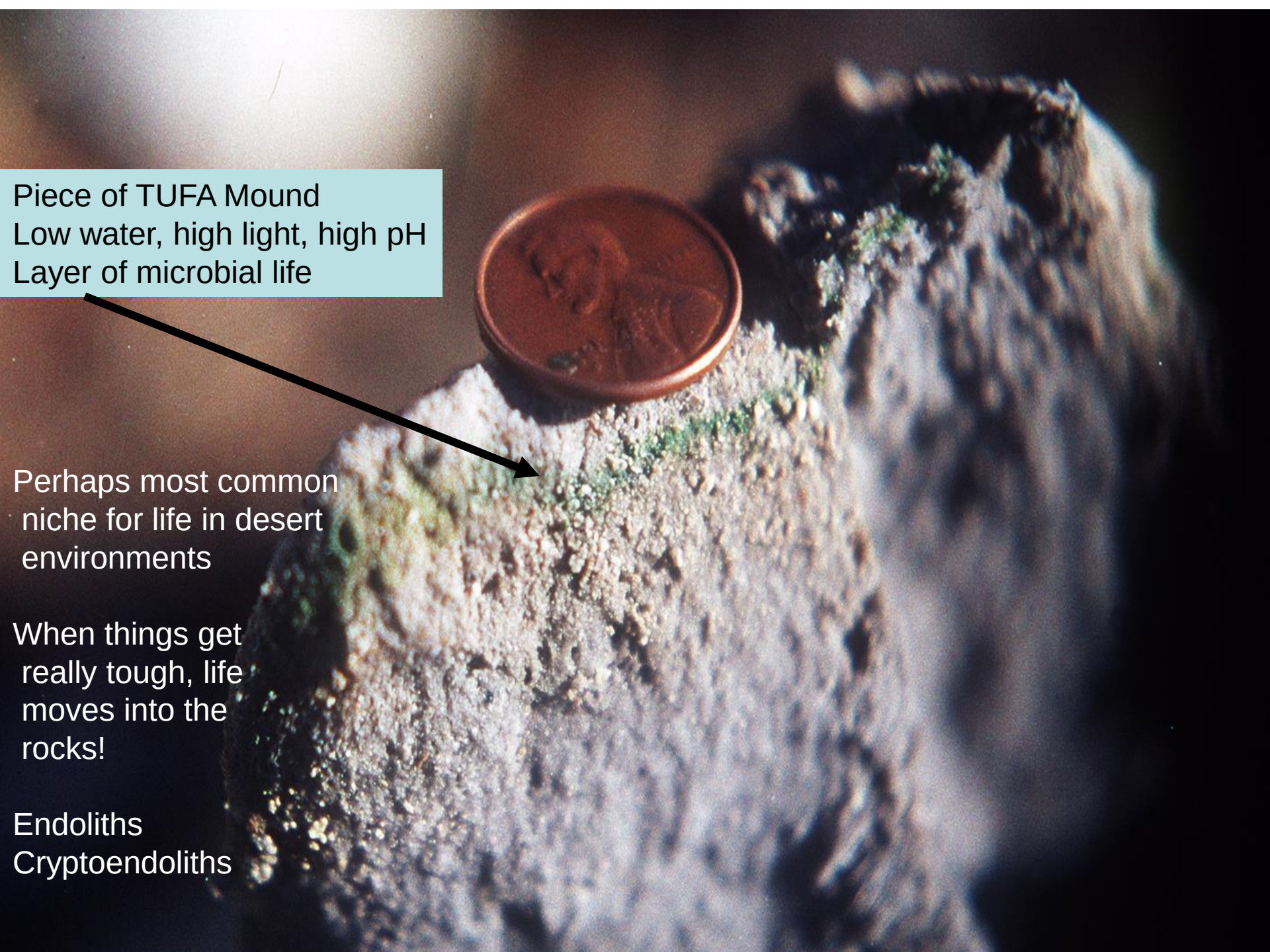
Served to expand our view of the limits of life

so-called "habitable zone"

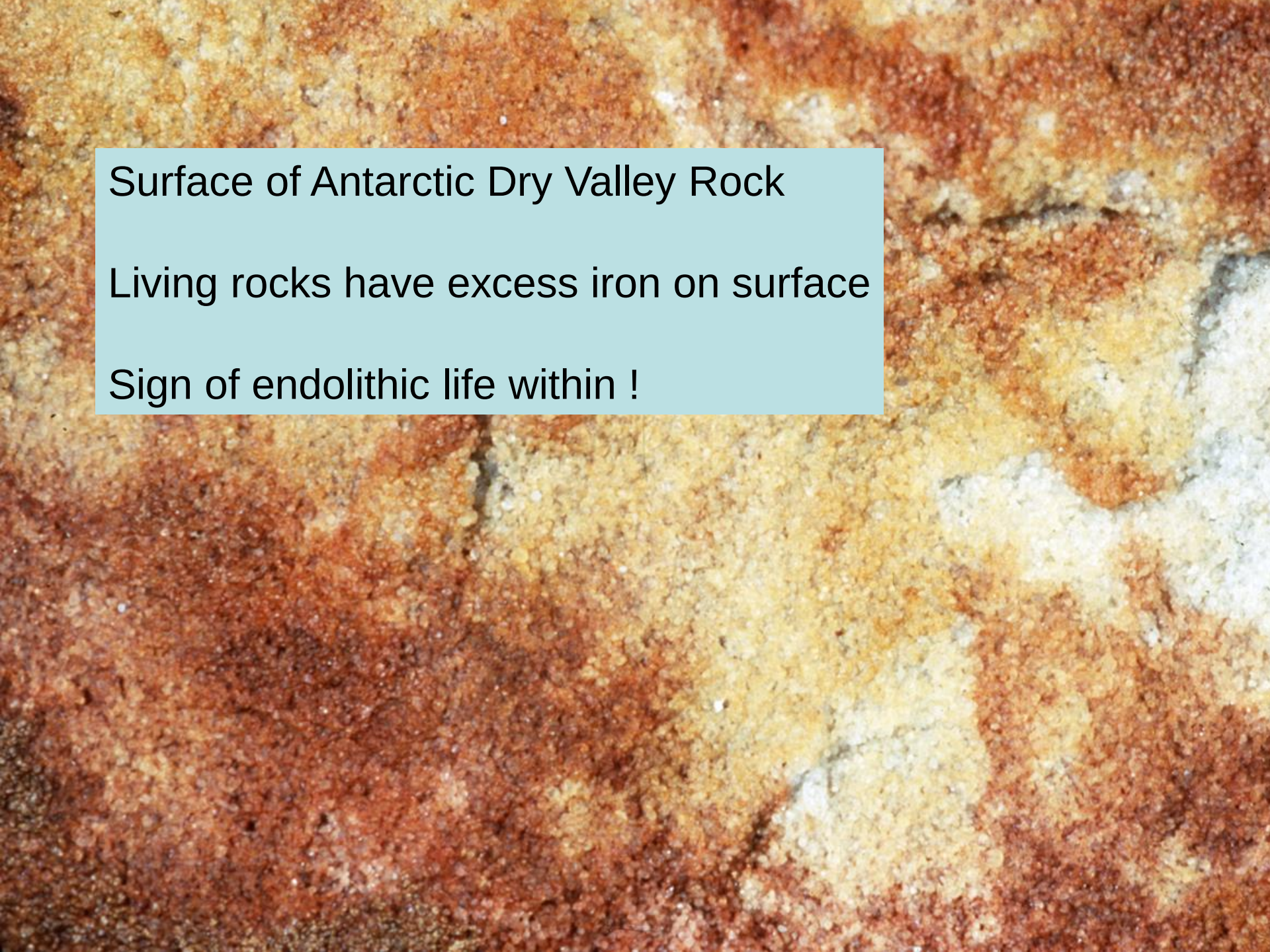
Biological molecules are fragile, and adapt to ranges!

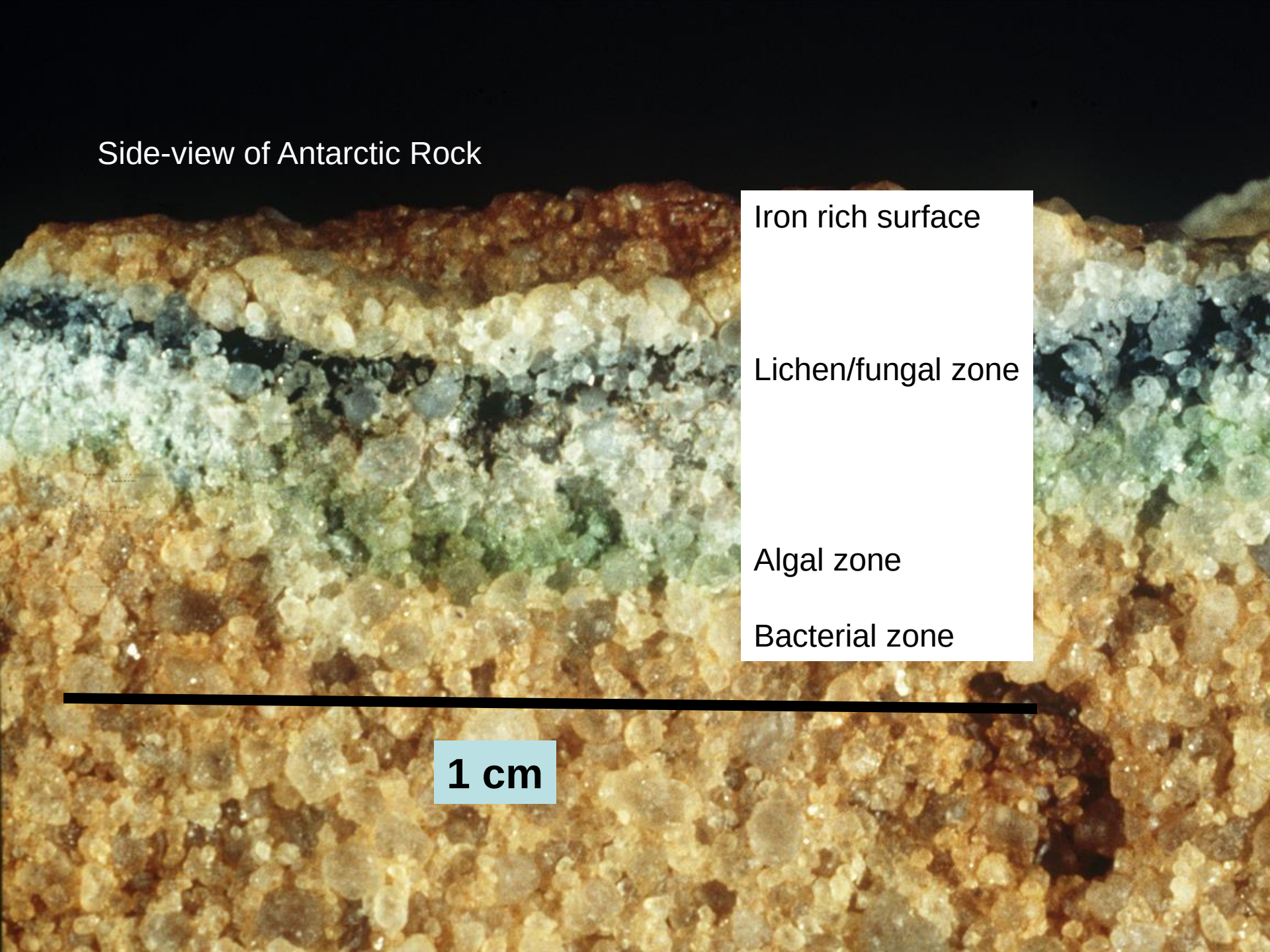
MONO LAKE, CALIFORNIA
High pH ~ 10.0
High metals concentration (As, Se, Wo, etc.)
High salinity, NaCl, sulfate
Anaerobic stratified




Piece of TUFA Mound
Low water, high light, high pH
Layer of microbial life
Perhaps most common niche for life in desert environments
When things get really tough, life moves into the rocks!
Endoliths
Cryptoendoliths

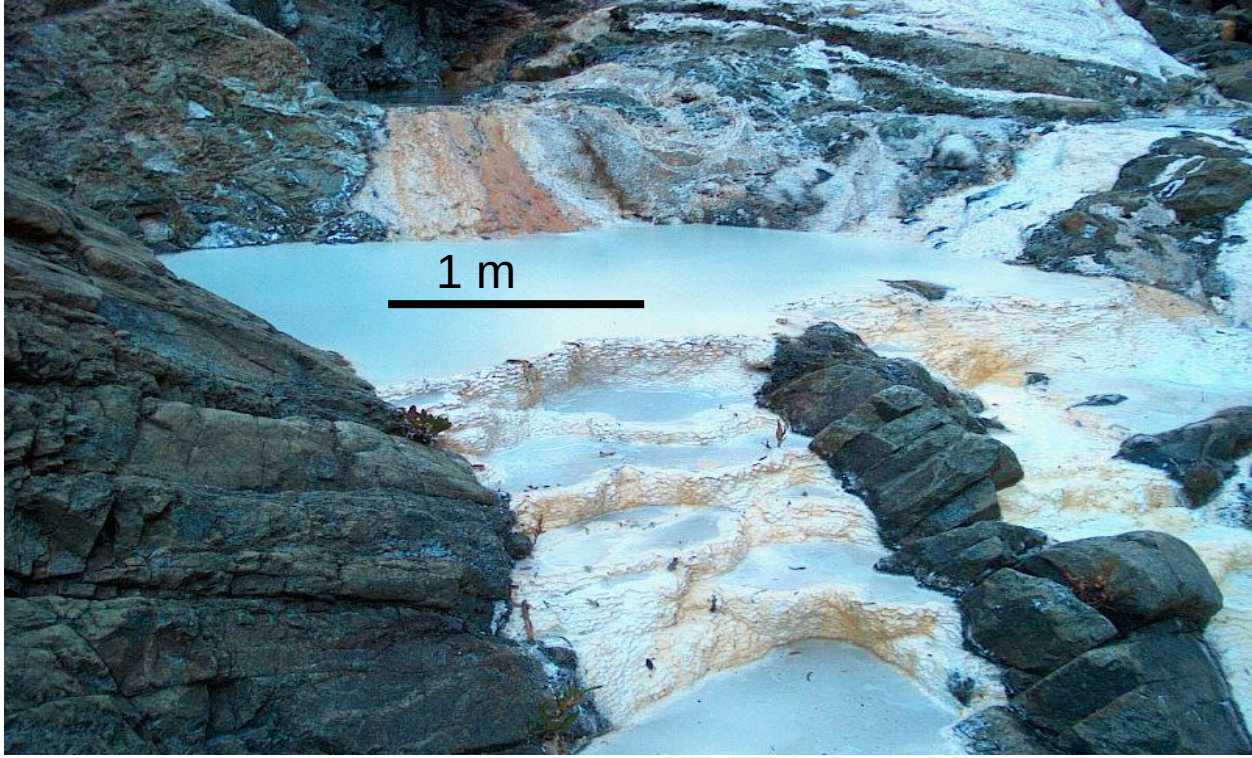

Antarctic Dry Valley Environment
Permanently below 0 °C
No liquid water – snow, ice
Thought for many years to be sterile


Surface of Antarctic Dry Valley Rock
Living rocks have excess iron on surface
Sign of endolithic life within !


Side-view of Antarctic Rock
Iron rich surface
Lichen/fungal zone
Algal zone
Bacterial zone
1 cm

The Cedars:

Typical large carbonate structure on serpentine-forming mountains.



Layers of carbonate grow up to 1 m each summer

pH ~ 12, low Eh ~ -500
High Ca, H_2, CH_4, low Na^+

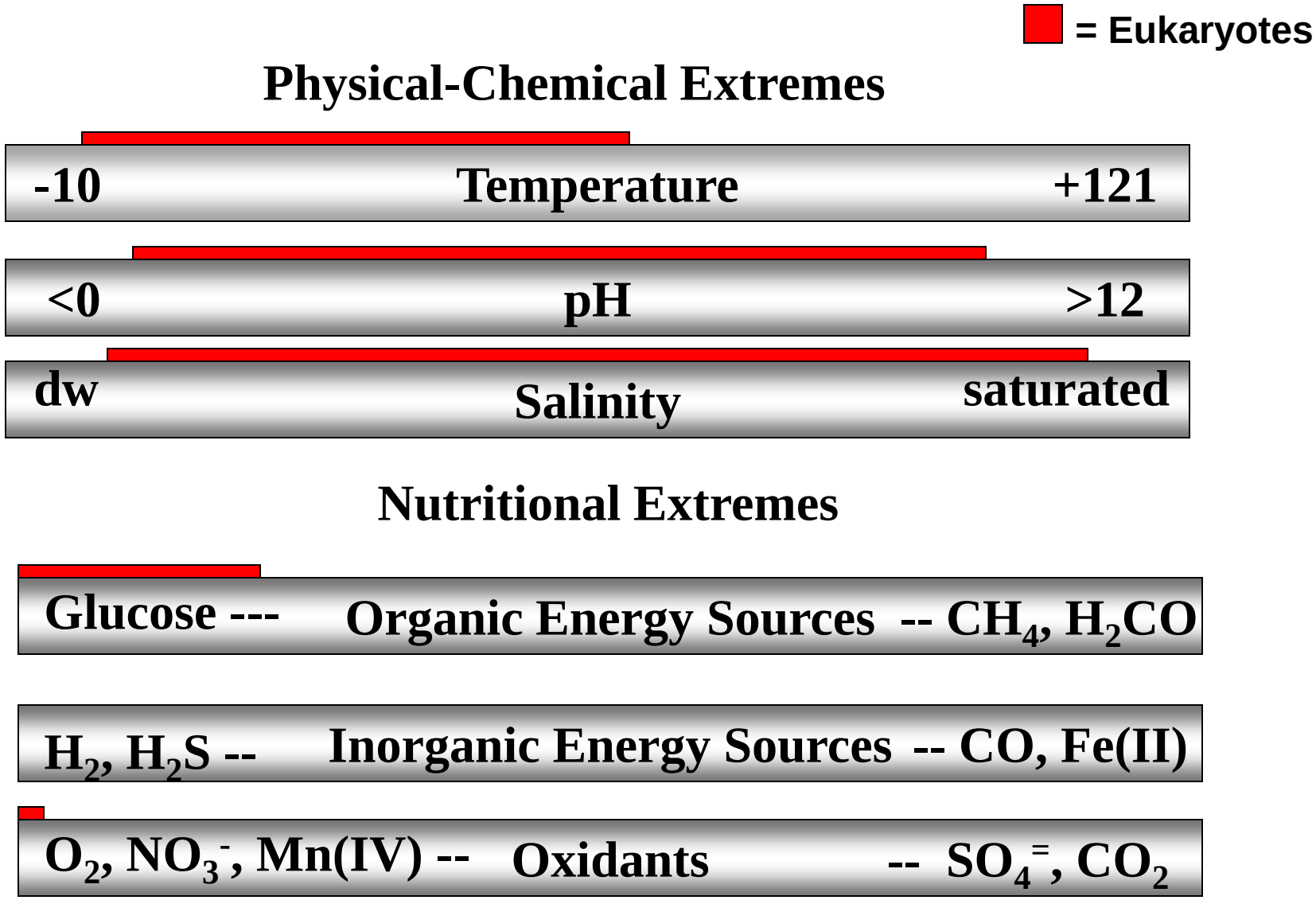
Major process where water flows through volcanic rock
Must have been what early Earth was like in many areas
Volcanoes, volcanic rock, water, lots of hydrogen, methane, heat, high pH

Outflow of Cedars' water has pH ~ 12
And Eh ranging down to -700 mV or more!

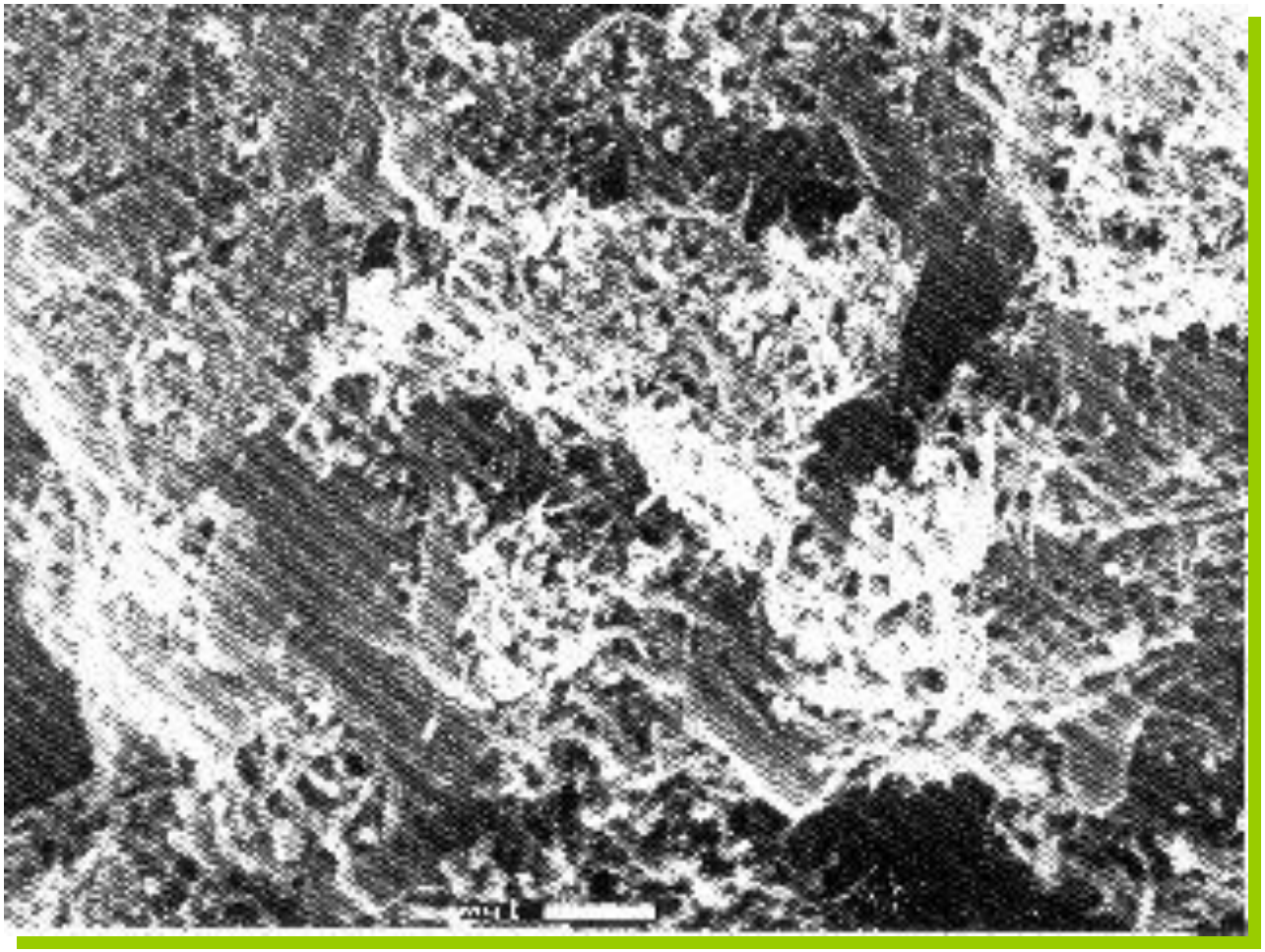
Low microbial population
10^3 - 10^5 ml^{-1} in water
Iron reducers
Hydrogen oxidizers

One of most extreme environments on Earth!
Combination of physical and chemical extremes!

Extremophiles -- Life at the edge



Unusual Life Form!!



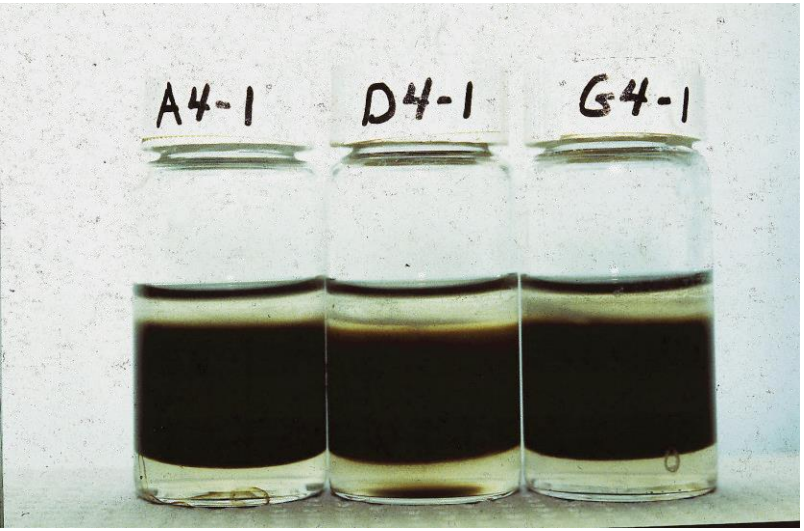
Shewanella oneidensis

Discovered in 1988

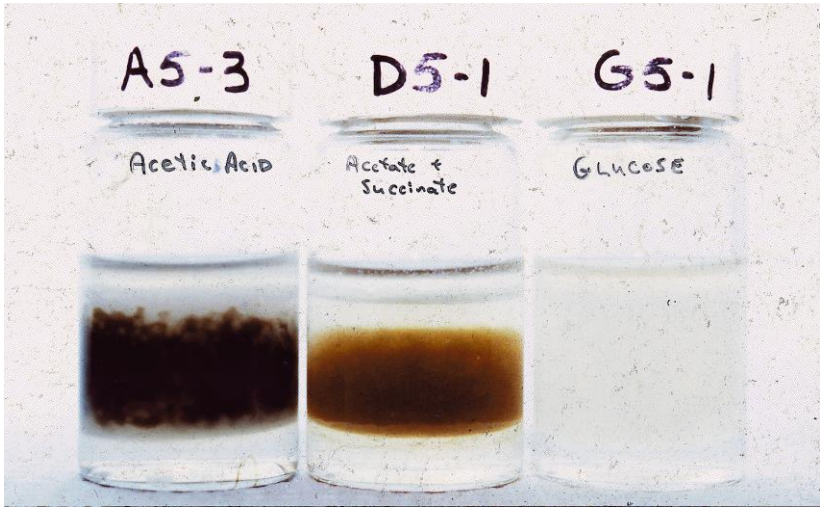
Energy source is hydrogen or formaldehyde

Breathes rocks! Mn oxides or Iron oxides

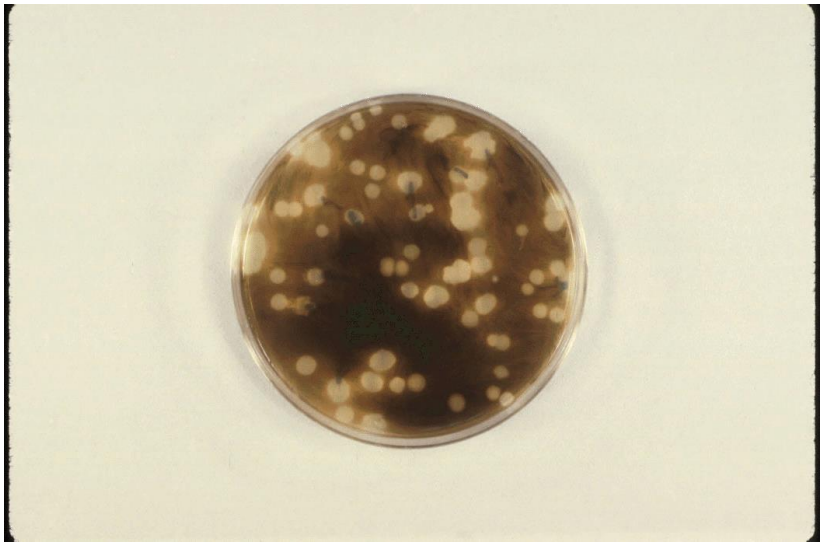
Enrichment Culture



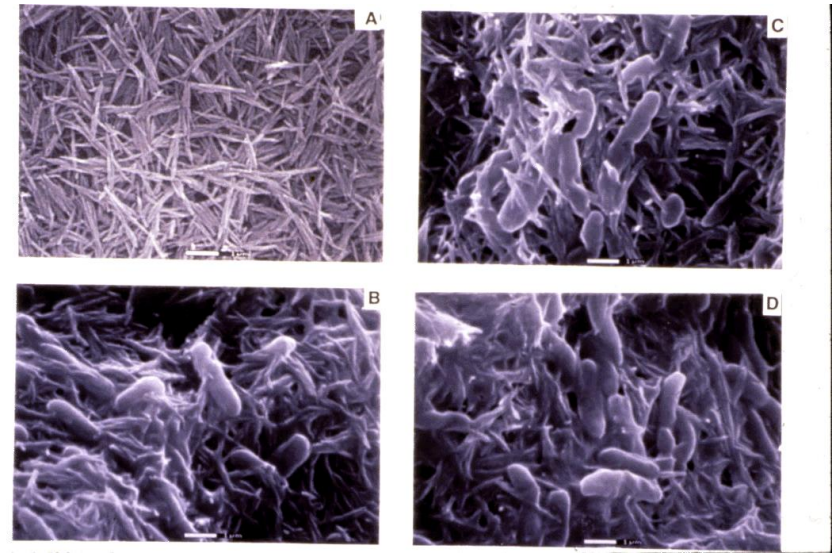
Five Days Incubation



Mn reduction on plates



Pure Culture on MnO_2

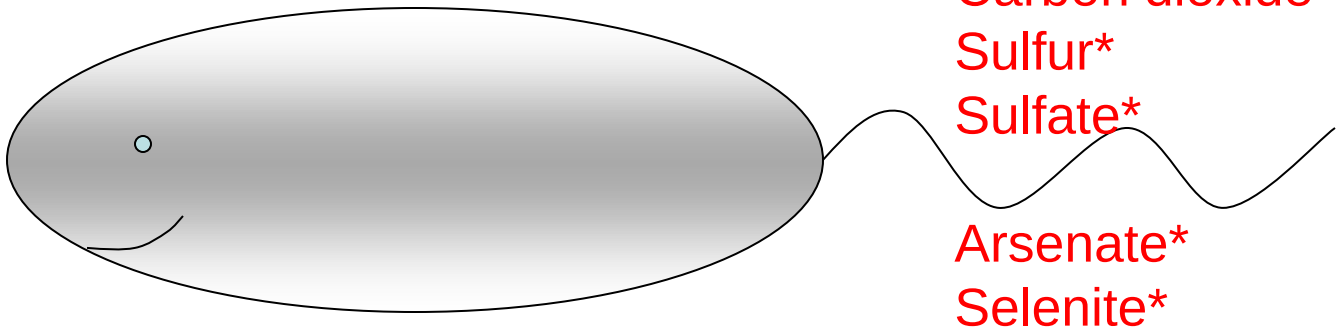


Fuels (EDIBLES!!)

SUNLIGHT

ORGANICS
- **Glucose**
- **Ethanol**
- Formaldehyde
- Methanol

Hydrogen
Ammonia
Hydrogen sulfide*
Sulfur*
Iron*
Manganese*
Carbon monoxide*
Arsenite*



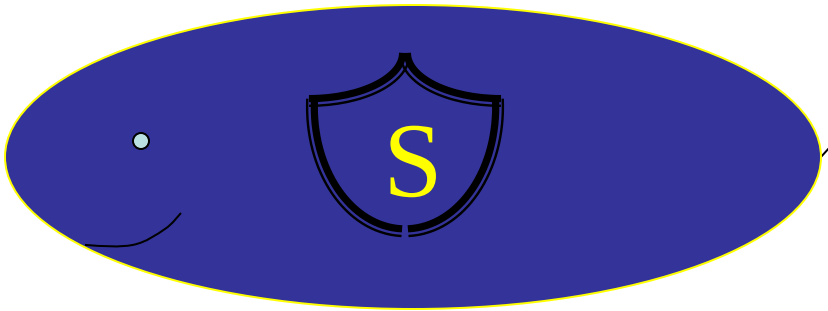
Oxidants (BREATH-ABLES !!)

ORGANICS
fumarate, DMSO
TMAO
Carbon dioxide*
Sulfur*
Sulfate*
Arsenate*
Selenite*
Iron*
Manganese*
Nitrate

Oxygen*

Asterisks indicate those that
End up in rocks or minerals! (N does not, many others do!)

Shewanella oneidensis – MR-1



Formate

Lactate

Pyruvate

Amino Acids

H_2

Mine waste
Black Sea
Oneida Lake
Green Bay

Panama Basin
Mississippi Delta
North Sea Interfaces

O_2

NO_3^-, NO_2^-

Mn(IV)

Mn(III)

Fe (III)

Fumarate

DMSO

TMAO

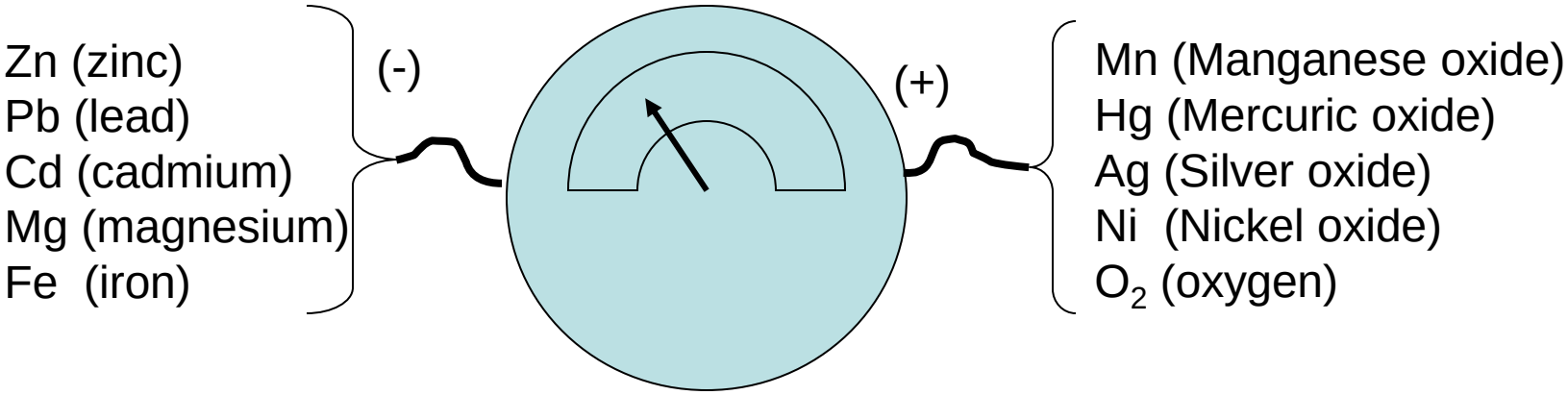
S^o

$S_2O_3^{2-}$

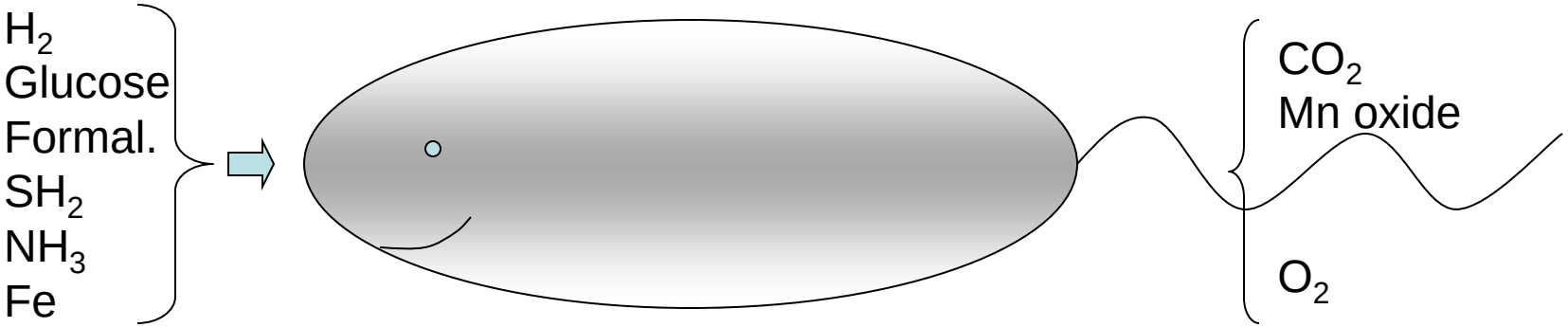
U(VI)

Cr(VI), Tc, As, Se, I,

These bacteria are GREAT for teaching chemistry !!

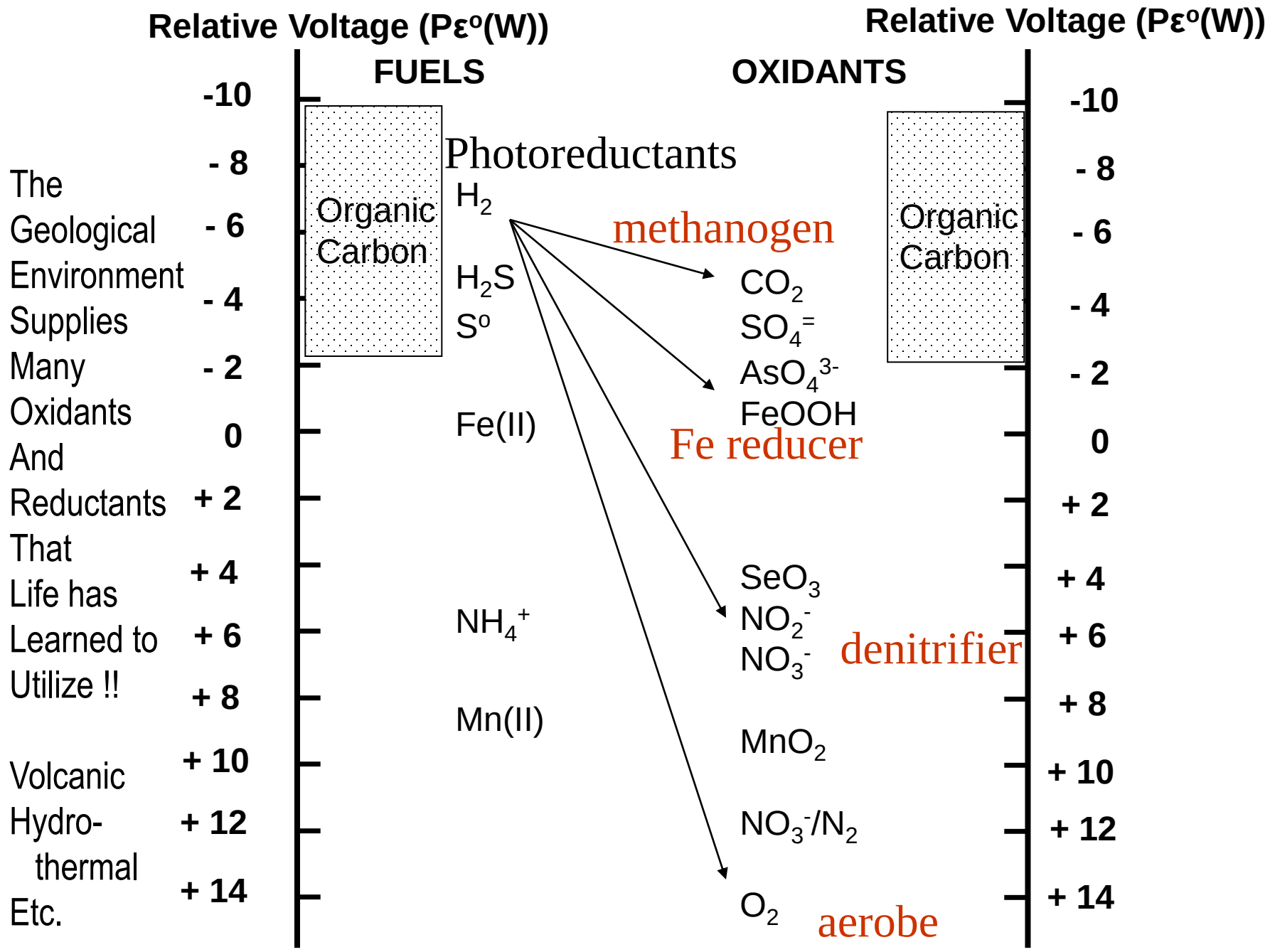


MANMADE BATTERIES !!

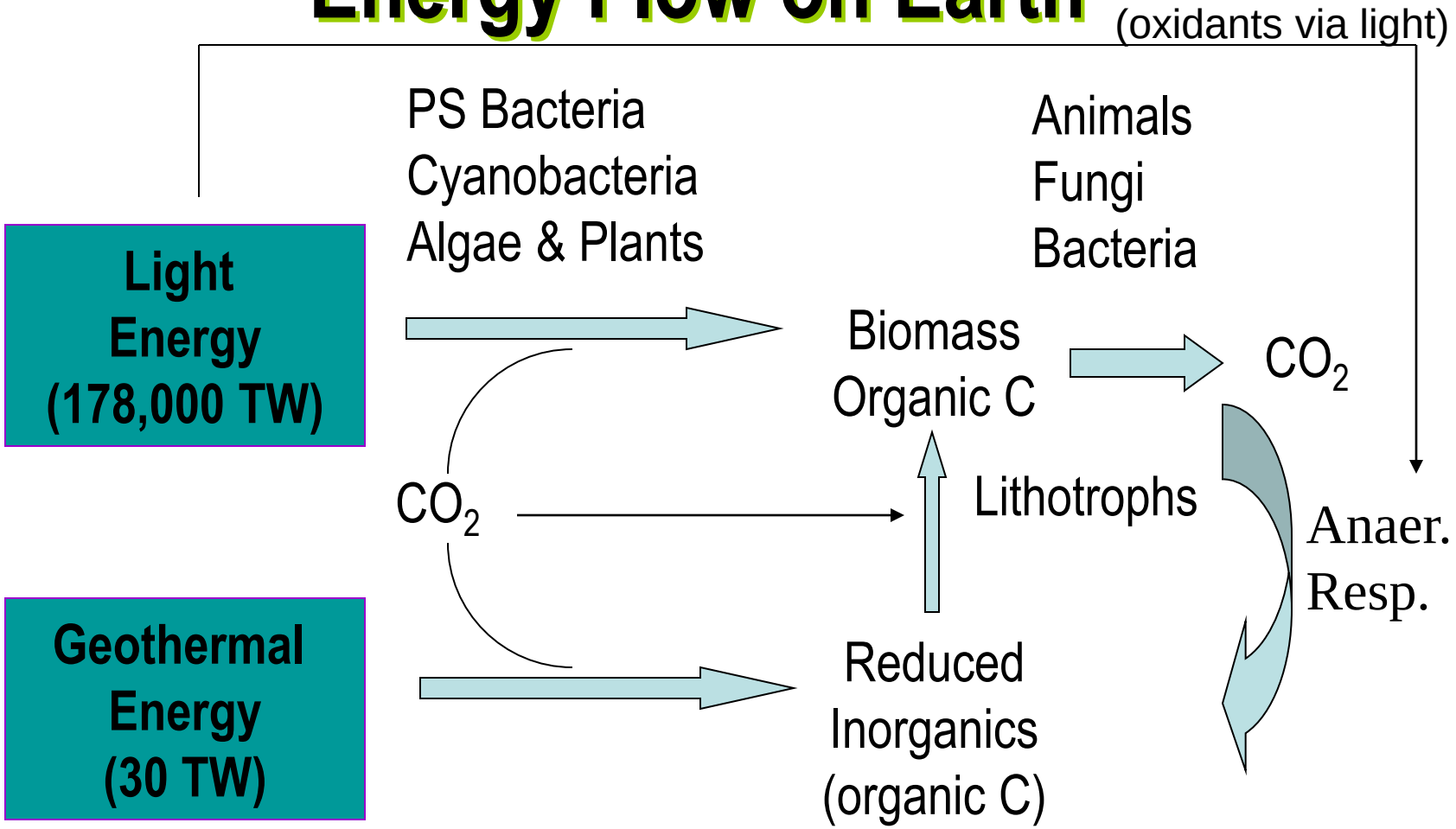


BIOLOGICAL BATTERIES !!

(versatile, rechargeable, solar or chemical !)


Relative Voltage (Pε°(W))
FUELS
OXIDANTS
Relative Voltage (Pε°(W))
-10
- 8
- 6
- 4
- 2
0
+ 2
+ 4
+ 6
+ 8
+ 10
+ 12
+ 14
The Geological Environment Supplies Many Oxidants And Reductants That Life has Learned to Utilize !!
Volcanic Hydro-thermal Etc.
Organic Carbon
Photoreductants
H2
H2S
So
Fe(II)
NH4+
Mn(II)
methanogen
CO2
SO4=
AsO43-
FeOOH
Fe reducer
SeO3
NO2-
NO3-
denitrifier
MnO2
NO3-/N2
O2
aerobe
Organic Carbon

Energy Flow on Earth



Nutritional Extremophily:

Continuing to eat and breathe when organic C and oxygen are not present?

As with other types of "extremophiles" – not remarkable
It is really a way of thinking

With regard to prokaryotic niches, it is critical

Organisms adapt to eat and breathe a wide variety of different things (rather than each other)

Prokaryotic "food chains" mainly involve eating nutrients rather than other organisms !!

Nutritional Extremophily:

The successful microbes are those that:

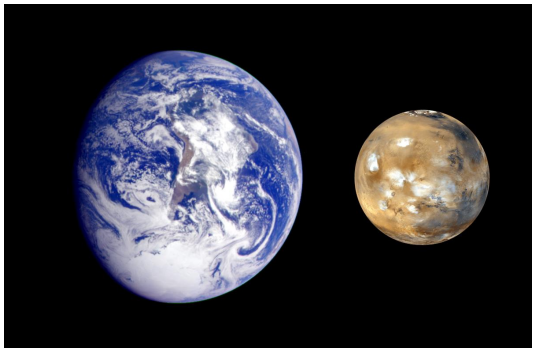
- **Know when to stop dividing**
- **Know how to change their diet**
- **Know how to keep their "partners" alive and happy and cooperative**

Nutritional Extremophily:

When faced with accumulation of waste products and depletion of resouces:

1. **Invent motility and move**
2. **Invent convection and move the environment**
3. **Invent the ability to use a new fuel or oxidant**
4. **Invent symbiosis and live with a friend**

This is what we expect to happen anywhere life has appeared and is evolving – this stress should drive evolution of metabolism

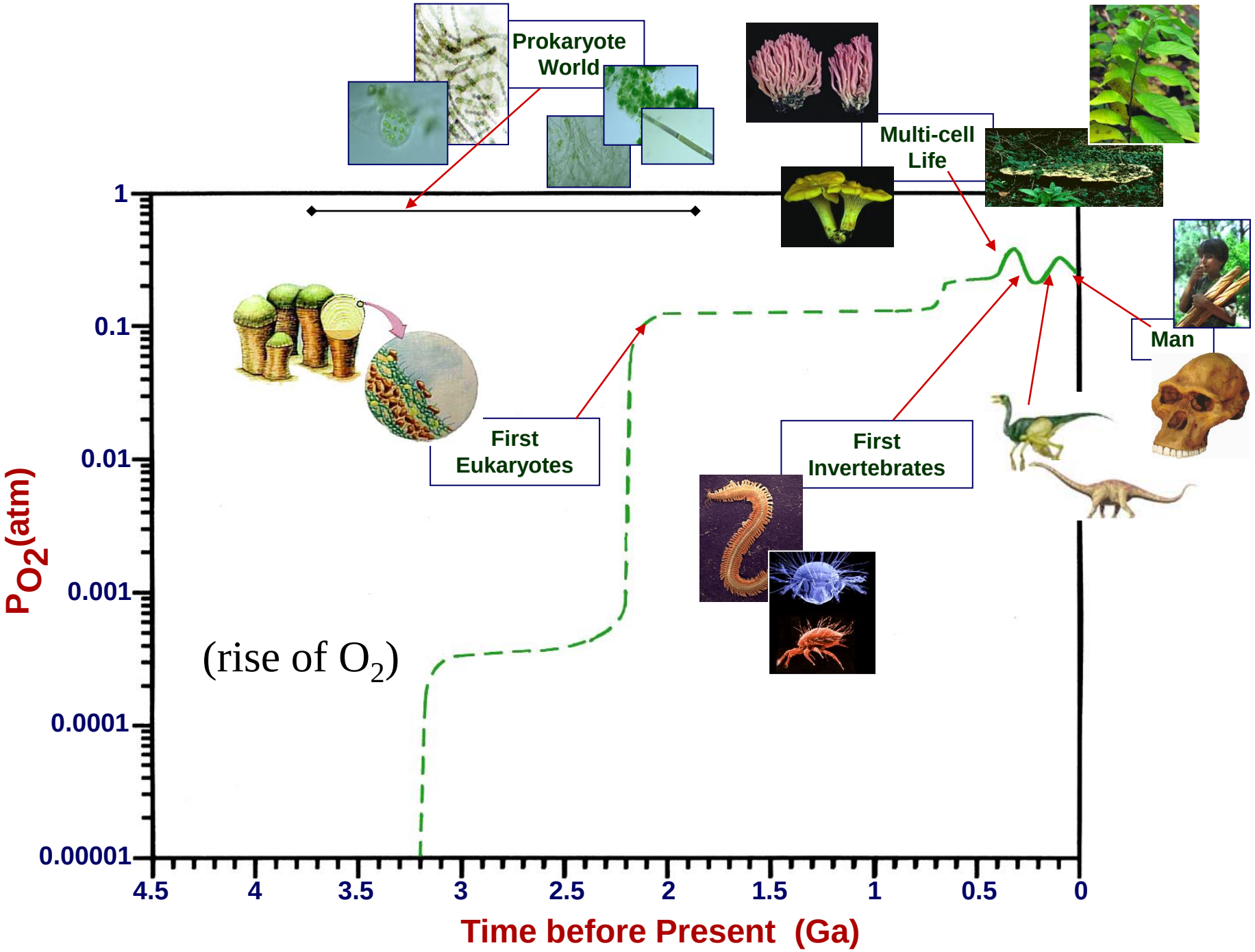


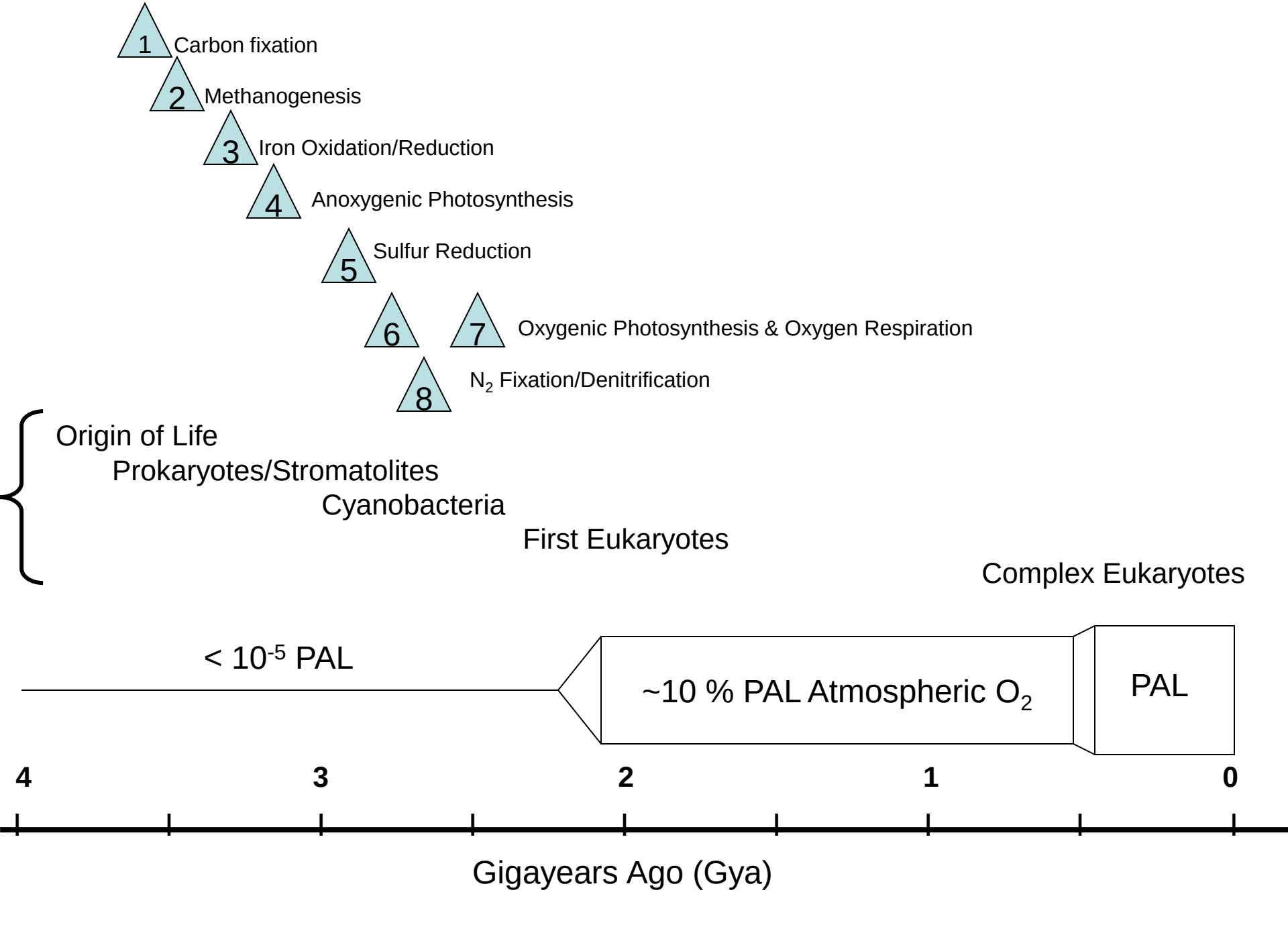
One very important element is that of time:

By a number of techniques, can estimate appearance of these abilities on the Earth (stable isotopes; mineralogical analyses, etc.)

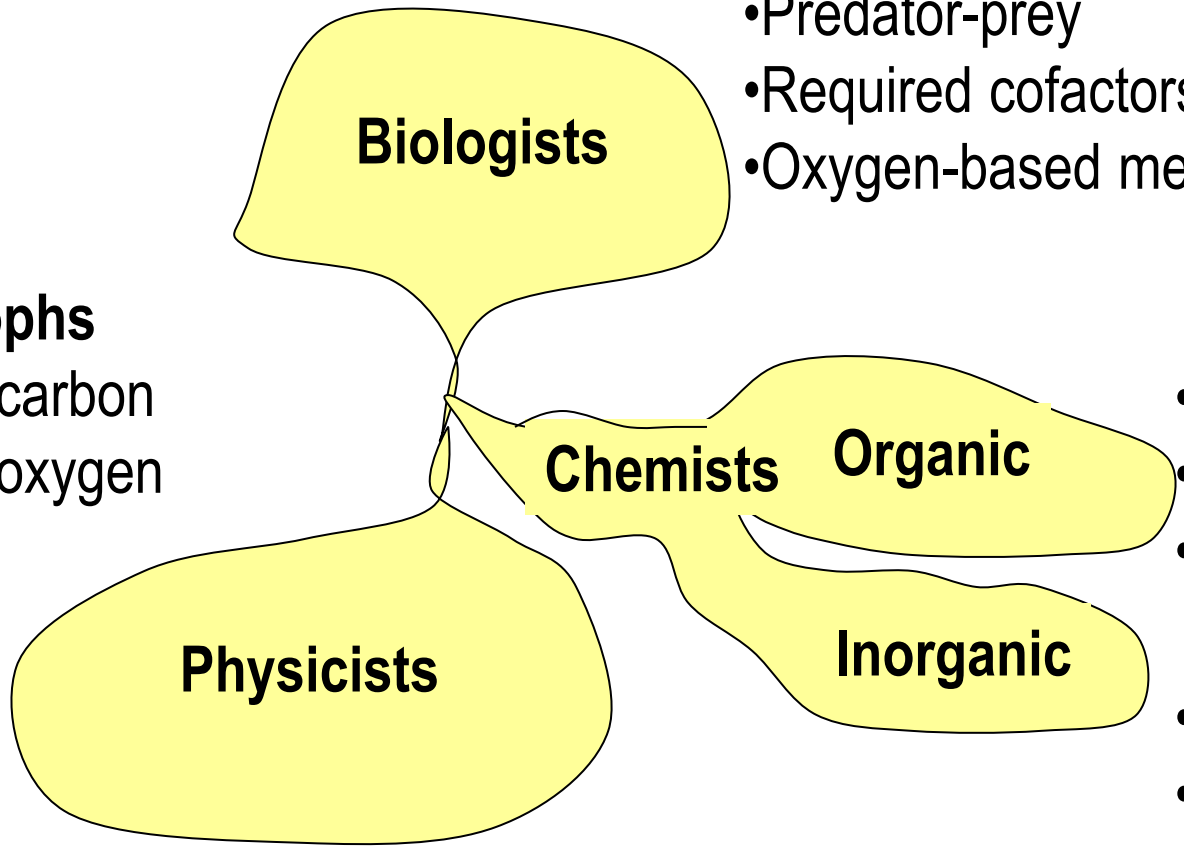
In general, metabolic interactions with rocks appear to have evolved very early (Redox chemistry; lithotrophy, autotrophy – C reduction; S redox chemistry)

Biomineral formation is a relatively late process


Prokaryote World
Multi-cell Life
Man
First Eukaryotes
First Invertebrates
(rise of O_2)
P_{O_2}(atm)
1
0.1
0.01
0.001
0.0001
0.00001
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Time before Present (Ga)


1
Carbon fixation
2
Methanogenesis
3
Iron Oxidation/Reduction
4
Anoxygenic Photosynthesis
5
Sulfur Reduction
6
7
Oxygenic Photosynthesis & Oxygen Respiration
8
N_2 Fixation/Denitrification
Origin of Life
Prokaryotes/Stromatolites
Cyanobacteria
First Eukaryotes
Complex Eukaryotes
< 10^{-5} PAL
~10 % PAL Atmospheric O_2
PAL
4
3
2
1
0
Gigayears Ago (Gya)

The Three Kingdoms of Life



- Predator-prey
- Required cofactors
- Oxygen-based metabolism

•Phototrophs
- Produce carbon
- Produce oxygen
- Plants
- Algae
- Bacteria
- Archaea

•Organotrophs
- Fungi, Bacteria
- Archaea

•Lithotrophs
- Bacteria
- Archaea

What does all this have to do with the search for life?

On Earth, life had adjusted to the major energy sources available

On Earth, life has pushed itself into the furthest and most extreme parts of the "low temperature" realm

Life leaves predominant signals in terms of chemical (mineralogical & physical) disequilibria.

We should expect the same of life anywhere.
Should be obvious to you – this has nothing to do with biology per se, but with life.

If I were organizing the search for life, I would try to leave the biologists (except of course, for myself!) out of it.

Fundamental Laws of Life Detection:

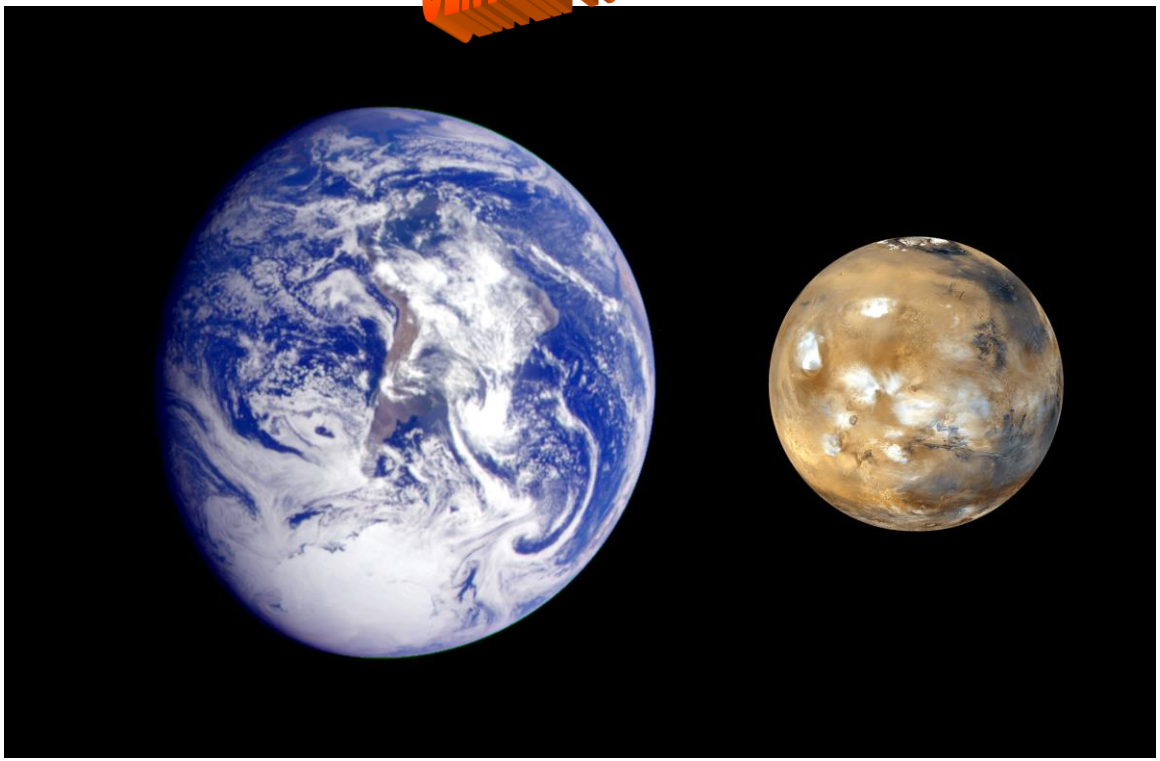
1. Know your planet
   physics, chemistry, geology
   edibles (reductants)
, breathe-ables (oxidants) etc.

2. Do non-earthcentric life detection

3. Keep an open mind

End where we began!!

What have we learned by studying the Earth, that may help us in the search for life on Elsewhere?



Life on our own planet is devious and clever.
It has occupied virtually every energetic niche.
We should expect no less anywhere else!

Ask the simple questions! --- THANK YOU FOR YOUR TIME!