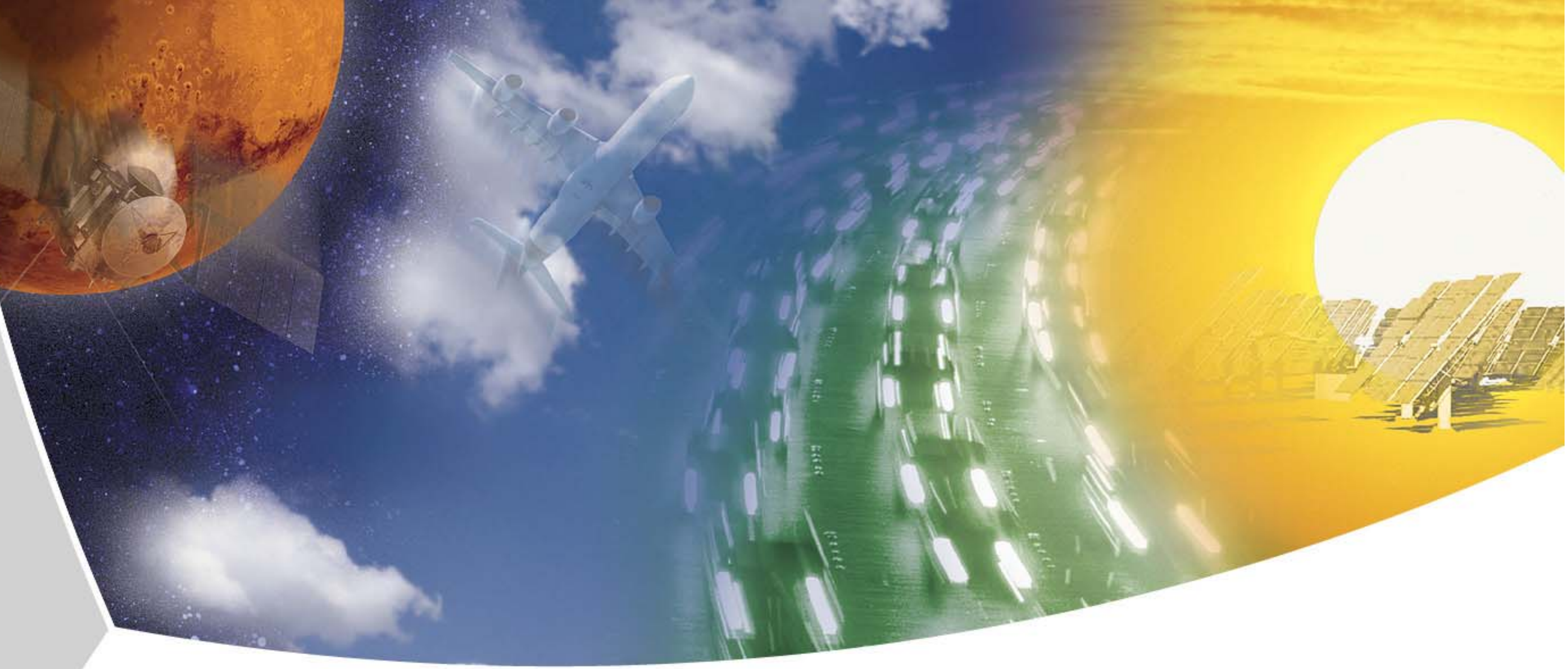
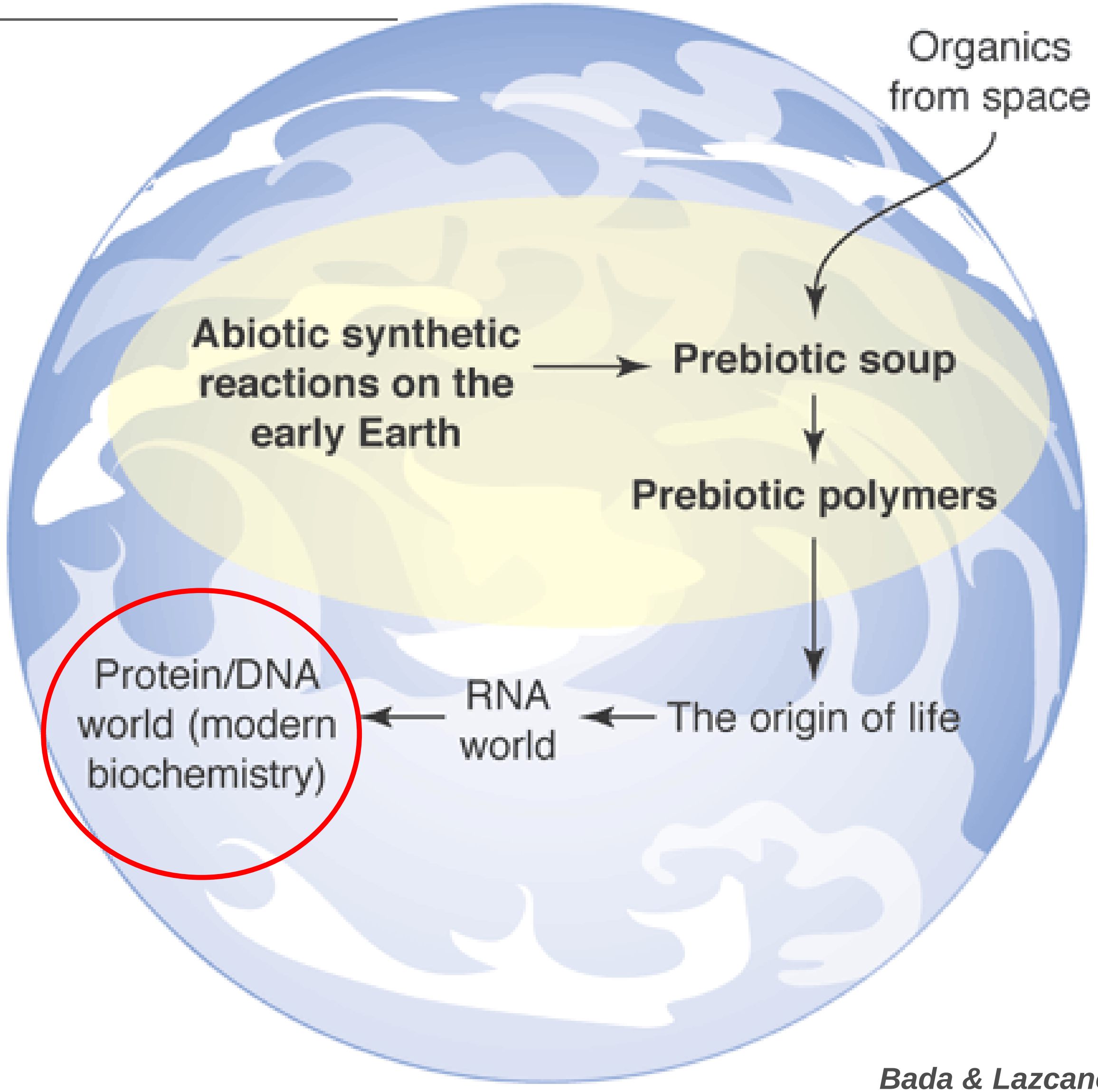


Adaptation of life to extreme conditions

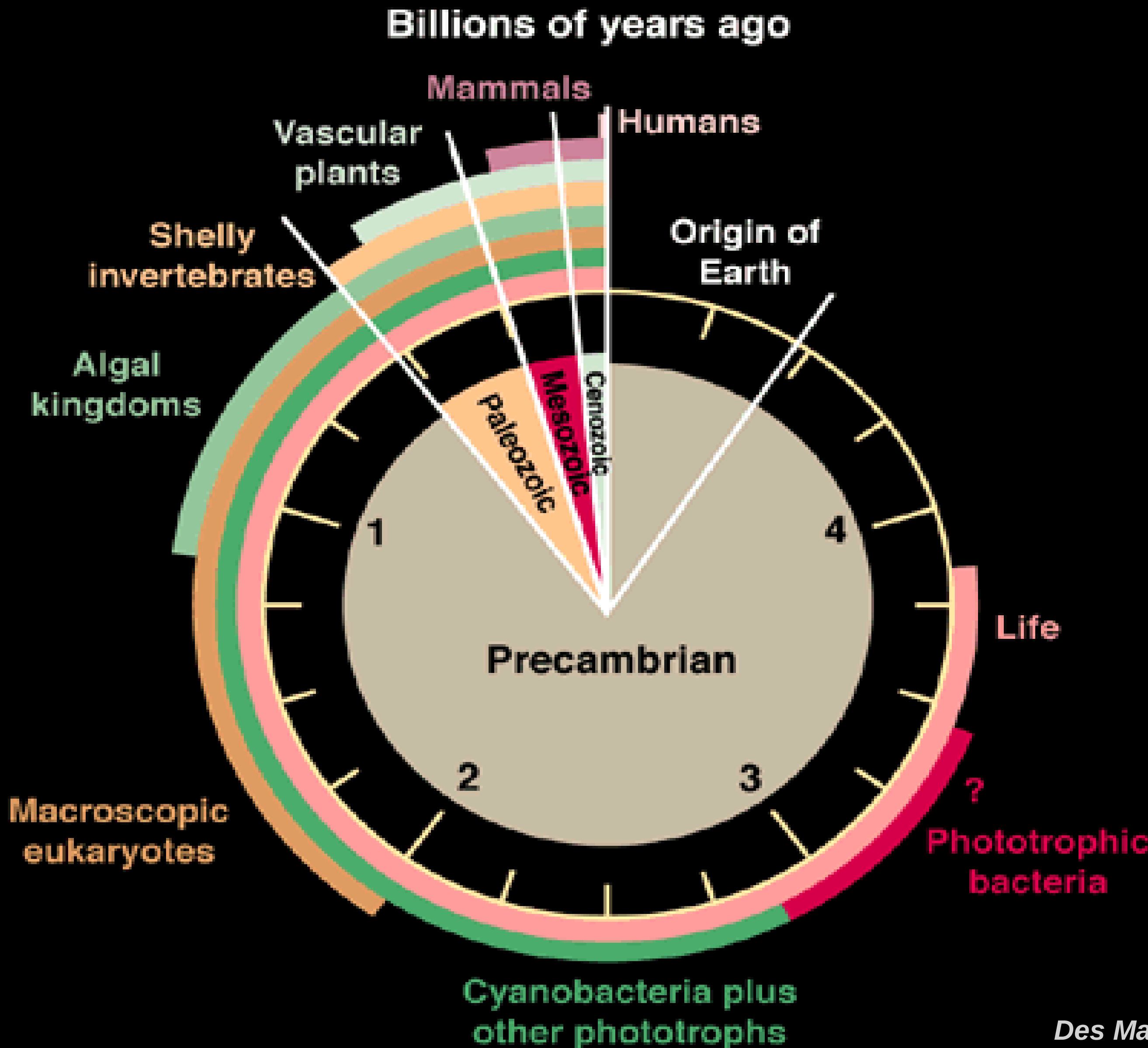
Gerda Horneck
DLR, Institut für Luft- und Raumfahrtmedizin, Köln
gerda.horneck@dlr.de

Steps to life on Earth



Bada & Lazcano (Science, 2002)

History of life on Earth: Fossil record

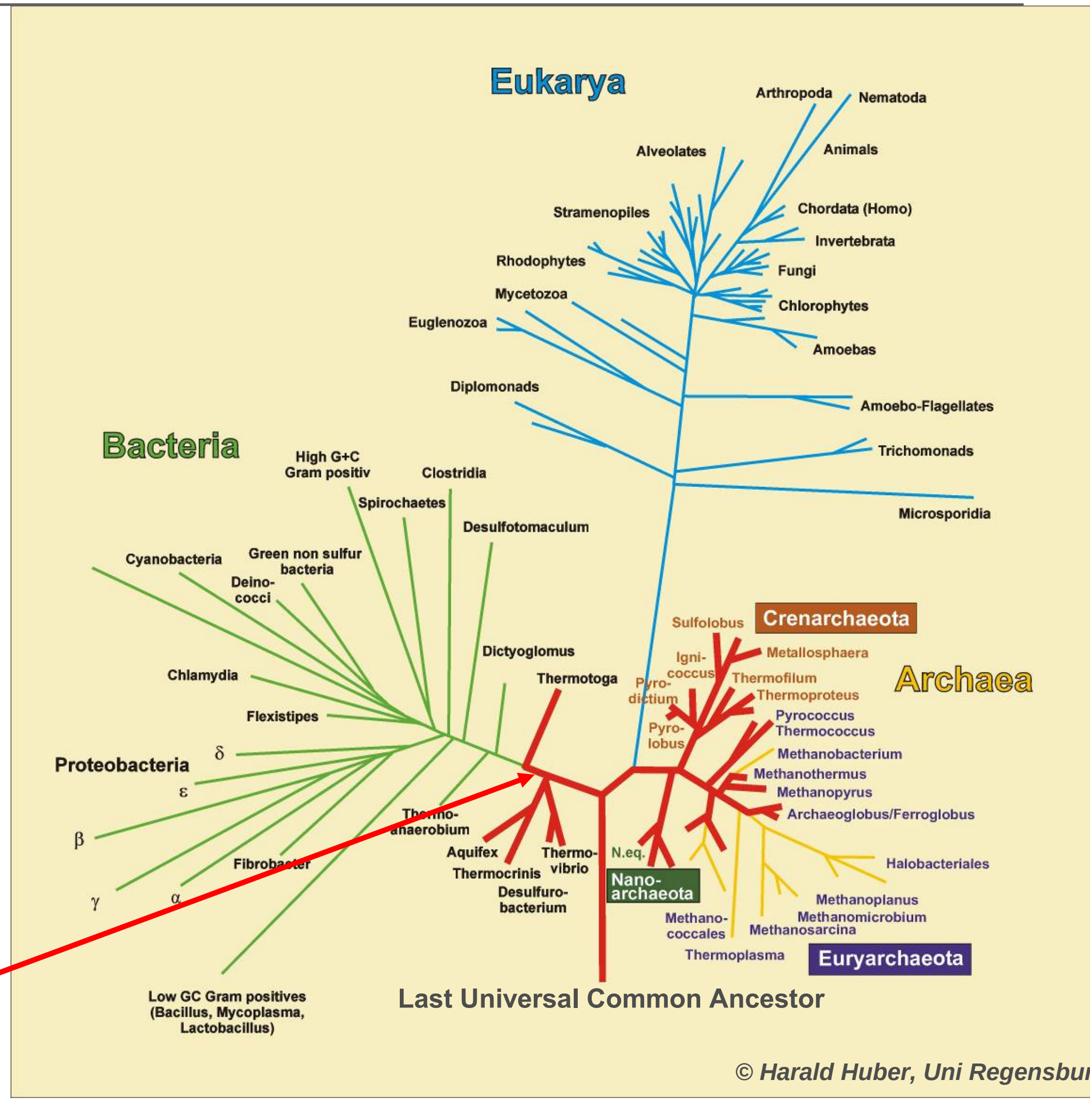


Des Marais (Science, 2000)

History of life on Earth: Molecular biology record

Phylogenetic tree of life

Hot springs as the cradle of life?



Hyperthermophilic microorganisms

History of life on Earth: Prebiotic evolution

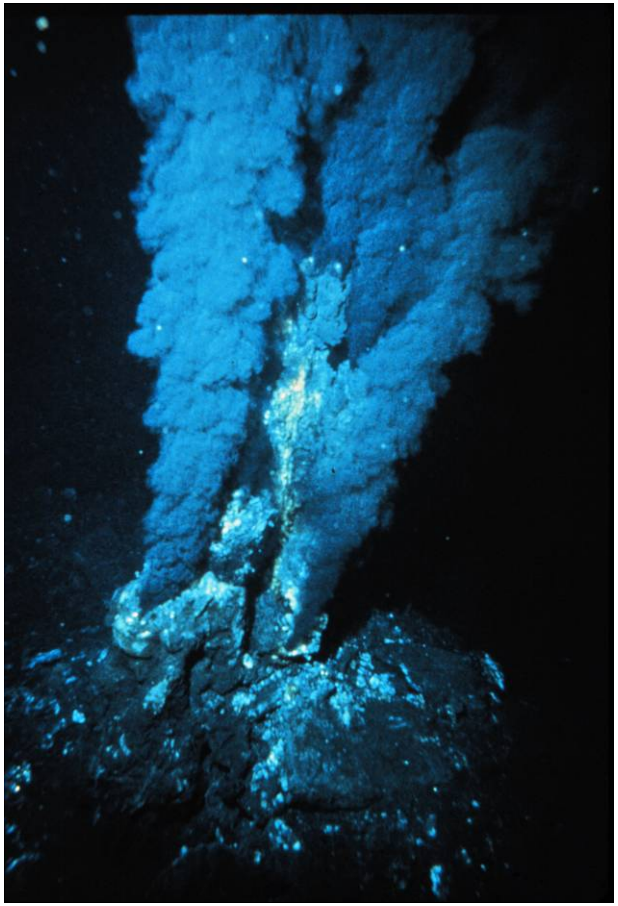
Reducing environment:

-H_2, H_2S, CO, CO_2, CH_4

-Clays and minerals as catalysts

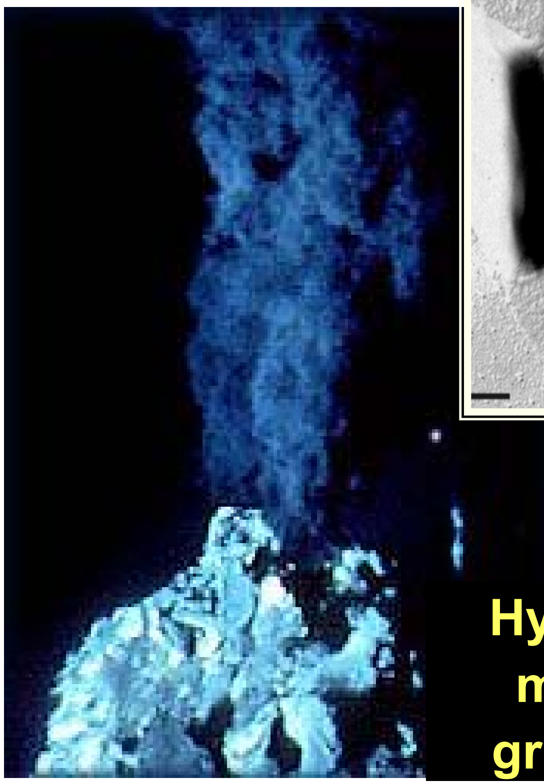
- High temperature gradient (350 °C to 2 °C)

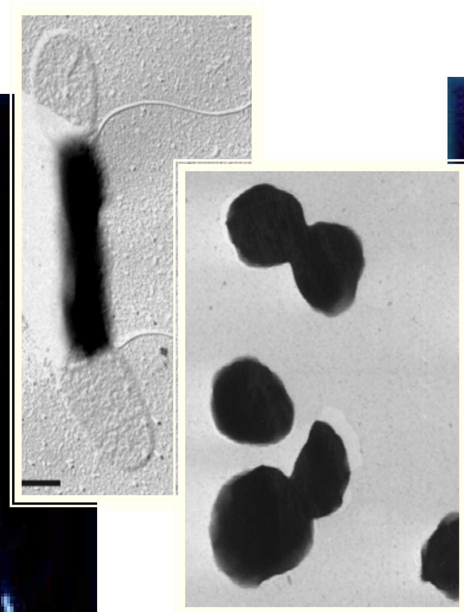
- Amino acids were produced in the laboratory under simulated conditions



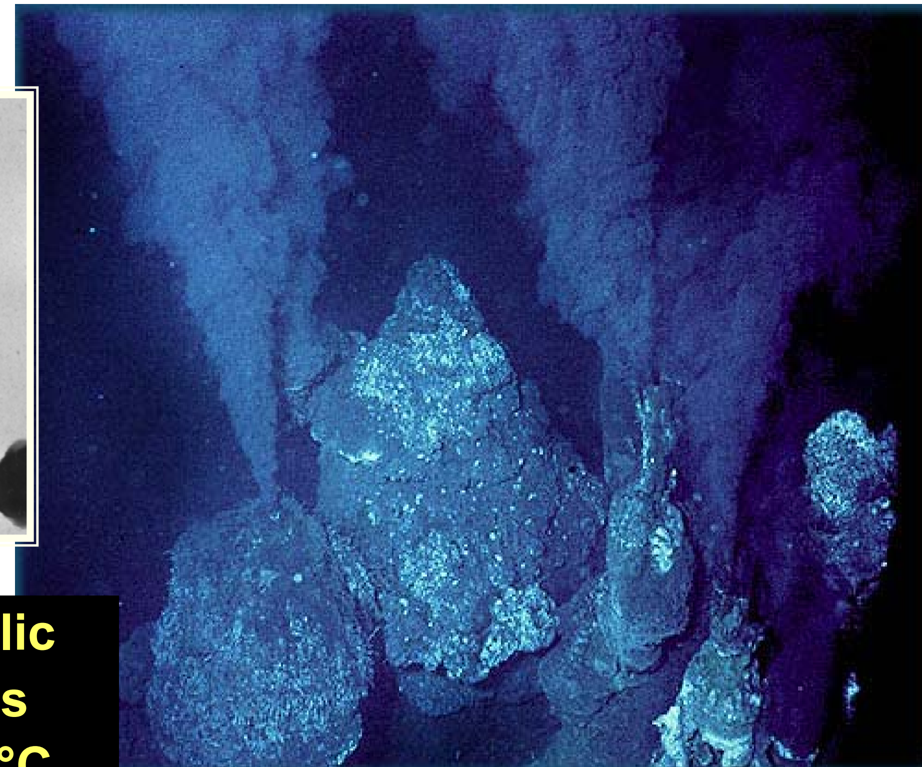
Hydrothermal vents

History of life on Earth: Hyperthermophiles





Hyperthermophilic microorganisms grow up to 113 °C



Black smokers

Optimum growth temperature: 80°C and above
No growth at 60°C or below

Karl Stetter

History of life on Earth: Hyperthermophiles

Black smokers

Hyperthermophiles are **chemolithotrophs**:
They obtain energy by the oxidation of electron donors in their environments.
These molecules are inorganic: H_2, S^o, etc.

Hyperthermophiles are **chemoautotrophs**:
In addition to deriving energy from chemical reactions, they synthesize all necessary organic compounds from carbon dioxide.

History of life on Earth: Hyperthermophiles

Main Energy-yielding Reactions:

H_2 →

CO_2	Methane
$Fe(OH)_3$	Magnetite
S°; SO_4^{2-}	Hydrogen Sulfide
NO_3^-	Nitrogen (NH_3)
O_2 (traces)	Water

S° (Pyrite) + O_2 → H_2SO_4 (+ $FeSO_4$)

Source of Cell Carbon: CO_2

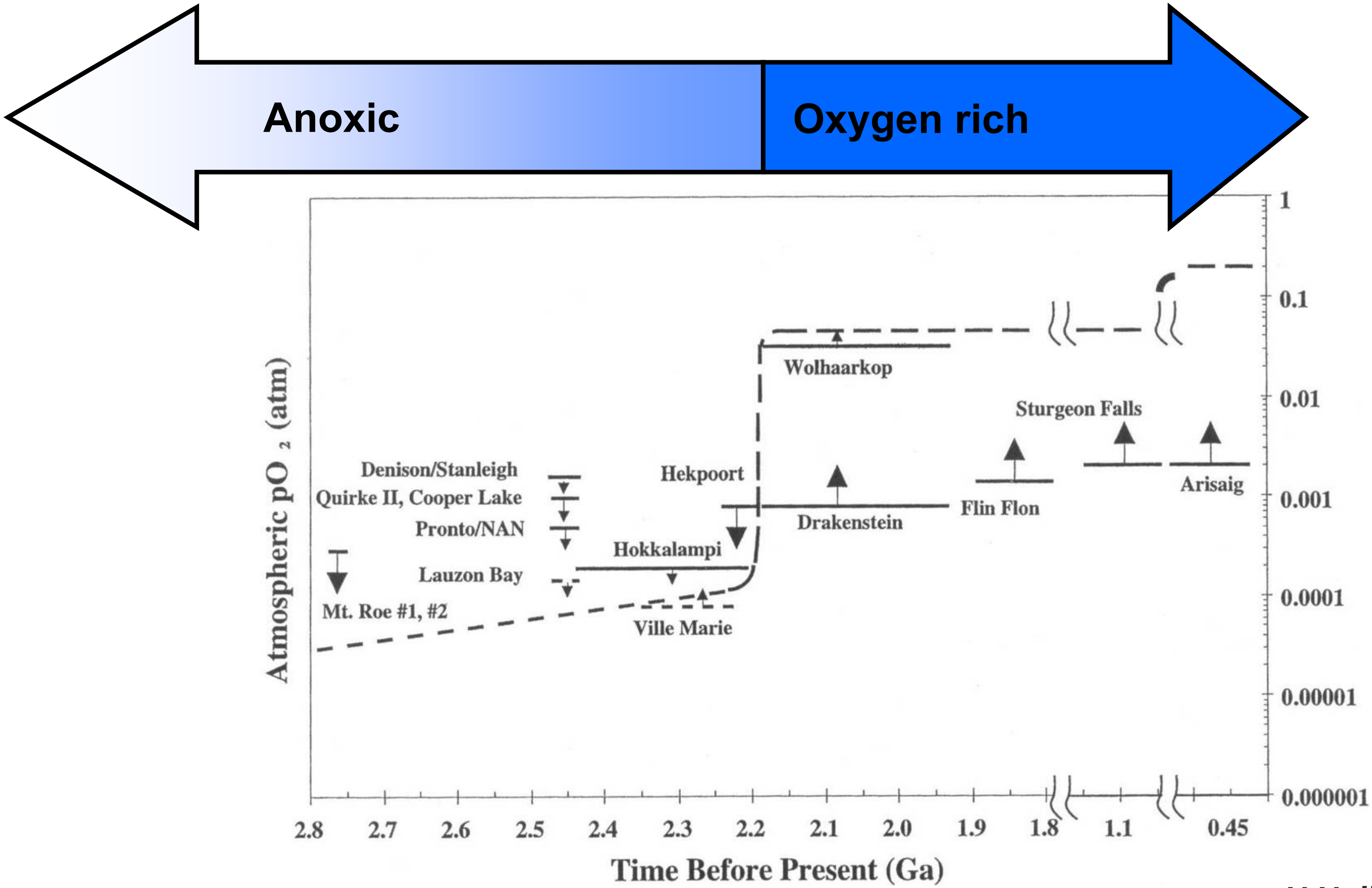
Additional Growth Requirements:

Heat (80 - 113 °C), Trace Minerals, Liquid Water.

History of life on Earth: Hyperthermophiles

Yellowstone National Park, USA

History of life on Earth: The early atmosphere



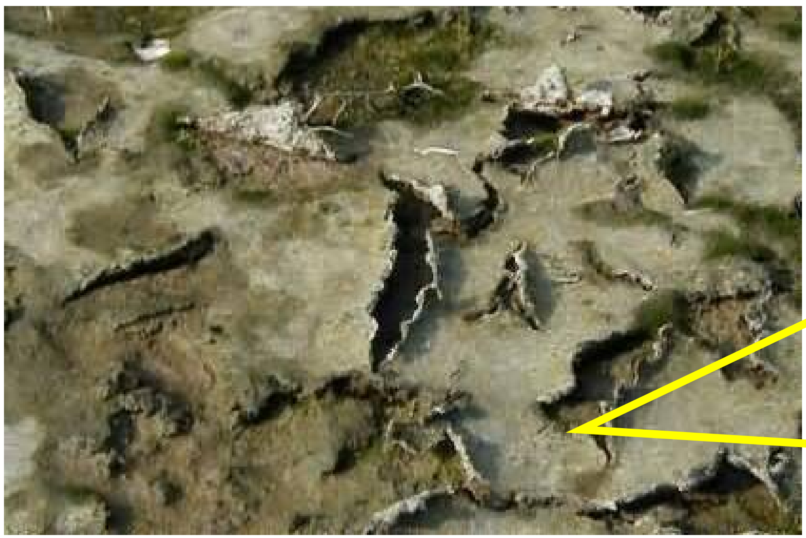
H.Holland

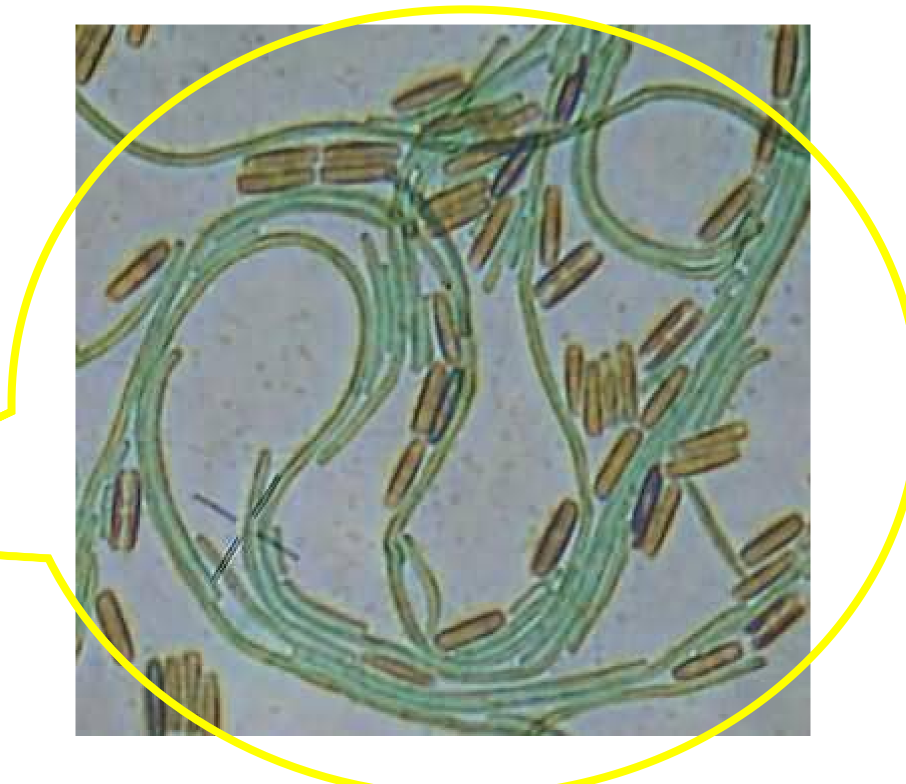
History of life on Earth: The rise of photosynthesis

Anoxygenic Photosynthesis: $CO_2 + 4 <H> \xrightarrow{\text{Licht}} <CH_2O> + H_2O$ ´$<H> = H_2S, H_2,$

$CO_2 + 4\,e^- + 4\,H^+ \xrightarrow{\text{Licht}} <CH_2O> + H_2O$ ´$<e^-> = Fe^{2+}, NO^{2-},$

Oxygenic Photosynthesis: $6\,CO_2 + 12\,H_2O \xrightarrow{h\nu} C_6H_{12}O_6 + 6\,O_2 + 6\,H_2O$ $\Delta H^0 = +2870\,\frac{kJ}{mol}$

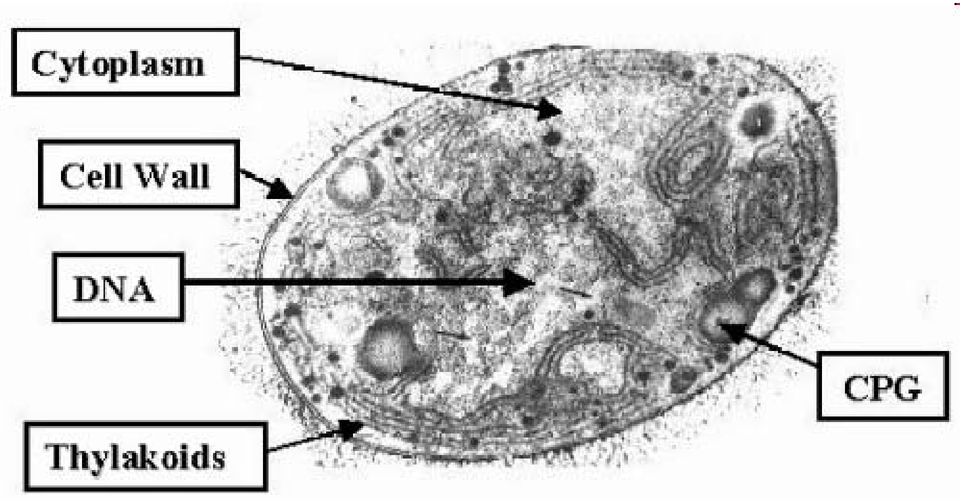




Microbial mat,
a community of organisms with cyanobacteria as primary producers

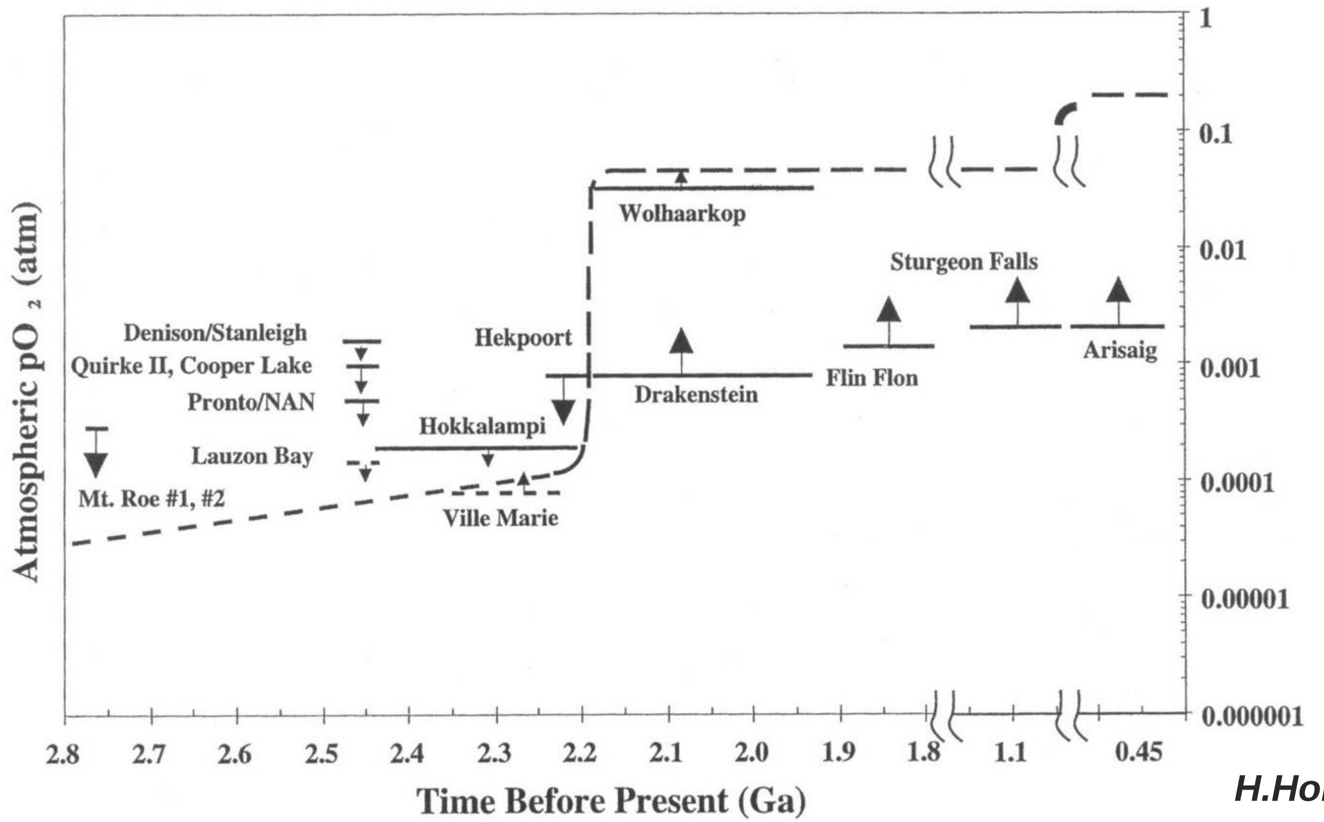
History of life on Earth: The rise of photosynthesis

- Highly organized system of internal membranes (thylakoids) which function in photosynthesis.
- Bluish pigment phycocyanin, which they use to capture light for photosynthesis.
- Photosynthesis in cyanobacteria generally uses water as an electron donor and produces oxygen as a by-product
  ⇒ oxygenic photosynthesis
- Some cyanobacteria use hydrogen sulfide as electron donor
  □ anoxygenic photosynthesis



Cyanobacteria

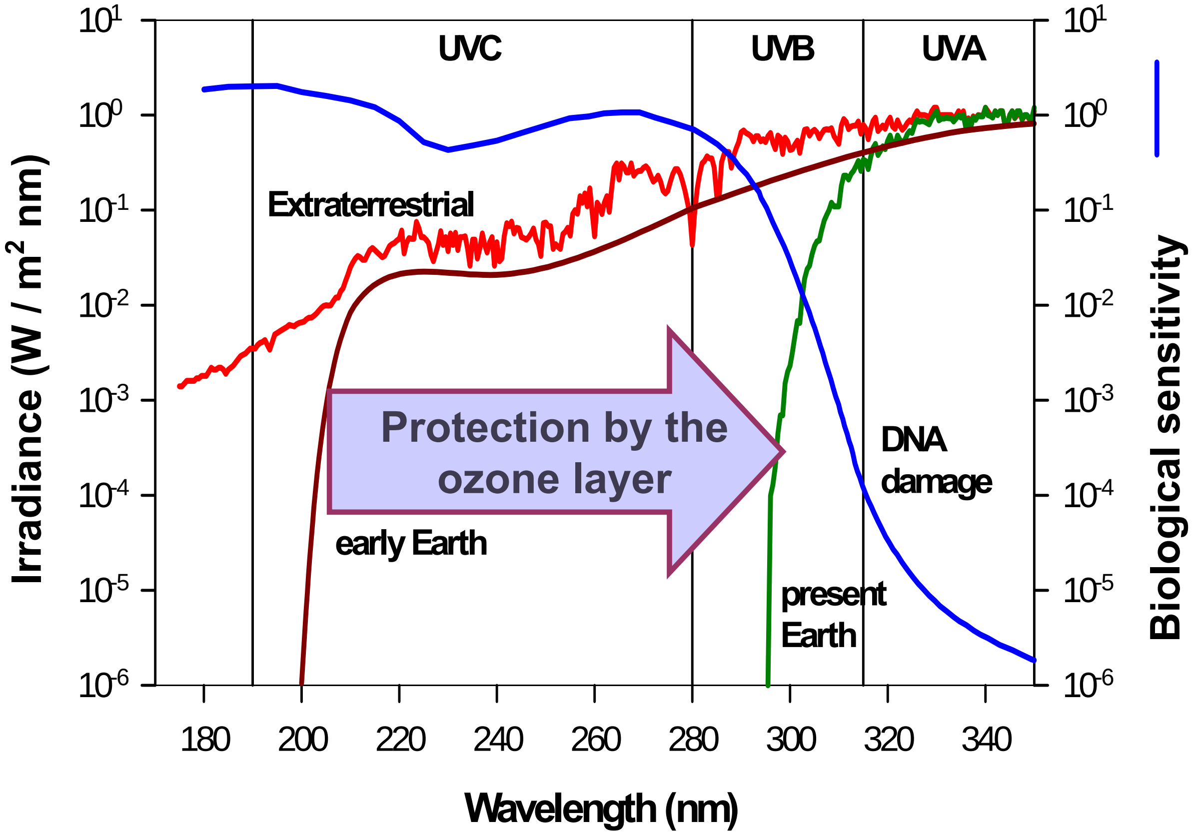
History of life on Earth: The rise of oxygen



H.Holland

The ability of cyanobacteria to perform oxygenic photosynthesis is thought to have converted the early reducing atmosphere into an oxidizing one, which dramatically changed the composition of life forms on Earth by stimulating biodiversity and leading to the near-extinction of oxygen-intolerant organisms.

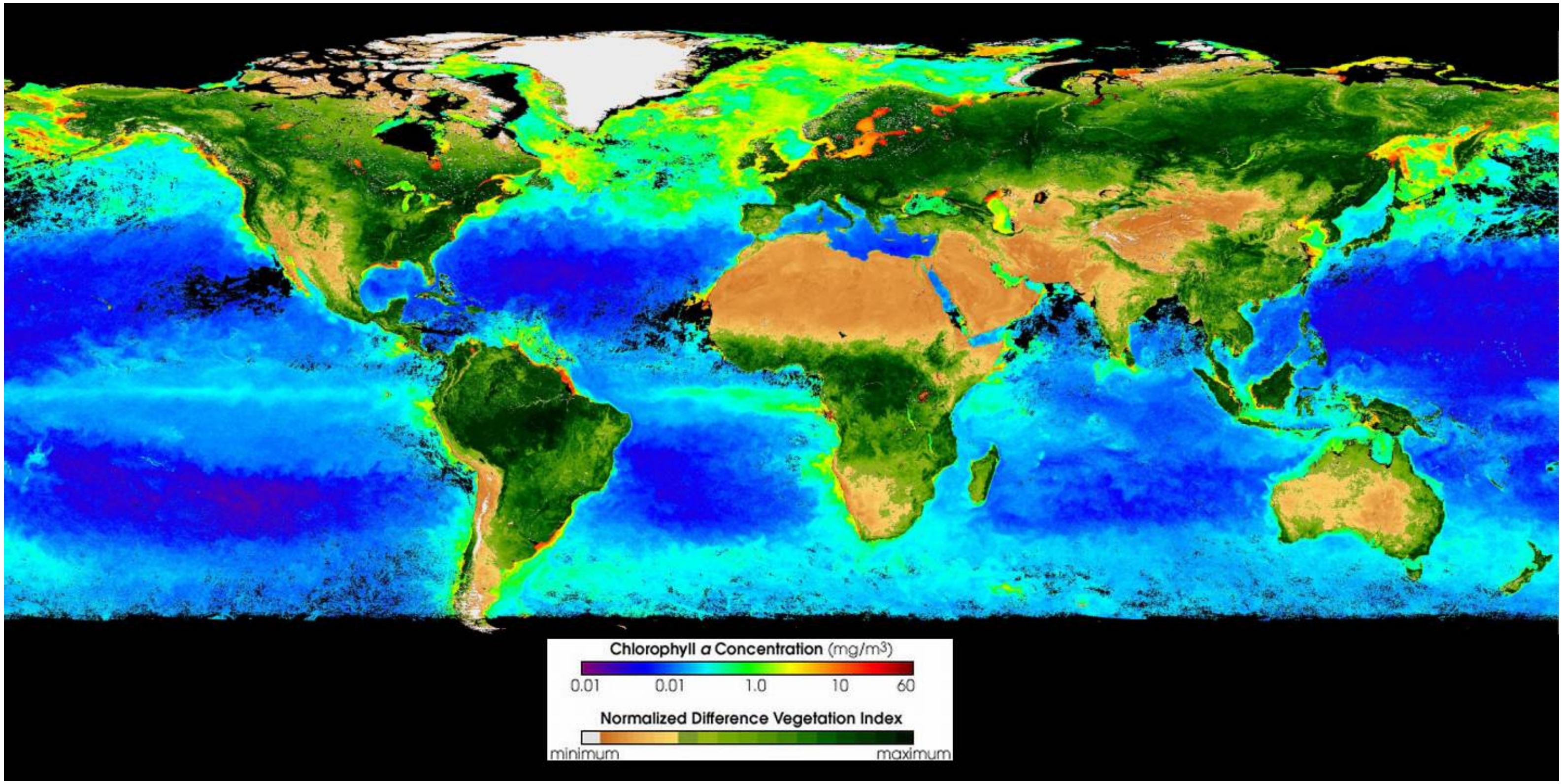
History of life on Earth: The change in UV-climate



The rise of oxygen has lead to the photochemical formation of the ozone layer in the stratosphere, thereby protecting life from harmful UVC and UVB radiation

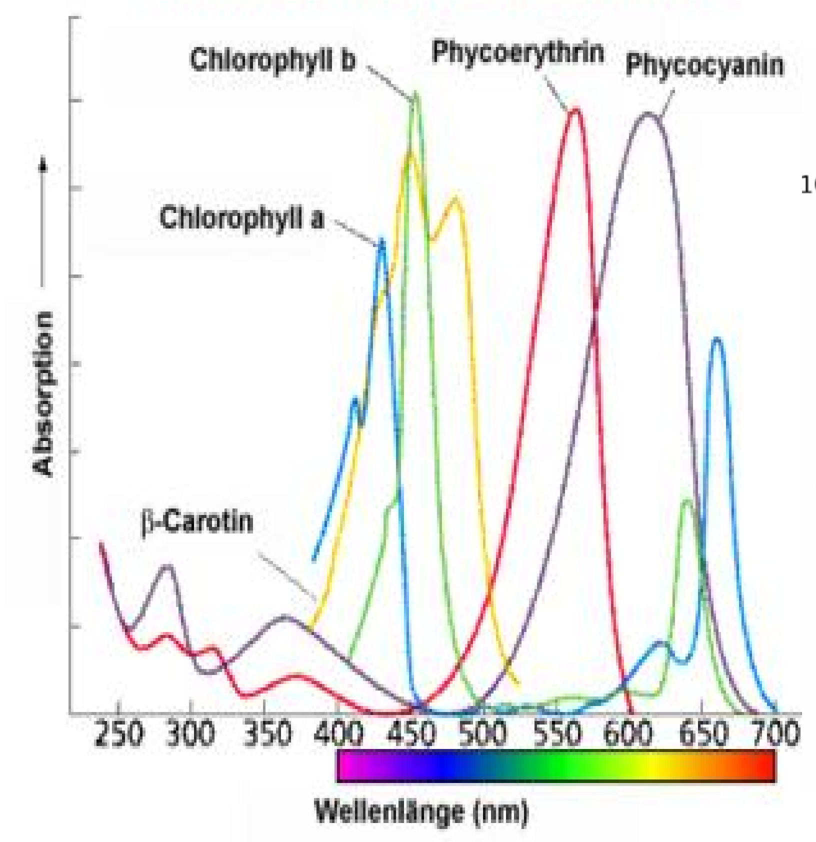
History of life on Earth: The spread of photosynthesis

Distribution of chlorophyll in the biosphere on Earth (2002)

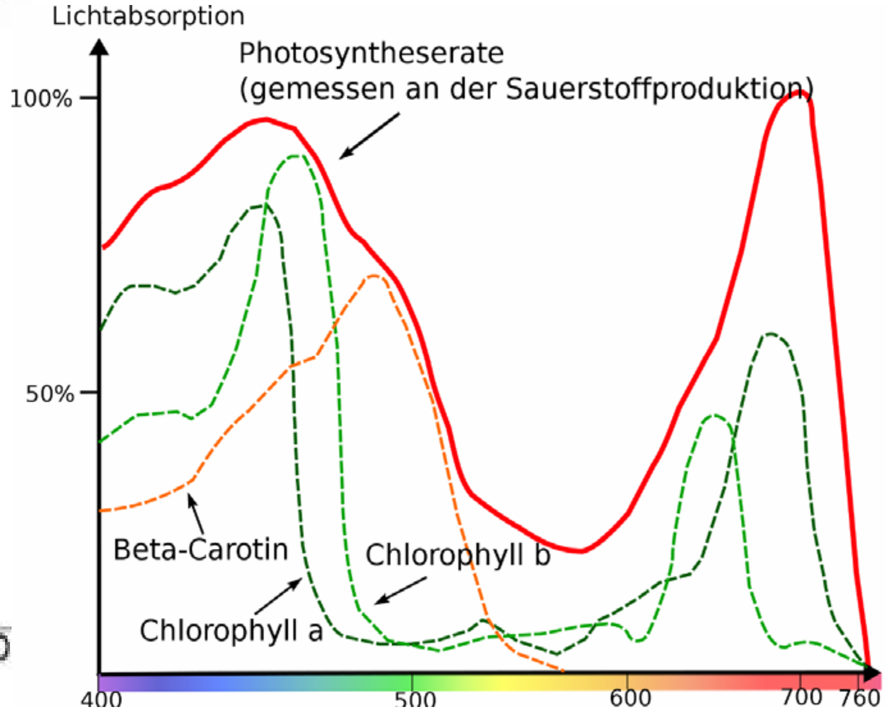


Carbon bound in the biomass: 80 × 10^{12} kg per year (80 Gt/a)

History of life on Earth: The spread of photosynthesis



Absorption spectra



Rate of PS: O_2 production

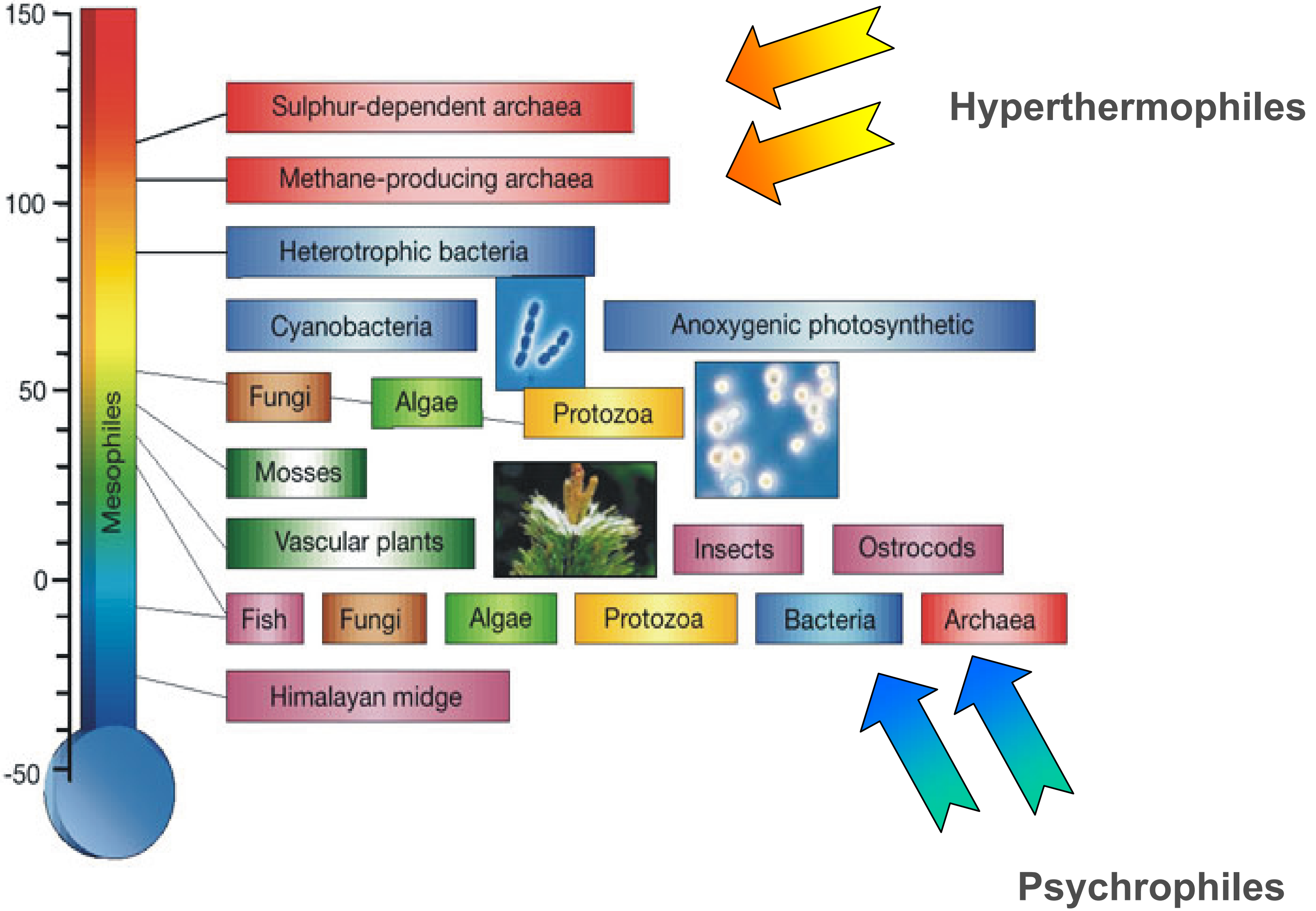
History of life on Earth

During life's evolution on Earth microorganisms

- have existed since the emergence of life
- are ubiquitous
- inhabit "extreme" niches

"What do you mean 'extreme'? We love it here!"

History of life on Earth: Life at extreme temperatures

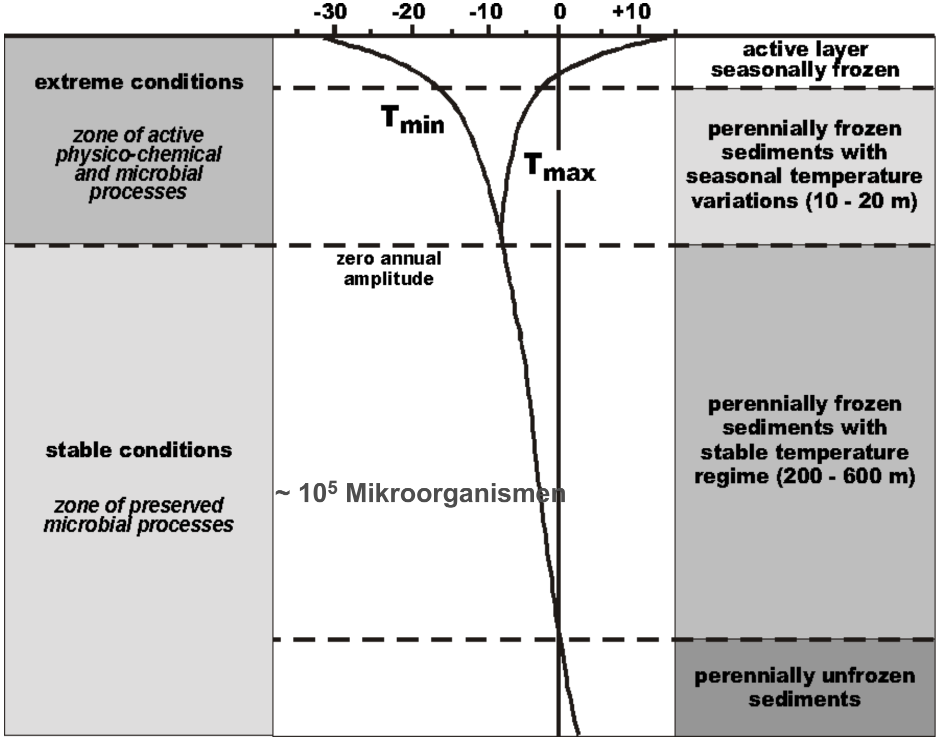


Mancinelli and Rothschild, Nature, 2001

History of life on Earth: Life in permafrost

Microorganisms in Permafrost

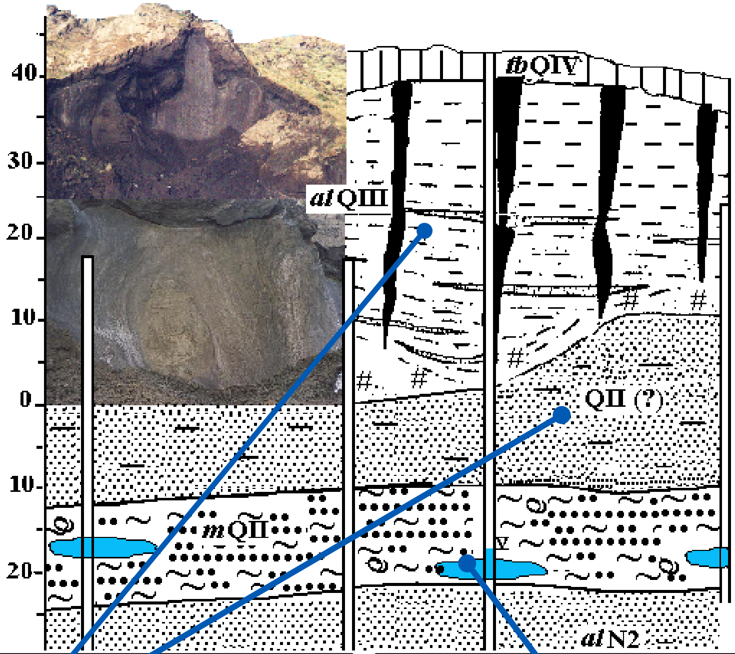
- ≈ - 10°C (Arctic), ≈ - 25°C (Antarctic)
- 92-97% frozen, 3-8 % liquid water



Permafrost in Sibiria

History of life on Earth: Life in permafrost

Brine water lenses in permafrost sediments

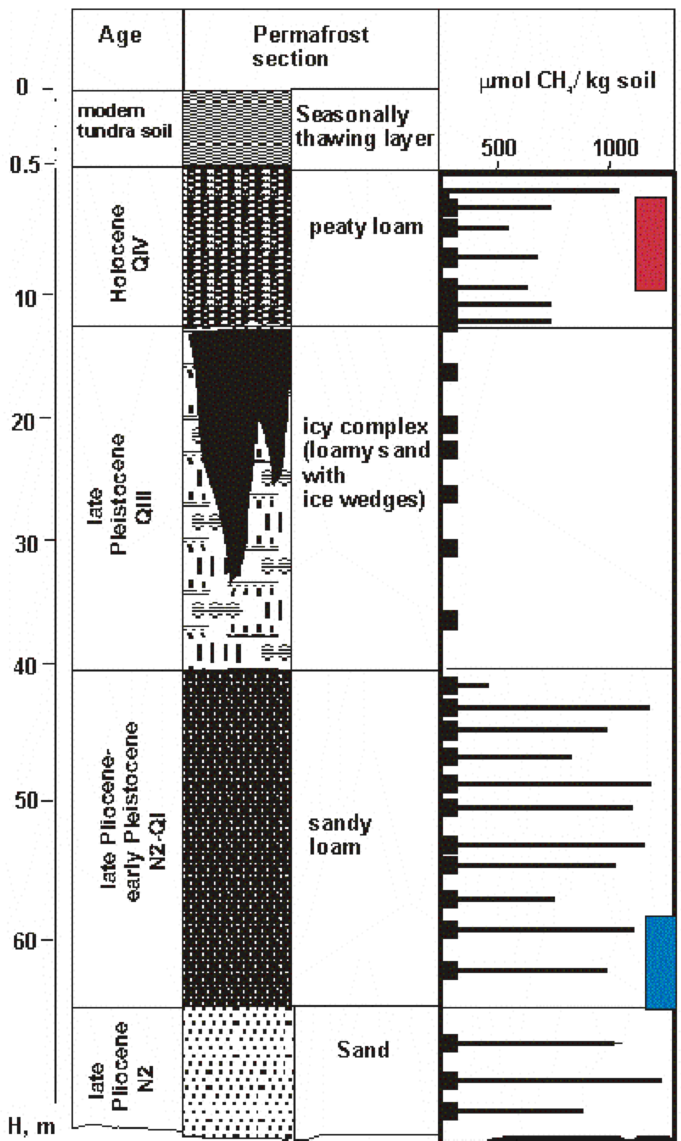


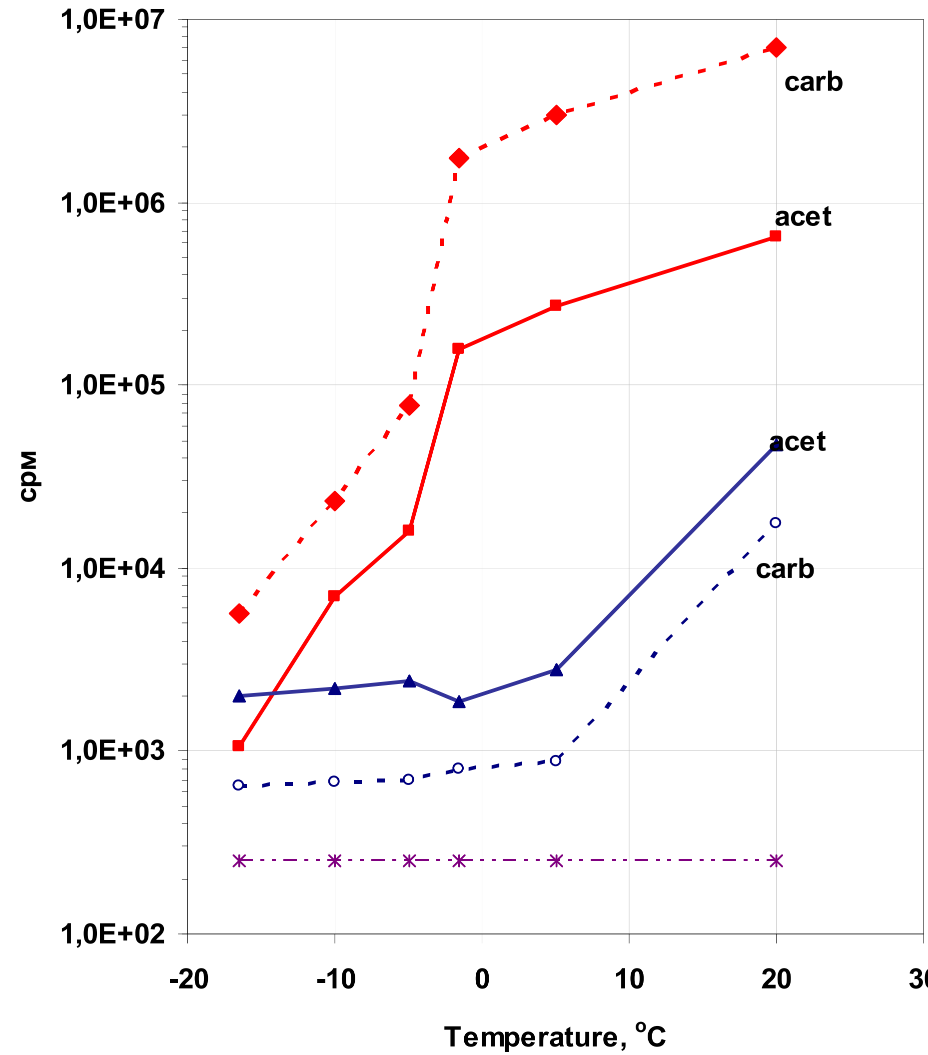
Permafrost	
•Temperature	-10°C
•Free water	no
•Ice content	25-30%
•Unfrozen water	1.5-2%
•Water extract salinity	1-10 %

Overcooled water lenses within permafrost (cryopegs)	
•Temperature	-10°C
•Free water	100%
•Salinity	170-300 %

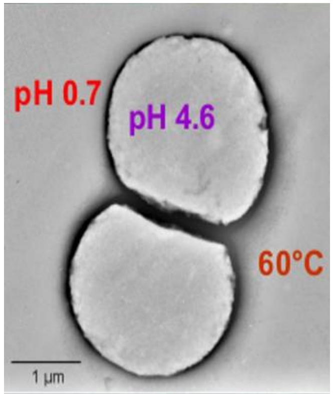
Gilichinsky et al., Astrobiology, 2003

Methane generation in permafrost sediments of different age from $H^{14}CO_3^-$ and $^{14}CH_3CO_2^-$

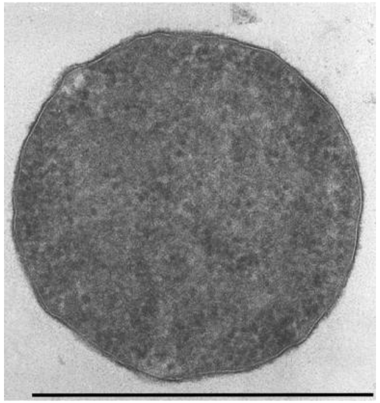




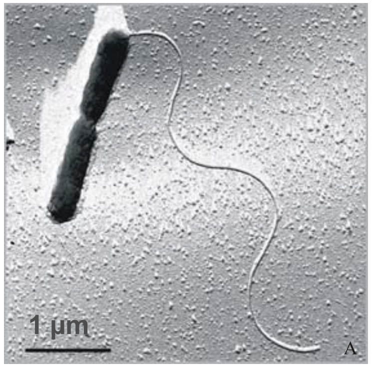
History of life on Earth: Life at extreme ph



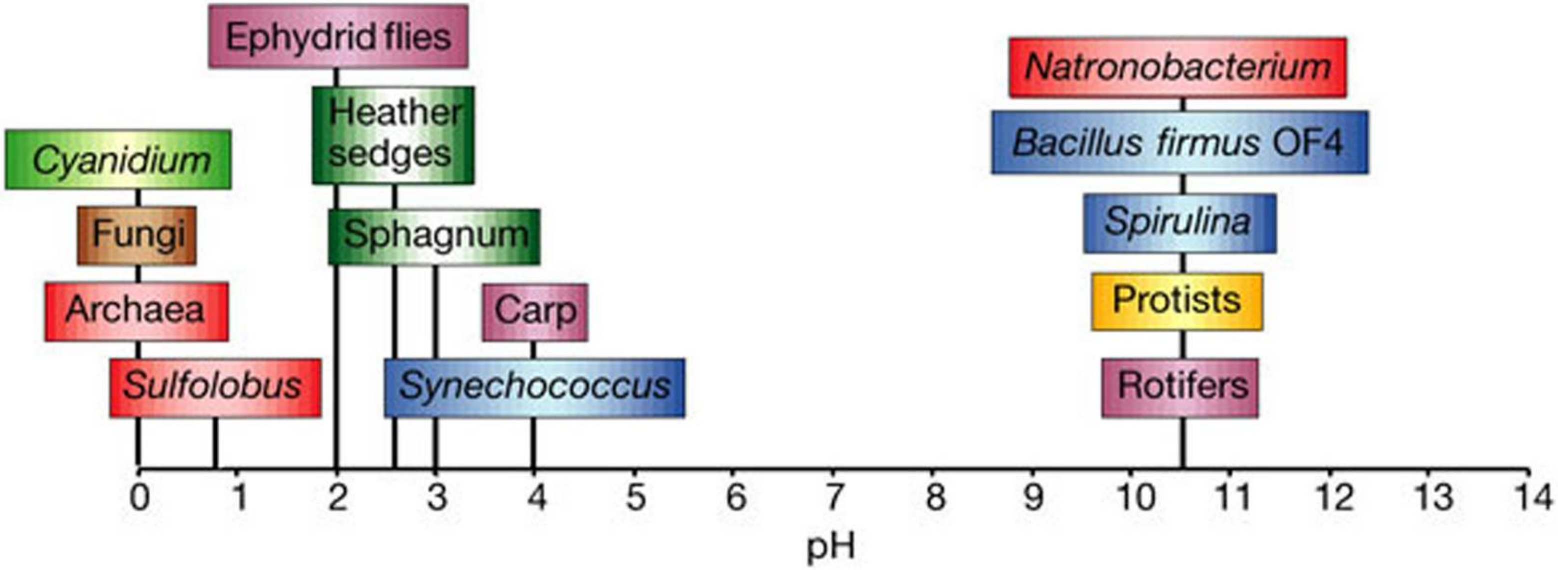
Picrophilus oshimae



Thermoplasma acidophilum



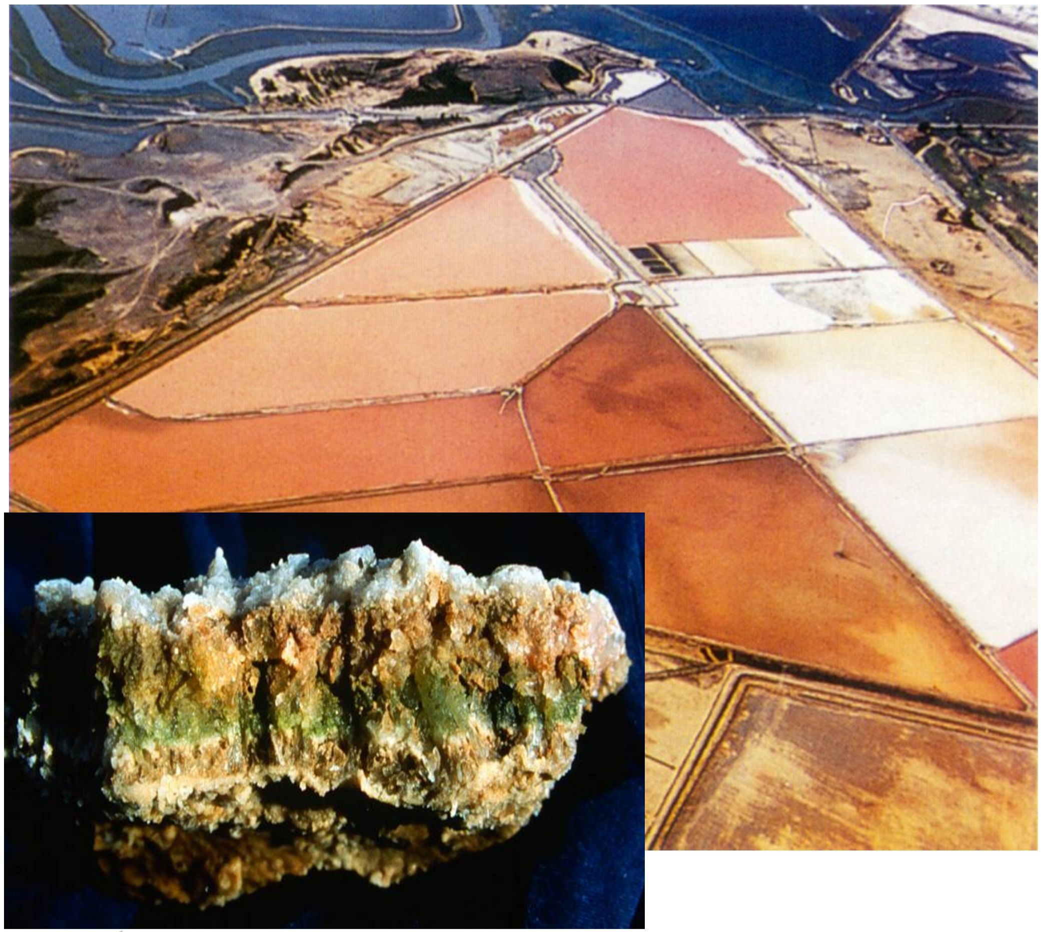
Natronobacterium



History of life on Earth: Life at extreme ph

Mono Lake, USA: Alkaline salt-lake

History of life on Earth: Life at high salt concentations

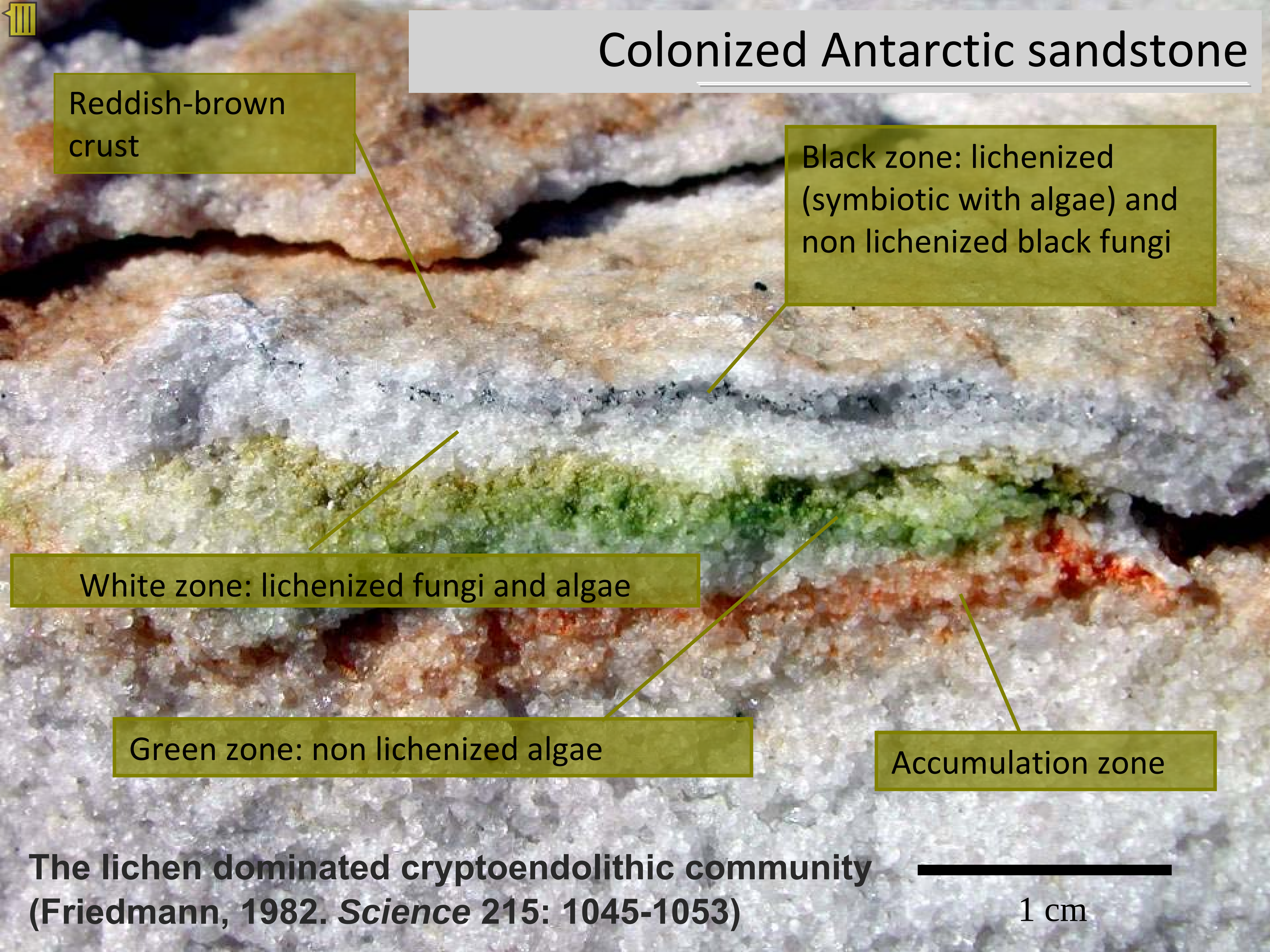


Halophiles live in brines or salt crystals

- salt-in-cytoplasm strategy: adapt interior protein chemistry to high salt concentrations (high K^+ or Na^+)
- organic-osmolyte strategy: cell interior free of salts, but enriched with uncharged, highly water-soluble, organic compounds (sugars, polyols, amino acids)

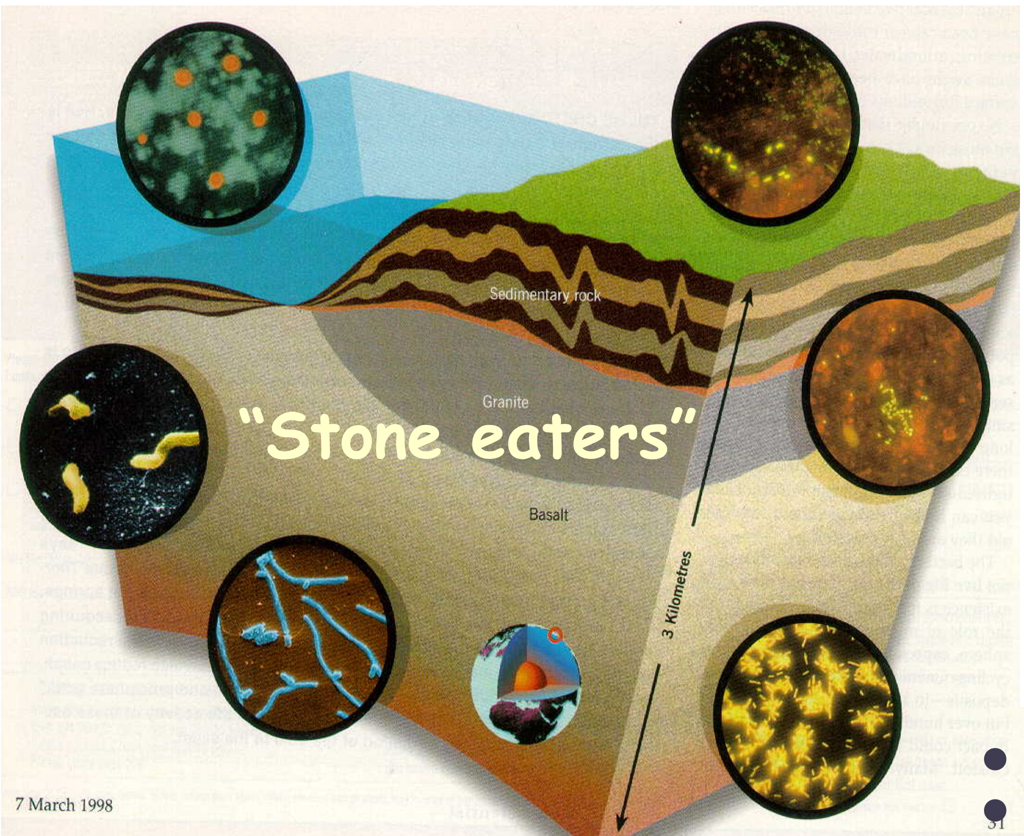
History of life on Earth: Endolithic communities

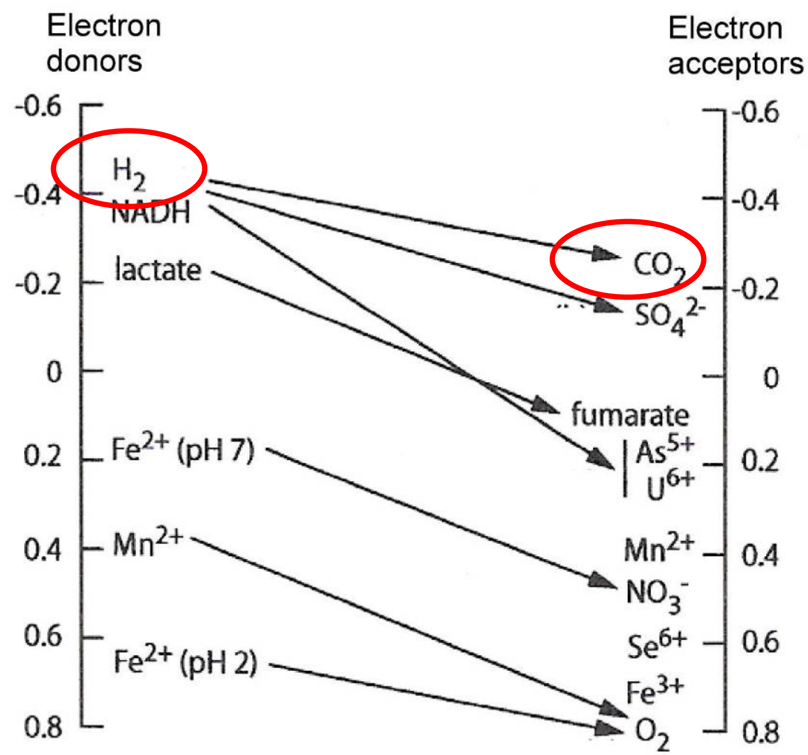
Colonized Antarctic sandstone



The lichen dominated cryptoendolithic community (Friedmann, 1982. *Science* 215: 1045-1053)

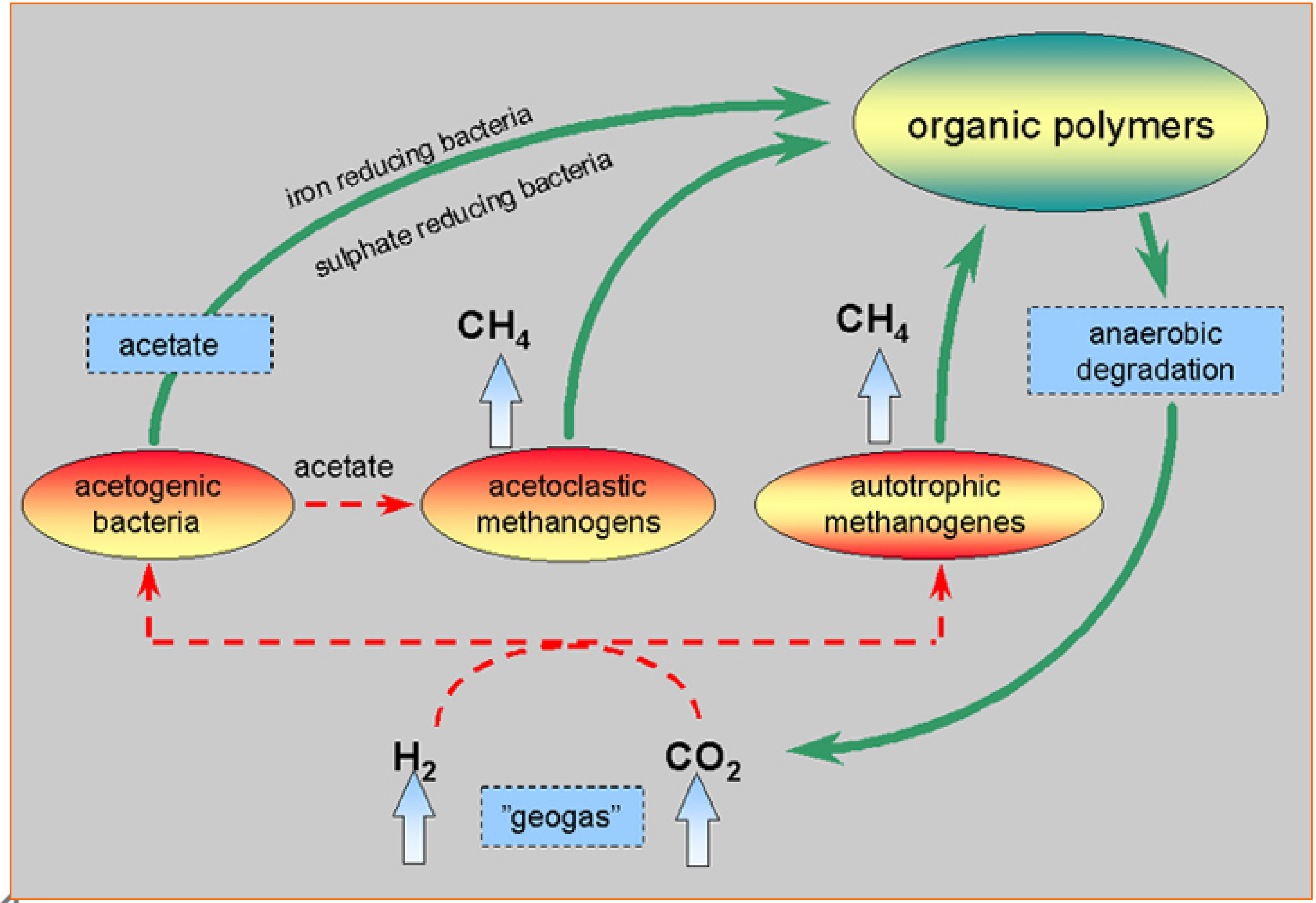
SLIME (Subsurface Lithoautotrophic Microbial Ecosystem)





- Chemolithotrophs
- Fraction of subsurface life still unknown

Deep subsurface biosphere



Limits of life for growth and metabolism

- **Temperature:** -20°C to +113°C
- **Water stress:** $a_w \geq 0.7$
- **Salinity:** Salt concentration ≤ 30 %, salt crystals
- **pH:** pH = 1-11
- **Nutrients:** High metabolic versatility
  Autotrophic or heterotrophic organisms
  High starvation tolerance
- **Oxygen:** Aerobic and anaerobic organisms
- **Radiation:** 60 Gy/hour

History of life on Earth: Bacterial spores

Atmosphere

B. stratosphericus

Soil

B. thermoterrestis

B. subtilis
„Heu-Bazillus)

Desert

B. sonorensis

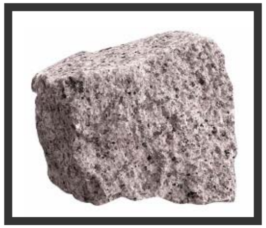
Subsurface

B. infernus

Clean room

B. pumilus SAFR

rock



B. simplex

Food

B. cereus

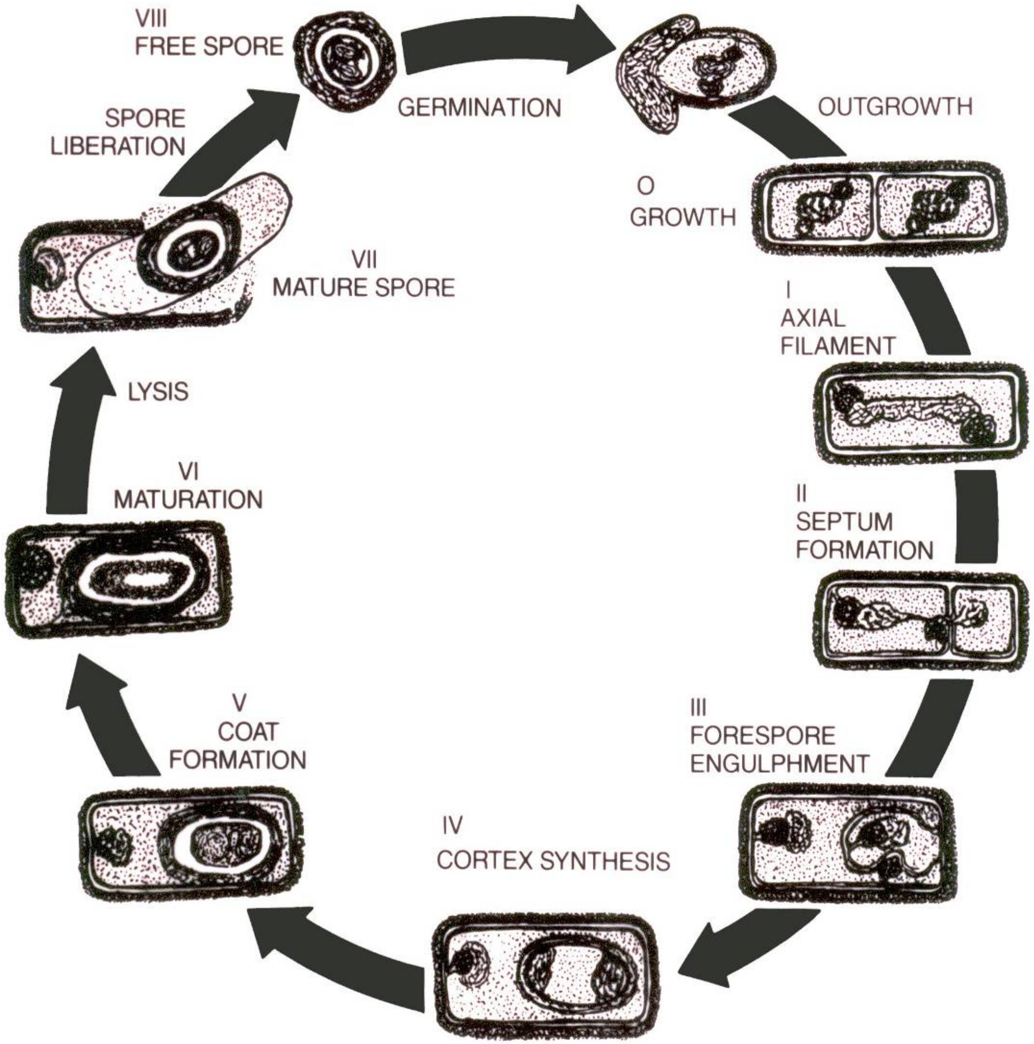
Pathogens

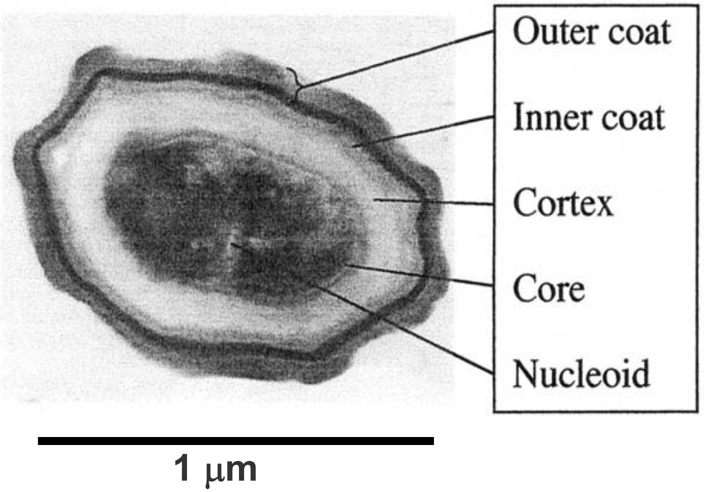
B. anthracis

Insects

B. thuringiensis

Survival of extreme conditions: Bacterial spores

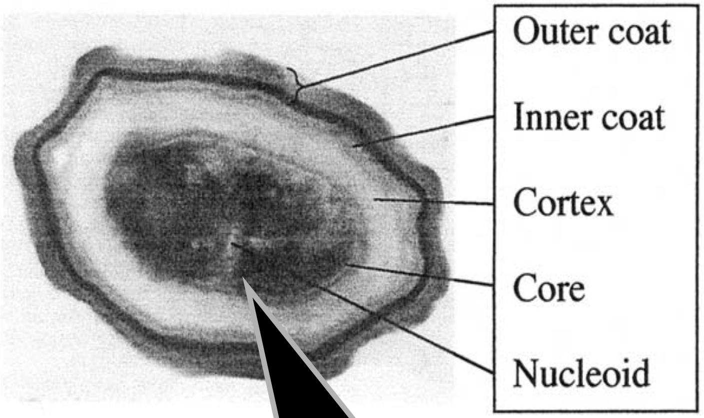




Sporulation
of *Bacillus subtilis*

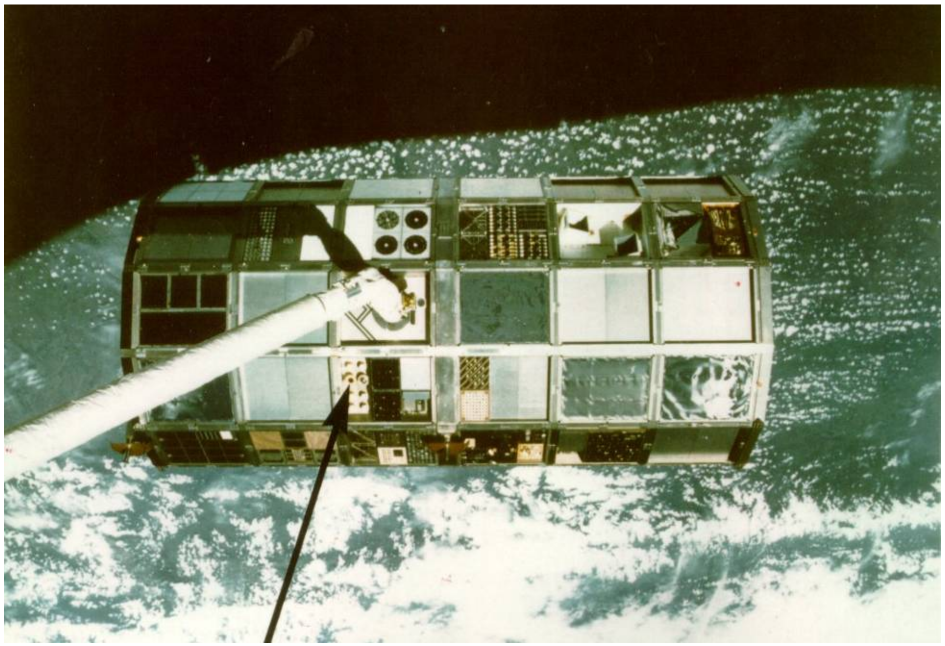
Survival of extreme conditions: Bacterial spores

- Protective spore coats
- Thick cortex
- Low core water content
- High mineral content (Ca^{2+})
- Small acid soluble proteins at DNA
- Repair of damage to macromolecules after germination
- Easy dissemination of the species
- Survival of severe environmental conditions
  - desiccation / intense radiation / heat
  - chemical aggressive agents (alcohol, acetone, acids)
- Escape temporally and/or spatially from unfavorable conditions

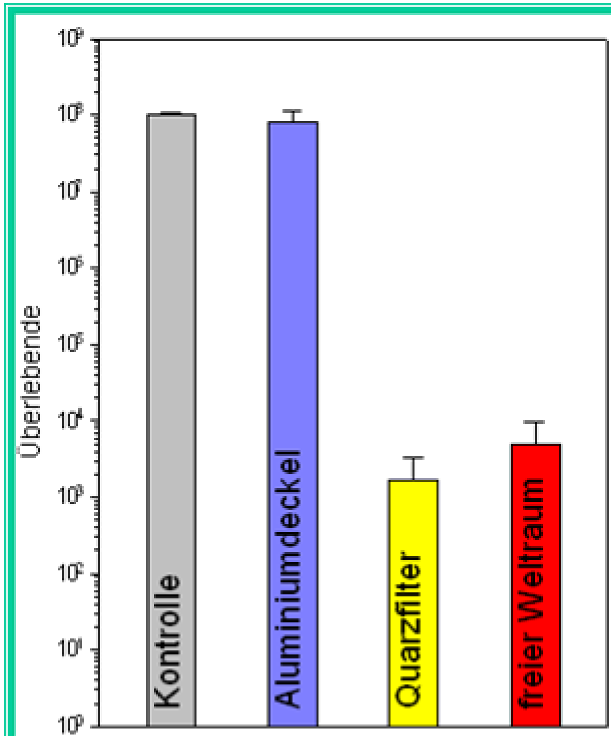


Anhydrobiosis

Survival of extreme conditions: Bacterial spores



Spores of *B. subtilis*



Long Duration Exposure Facility (LDEF) : 6 years in space

~ 86 % of spores of *Bacillus subtilis* survived after 6 years in space (if protected from solar UV radiation)

Limits of life for survival

- **Temperature:** ≤ -263°C to +150 °C or even higher
- **Water stress:** $0 \leq a_w \leq 1.0$
  Spores survive in vacuum (10^{-6} Pa)
- **Salinity:** Salt crystals (endoevaporites)
- **pH:** pH = 0 - 12.5
- **Nutrients:** not required, better without
- **Oxygen:** not required, better without
- **Radiation:** 5 kGy of ionizing radiation
  Spores repair damage during germination
- **Time:** $\leq 25 - 40 \times 10^6$ a

Looking for habitble planets ?

"The Earth is the only planet known to harbour life"

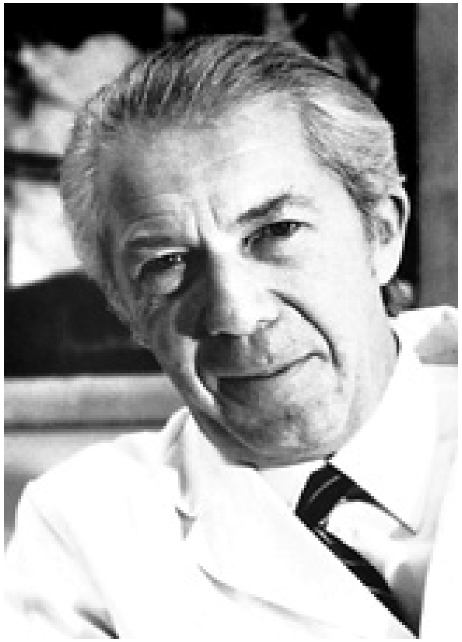
Carl Sagan, Pale Blue Dot, 1994

Life as a cosmic imperative

" Life emerges at a certain stage of either cosmic or planetary evolution,

if the right environmental physical and chemical requirements are provided "

Christian De Duve, 1994



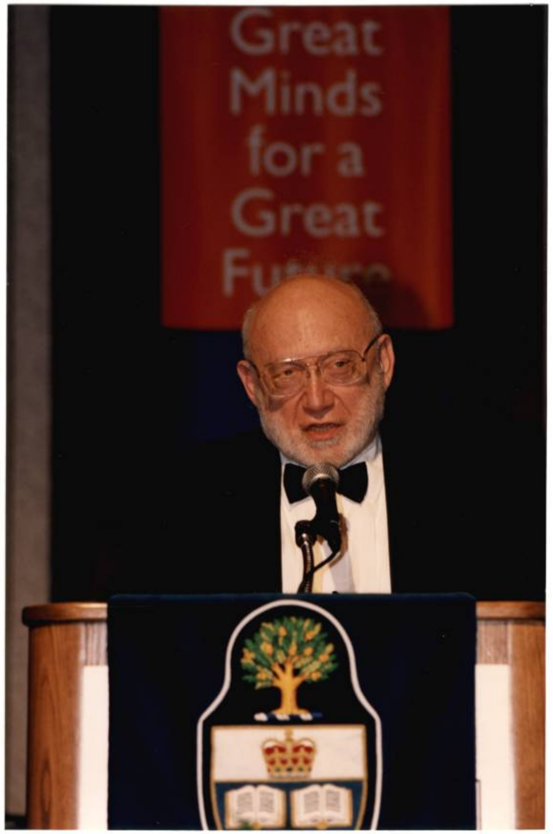
Christian De Duve (born 1917) Nobel Price (1974) for his work on the structure and function of organelles in biological cells

Life a cosmic phenomenon ?

"The exploration of space has

- widened the horizon of the physical world: the concepts of mass and energy are valid throughout the universe
- led to generalization of chemistry: the spectra of the stars testify the universality of the concepts in chemistry
- has the potential to inspire biology: to build the foundations for the construction and testing of meaningful axioms to support a theory of life"

⇒ Towards a universal definition of life



Joshua Lederberg, 1925-2008
Nobel price in medicine 1959

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11. European Workshop on Astrobiology

11.-14. Juli 2011

Köln

http://www.eana2011.de/

History of life on Earth: Life at extreme ph

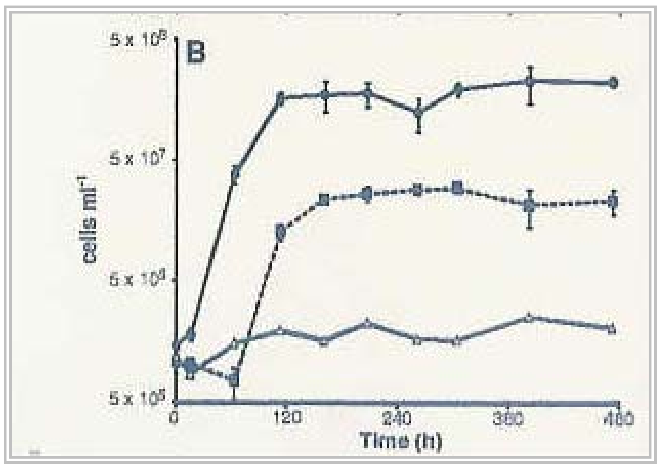
Hypothesis:

Arsenate can replace phosphate in the nucleic acids of strain GFAJ-1)

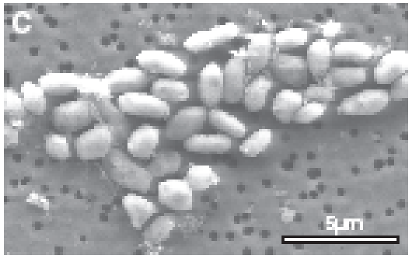
Geomicrobiologist Felisa Wolfe-Simon, collecting lake-bottom sediments in the shallow waters off Mono Lake's 10 Mile Beach. Credit: ©*2010 Henry Bortman*

Hypothesis:

Arsenate can replace phosphate in the nucleic acids of strain GFAJ-1)

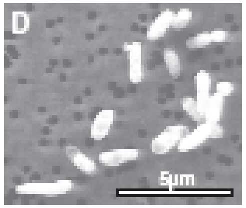


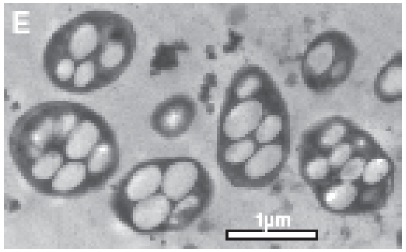
-As/+P



+As/-P

-As/-P





+As/-P

GFAJ-1: Isolate from Mono Lake (200 µM AsO_4^{3-})

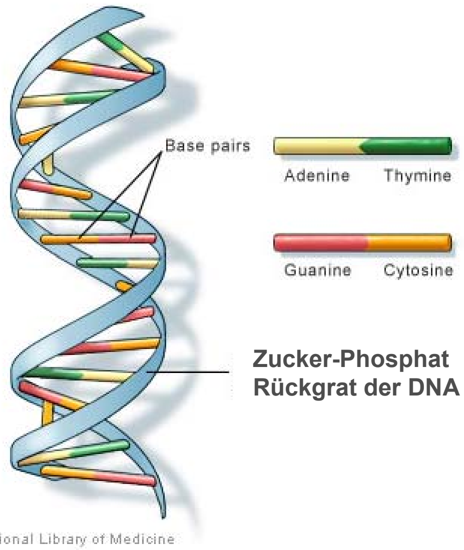
Wolfe-Simon et al. Science, 2010

Hypothesis:

Arsenate can replace phosphate in the nucleic acids of strain GFAJ-1)

Intracellular Distribution of radioactively labeled arsenate: $^{73}AsO_4^-$

Sub-cellular fraction dissolved in	(%)
Phenol (Protein + metabolites)	80.3 ± 1.7
Phenol:Chloroform (Proteins + Lipides)	5.1 ± 4.1
Chloroform (Lipides)	1.5 ± 0.8
Resid. Aqueous fraction (DNA/RNA)	**11.0 ± 0.1**



Conclusion: In GFAJ-1 phosphate in Sugar-phosphate back bone of DNA has been replaced by arsenate

NASA: "Definition of Life must be newly defined"

Warning: Exceptional statements require exceptional proofs.

Wolfe-Simon et al. Science, 2010