Chemosynthesis: What it we can learn from hydrothermal vents

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Geol 062

I. Intro to Metabolism

1. Carbon fixation and Photosynthesis
2. Familiar oxidative metabolism
3. Oxygenic Photosynth.
4. Geologic consequences

II. Chemosynthesis

1. Hydrothermal Vents
2. Archean
3. Chemosynthetic metabolism: Microbes Rule!!!
4. Chemosynthetic ecosystems

III. Why are extremophiles so cool?

1. Biomedical
2. Industrial
3. What extremophiles teach us about early life
4. Exobiology

IV. Exobiology

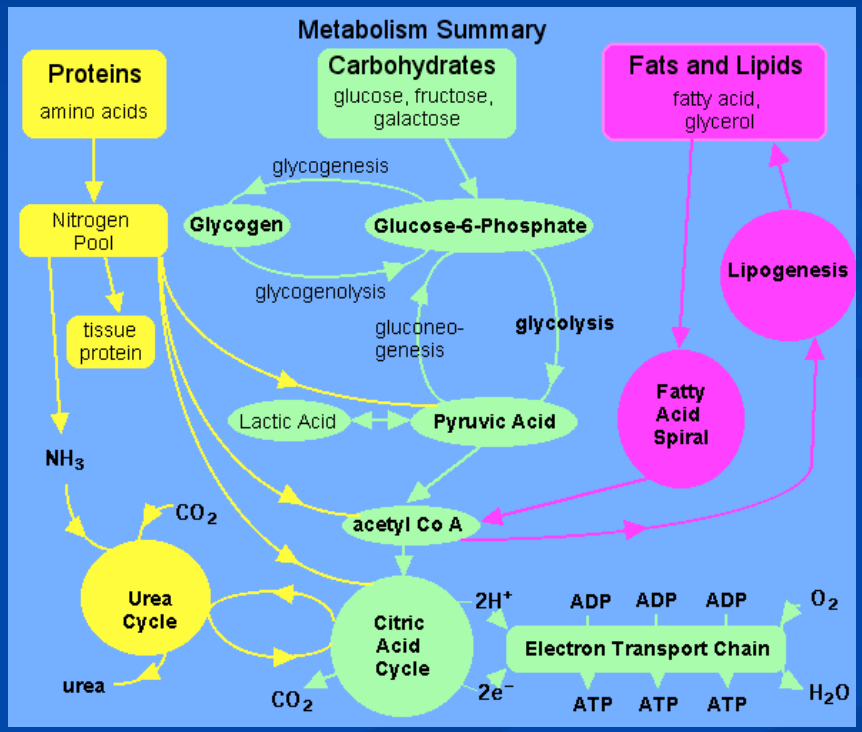
Prebiotic Chemistry on Earth

Possible (probable?) origins of life.

Possibile life elsewhere in the solar system.

Metabolism

- The complete set of chemical reactions that take place within a cell.
- Basis of all life processes.
- Catabolic and Anabolic



Metabolism

- Catabloic metabolism-- high energy molecules (electron-donors, food) are oxidized, having their electrons transferred to an electron-acceptor.
- Electron passes down electron transport chain…terminal electron acceptor.
- Energy released --> ATP

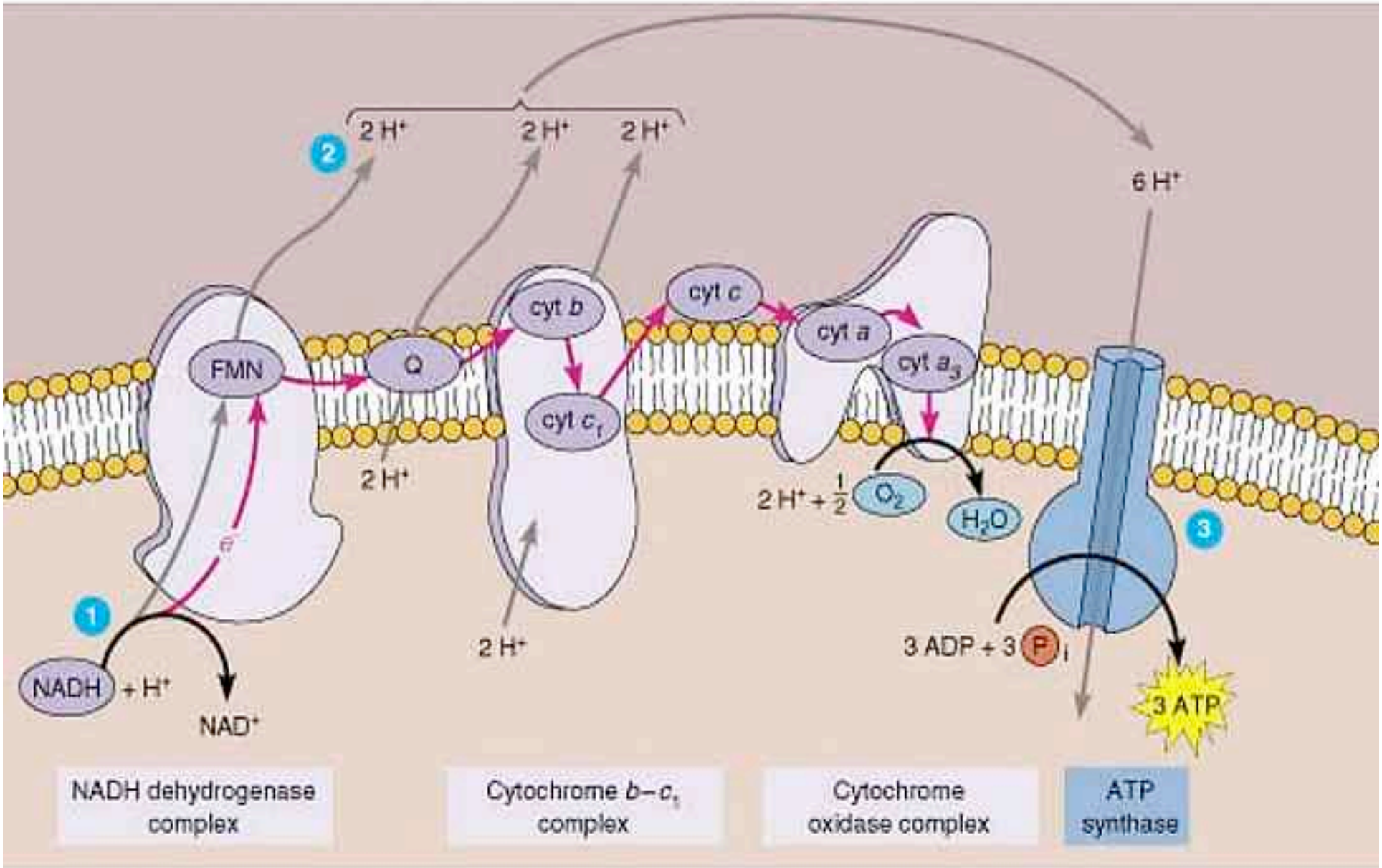
Metabolism

- Electron-donor + Electron-acceptor -->
  - Oxidized molecule + reduced molecule + ENERGY

Metabolism

- $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O +$ ENERGY
- e-donor + e-acceptor --> you get the picture

ELECTRON TRANSPORT CHAIN



Metabolism

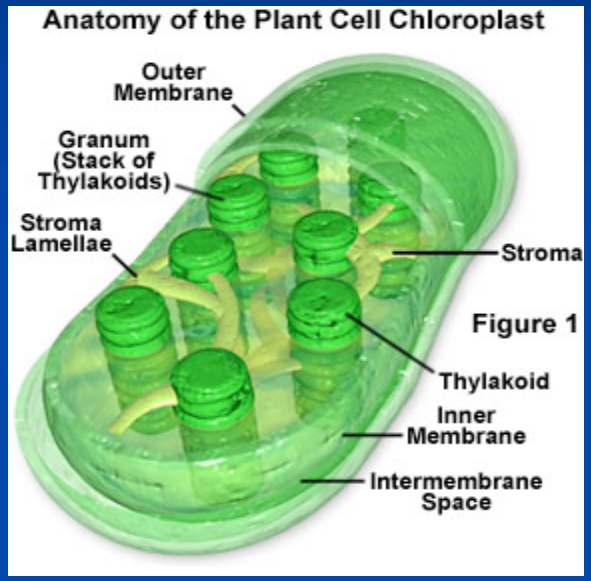
- Reduction: Gaining electrons
- Oxidation: Loosing electrons

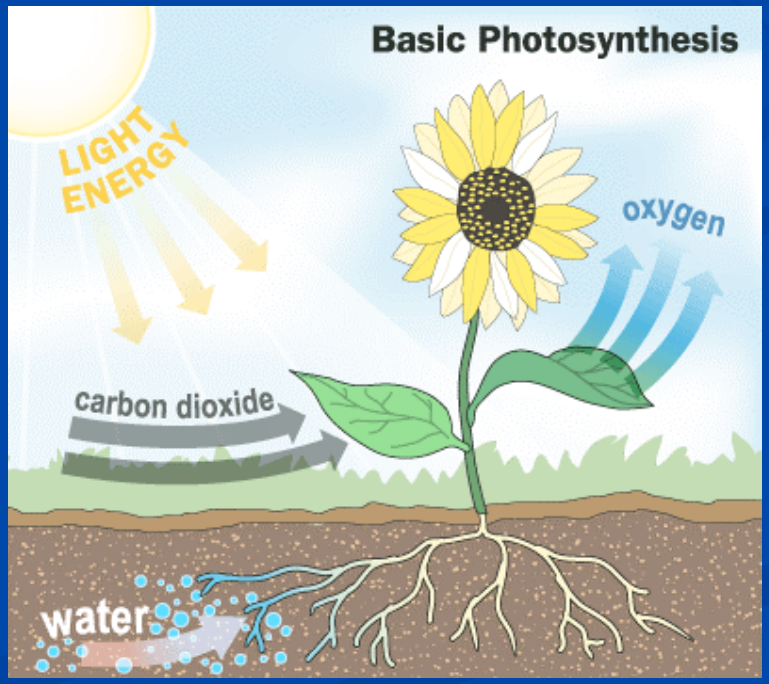
- Oxidant gets reduced.
- Reductant gets oxidized.

Metabolism

- For most eukaryotes, the food (e-donor) is Glucose.
- Glucose is oxidized by O_2.

So where do we get the Glucose???



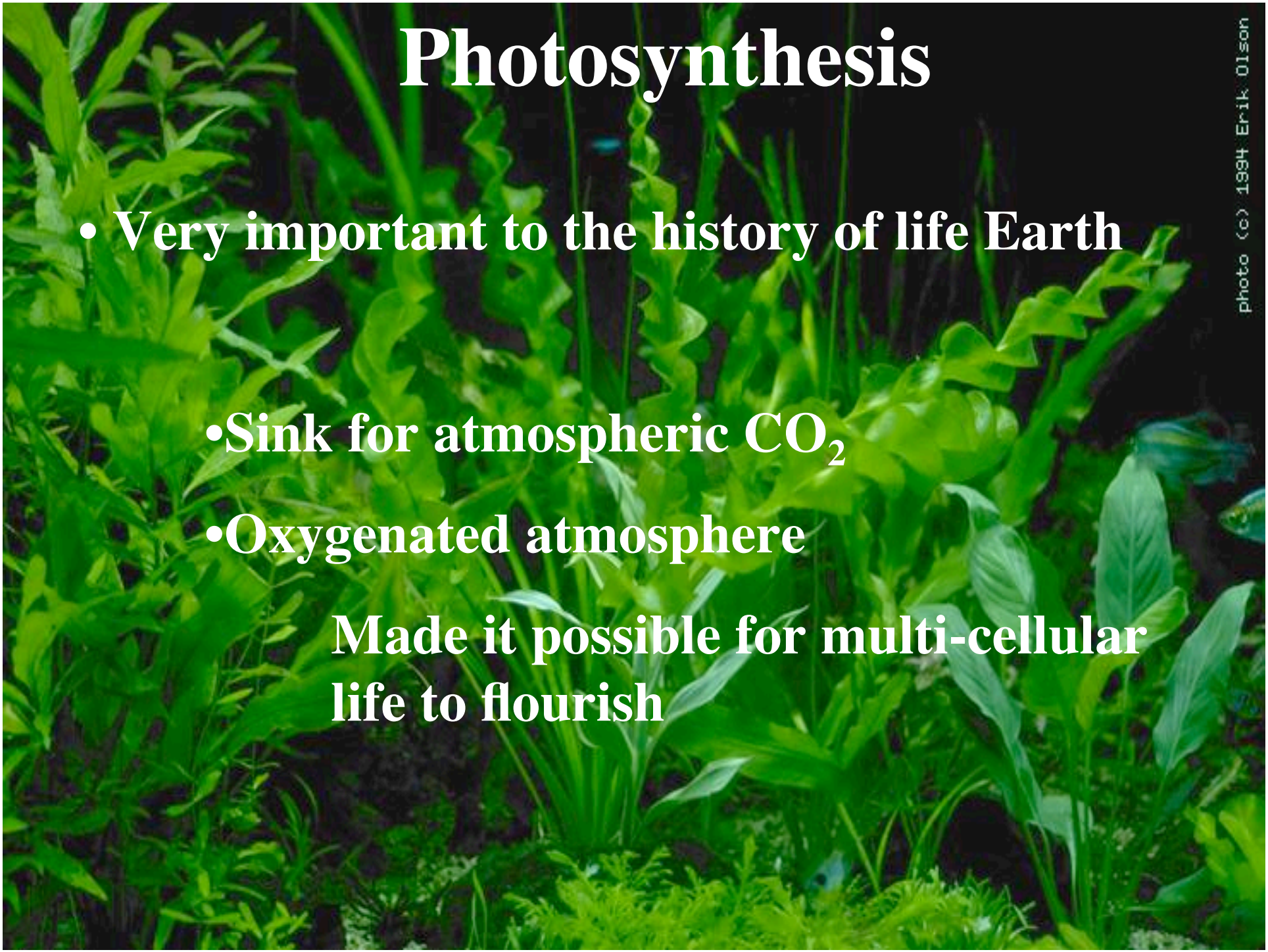


Photosynthesis

Process by which plants, algae, and photosynthetic bacteria derive energy from the sun to "fix" CO2 from the atmpsphere into organic molecules.

$$6CO_2 + 6H_20 + SUN \rightarrow C_6H_{12}O_6 + O_2$$

Photosynthesis



- Very important to the history of life Earth
  - Sink for atmospheric CO_2
  - Oxygenated atmosphere

    Made it possible for multi-cellular life to flourish

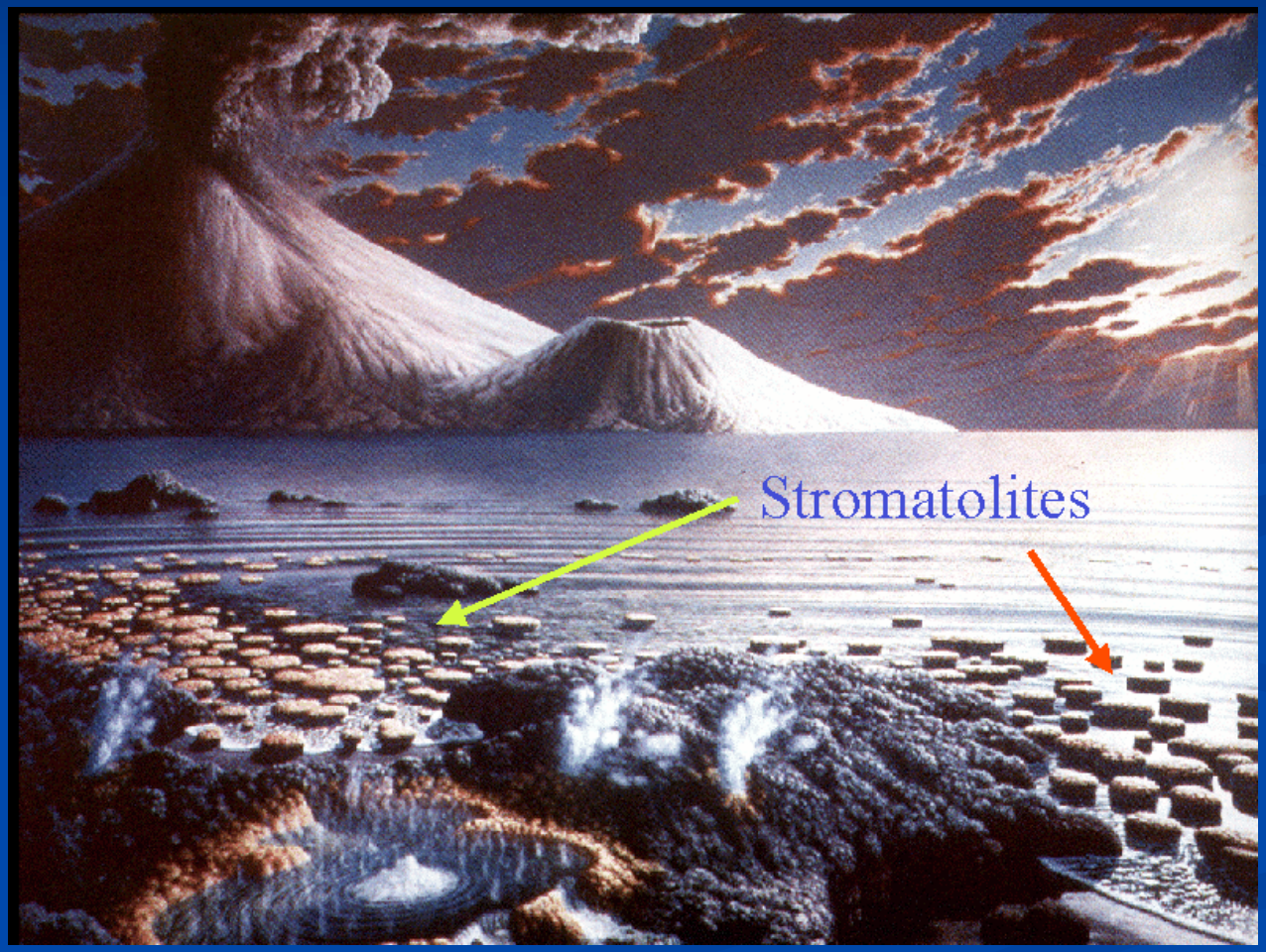
Oxygen Atmosphere

- Drastically changed the environment
- Probably drove many microbial species to extinction (toxic)
- Banded Iron Formations

  soluble Fe^{2+} quickly oxidized to FeOOH.

But before all of that oxygenic coolness….

The Archaean
(3.8 to 2.5 billion years ago)



The Archaean

- Reducing atmosphere of methane, ammonia, and other gases which would be toxic to most life on our planet today.
- Rampant volcanism
- Acidic oceans, dissolved metals
- Really a pretty nasty place to live :(

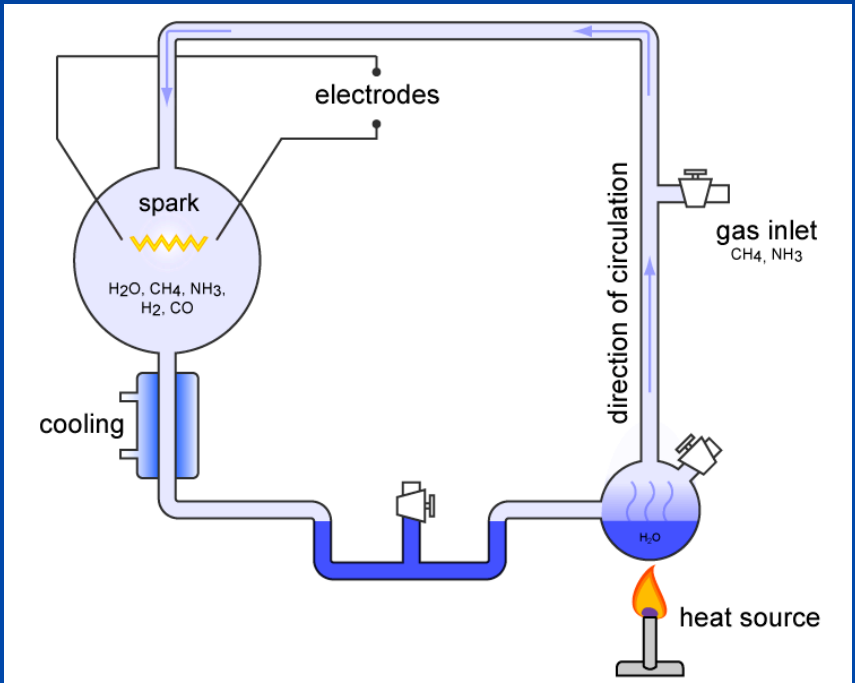
Archaean Stromatolites

- W. Australian, 3.5 Ga
- Oldest rocks, 3.8 Ga
- Fossilized remnants of cyanobacterial colonies
- Photosynthetic organisms

Wicked cool….

Even before oxygenic cyanobacteria were building stromatolites….

Urey-Miller Experiment, 1953



- water (H2O),
- methane (CH4),
- ammonia(NH3)
- hydrogen(H2)

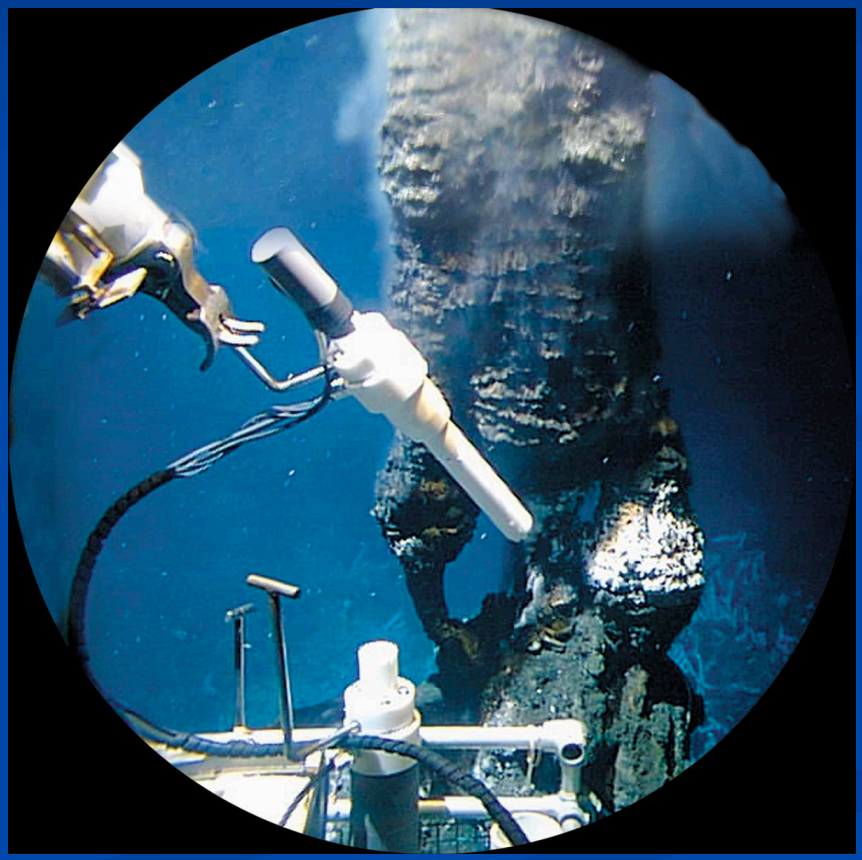
- Archaean conditions

Urey-Miller Experiment

- After one week, 15% of the carbon was in the form of organic compounds
- 13 of the 22 amino acids
- Carbohydrates, lipids, and nucleic acids (DNA and RNA)

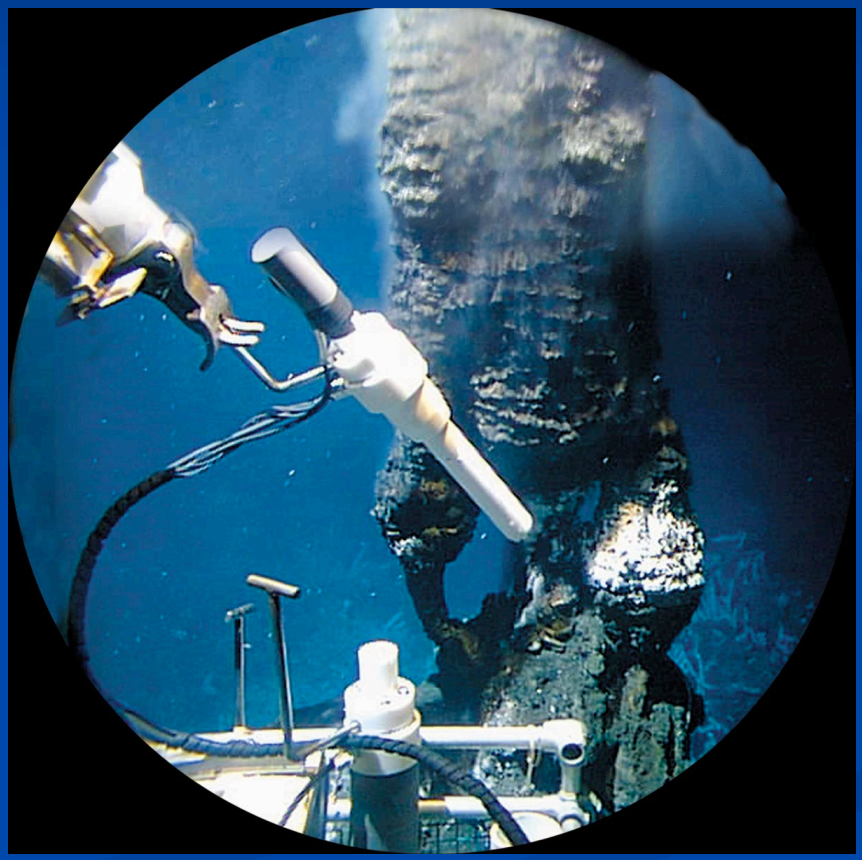
Discovery of Hydrothermal Vents

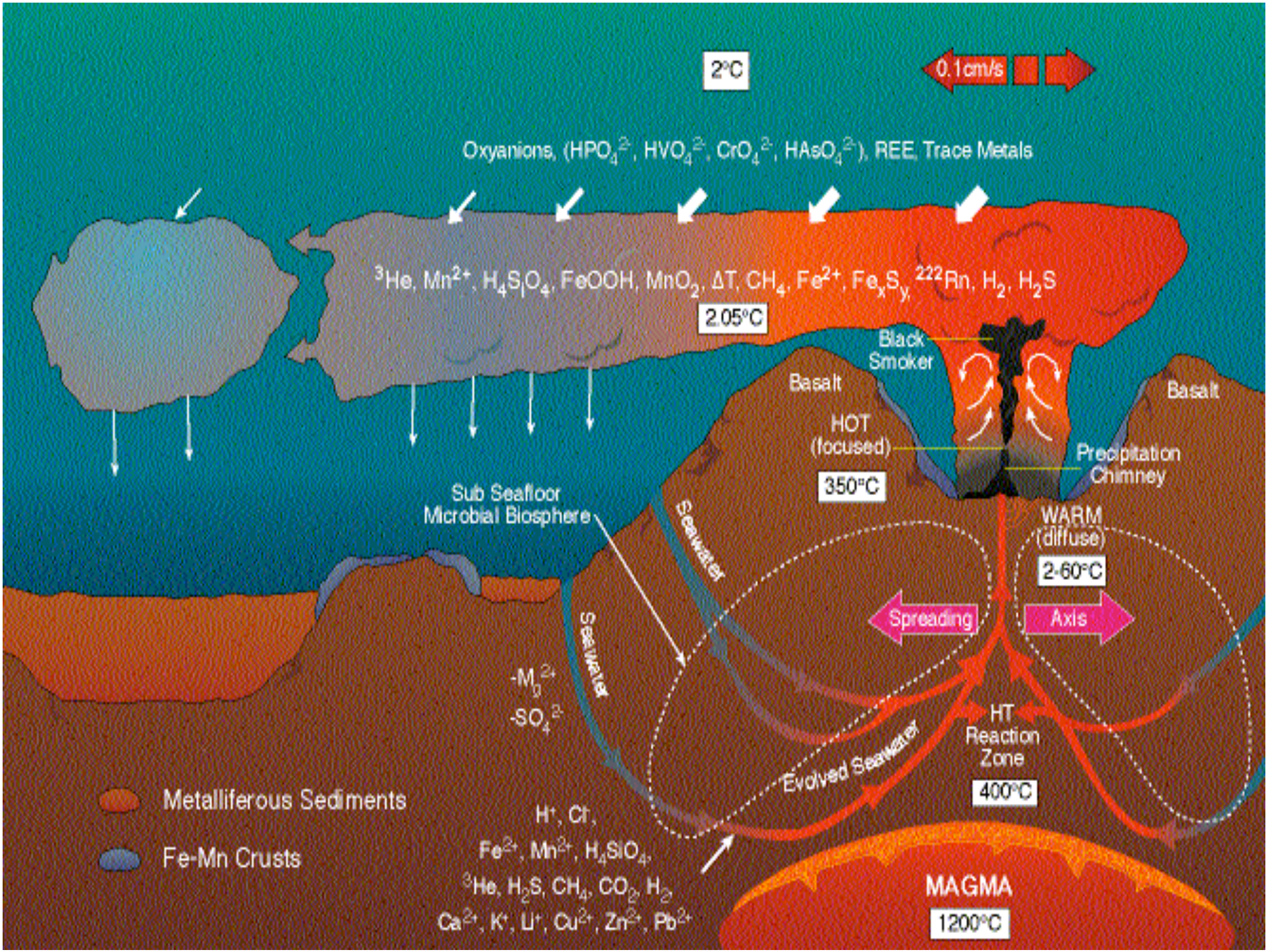
- Discovered along the Galapagos Rift in 1976 by a group of marine geologists studying ocean temperatures



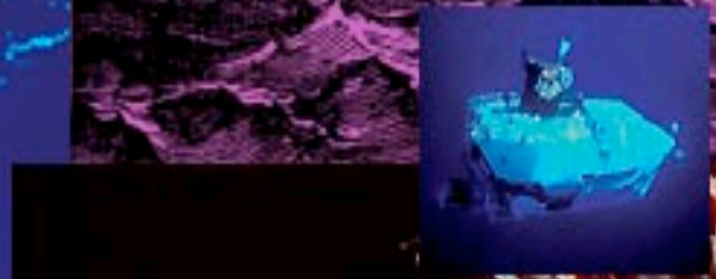
Hydrothermal Vents

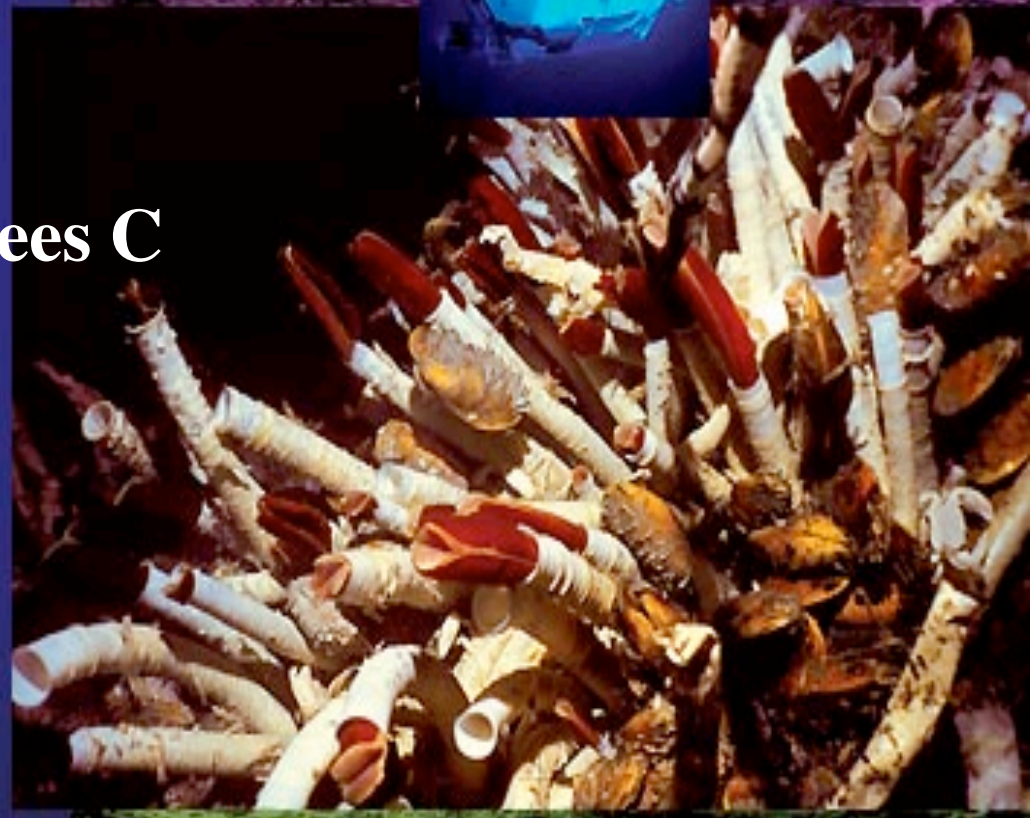
- Typically form along Mid-Ocean Ridge
- 80 - 400°C
- Chimneys ~60m high

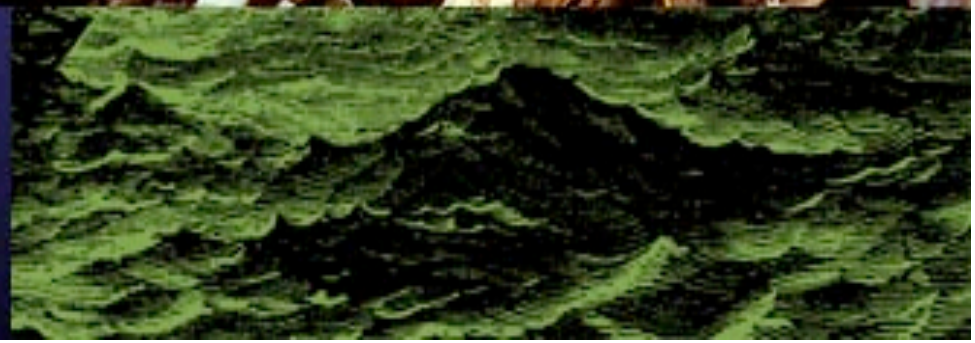



2°C
0.1cm/s
Oxyanions, (HPO_4^{2-}, HVO_4^{2-}, CrO_4^{2-}, $HAsO_4^{2-}$), REE, Trace Metals
^3He, Mn^{2+}, H_4SiO_4, FeOOH, MnO_2, ΔT, CH_4, Fe^{2+}, Fe_xS_y, ^{222}Rn, H_2, H_2S
2.05°C
Black Smoker
Basalt
Basalt
HOT (focused)
350°C
Precipitation Chimney
Sub Seafloor Microbial Biosphere
Seawater
WARM (diffuse)
2-60°C
Spreading
Axis
Seawater
$-Mg^{2+}$
$-SO_4^{2-}$
HT Reaction Zone
400°C
Evolved Seawater
Metalliferous Sediments
Fe-Mn Crusts
H^+, Cl^-,
Fe^{2+}, Mn^{2+}, H_4SiO_4,
^3He, H_2S, CH_4, CO_2, H_2,
Ca^{2+}, K^+, Li^+, Cu^{2+}, Zn^{2+}, Pb^{2+}
MAGMA
1200°C

Hydrothermal Vents







Analogous to Archaen Environment

Very warm: 80 - 400 degrees C

Reduced species:

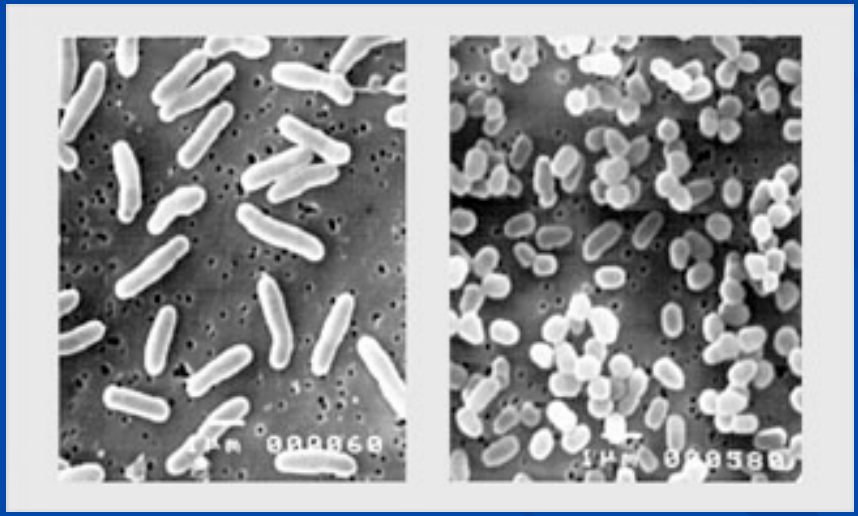
H_2S, H_2, CH_4, Fe^{2+}

Oxidized species:

NO_3, CO_2, SO_4

Chemosynthesis

Reduced molecules provided directly from the plume are oxidized for *chemosynthetic organisms* to derive energy.



Chemosynthesis

Examples of REDOX pairs:

Fe3+ / H_2 and organics
CO2 / H_2S and H_2
S and SO_4 / H_2S, H_2, organics

Chemosynthesis

- Many of the microbes found at hydrothermal vents are called "extremophiles"

- 70 - 103 degrees C
- Extremely low pH
- High pressures

Current record holders for extremophiles

High temperature	Hyperthermophile *Pyrolobus fumarii*	90°C	106°C	113°C
Low temperature	Psychrophile *Polaromonas vacuolata*	0°C	4°C	12°C
Low pH	Acidophile *Picrophilus oshimae*	-0.06	0.7 (60°C)	4
High pH	Alkaliphile *Natronobacterium gregoryi*	8.5	10 (20%NaCl)	12
Pressure	Barophile Strain MT41	500 atm	700 atm	>1000 atm
Salt	Halophile *Halobacterium salinarum*	15%	25%	>32% (saturated)

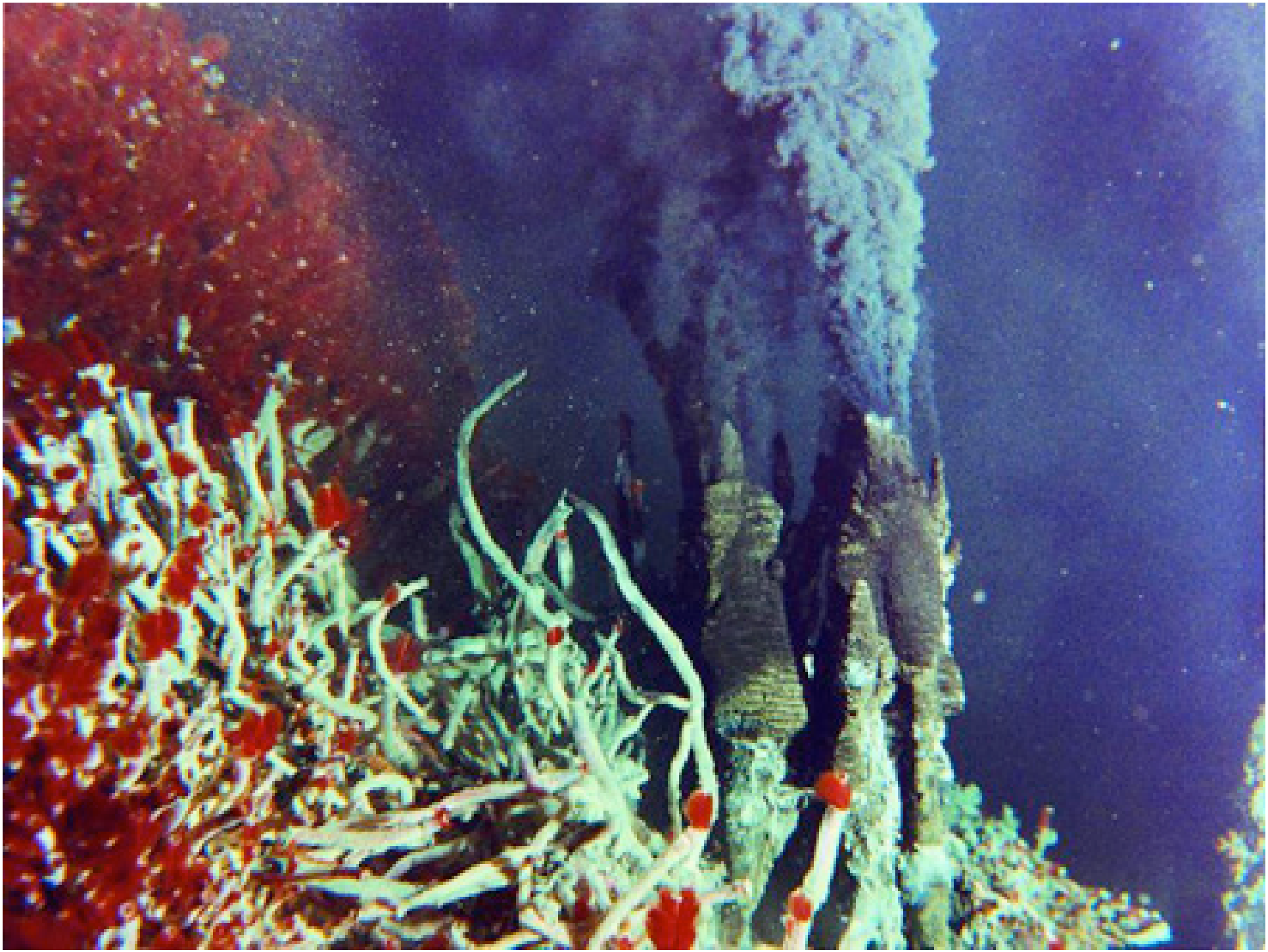
From 'Brock Biology of Microorganisms'

Extremophiles

- Most found at hydrothermal vents are *chemoautotrophic*
  - CO2 as Carbon source
  - (remind you of anything?)
  - Derive reducing power from H_2S, H_2, rarely CH_4

Extremophiles

- Inhabit spaces between crystal grains within the black smoker chimneys
- Hyperthermophiles live directly within plume of super-hot liquid
- Less heat-tolerant organisms form mats in vicinity of plume

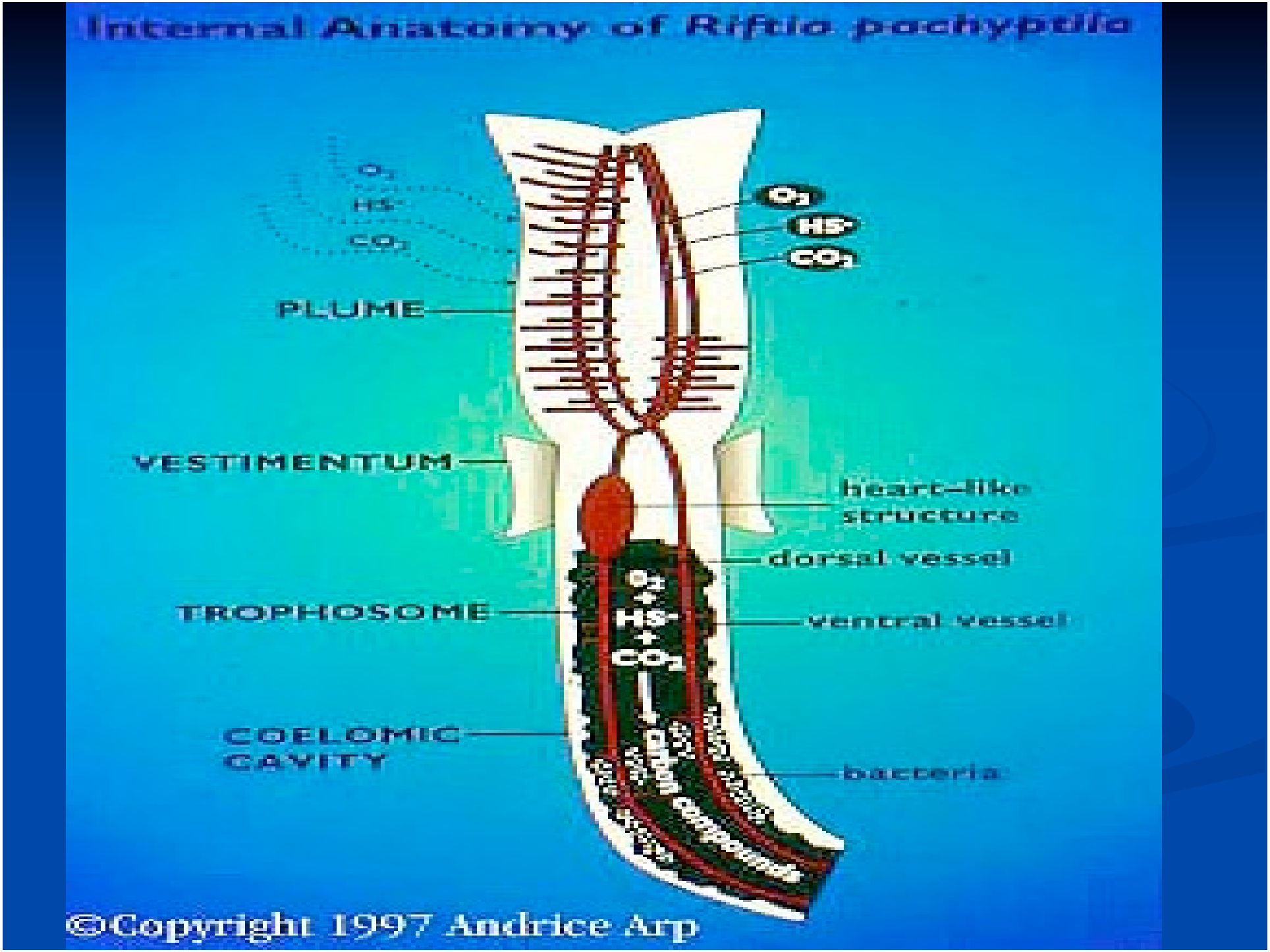


Chemosynthetic food webs

- Chemosynthetic organisms form base of the food web
- Analogous to the role of plants on the surface
- Fix carbon into organic forms used by higher organisms
- Often live in symbiotic associations with vent animals

Riftia pachyptila

- Tubeworm, most famous vent animal
- Red gill plume carries H2S and O2 through blood stream
- Bacteria within gut

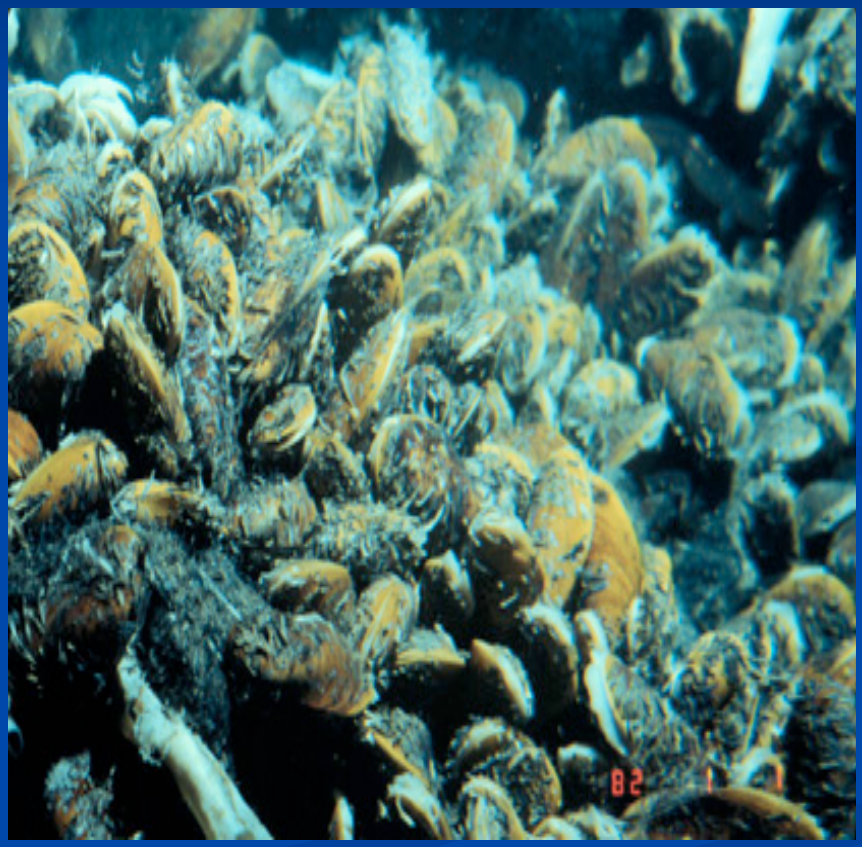

Internal Anatomy of Riftia pachyptila
PLUME
VESTIMENTUM
TROPHOSOME
COELOMIC CAVITY
heart-like structure
dorsal vessel
ventral vessel
bacteria
©Copyright 1997 Andrice Arp

Other symbiotic associations

- Giant mussels (*Bathymodiolus elongatus)*

  bacteria live within gills

  Very heat tolerant



Other vent animals

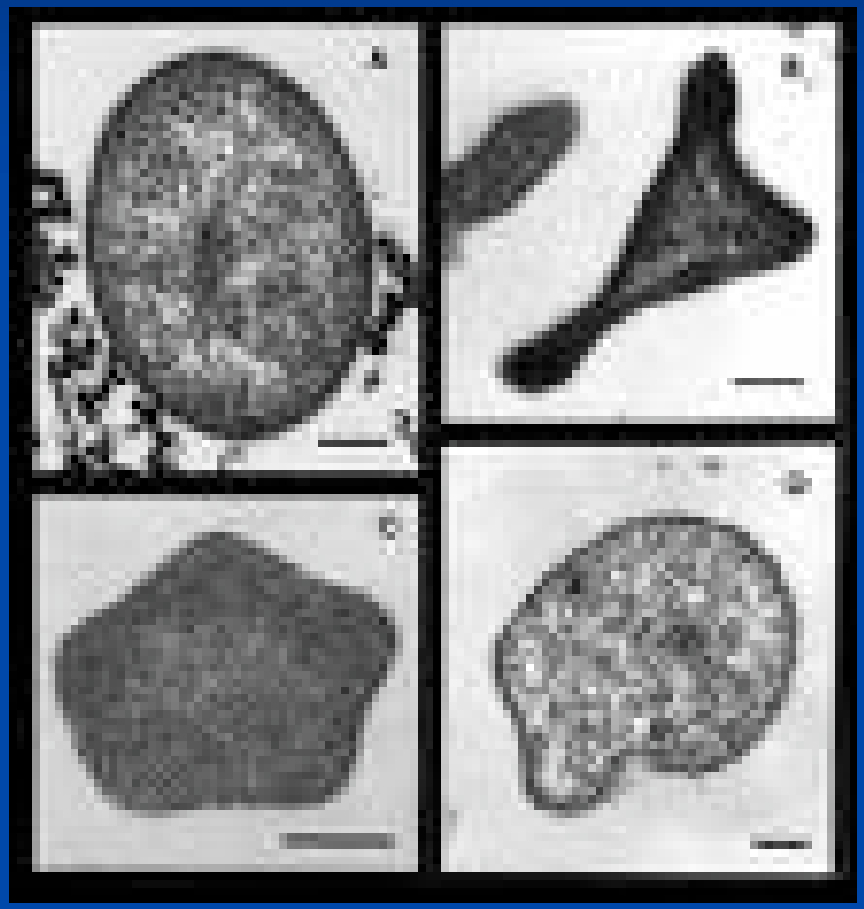
- Vent crab (*Bythograea thermydron)*
- Grazes on bacterial mats

Other vent animals

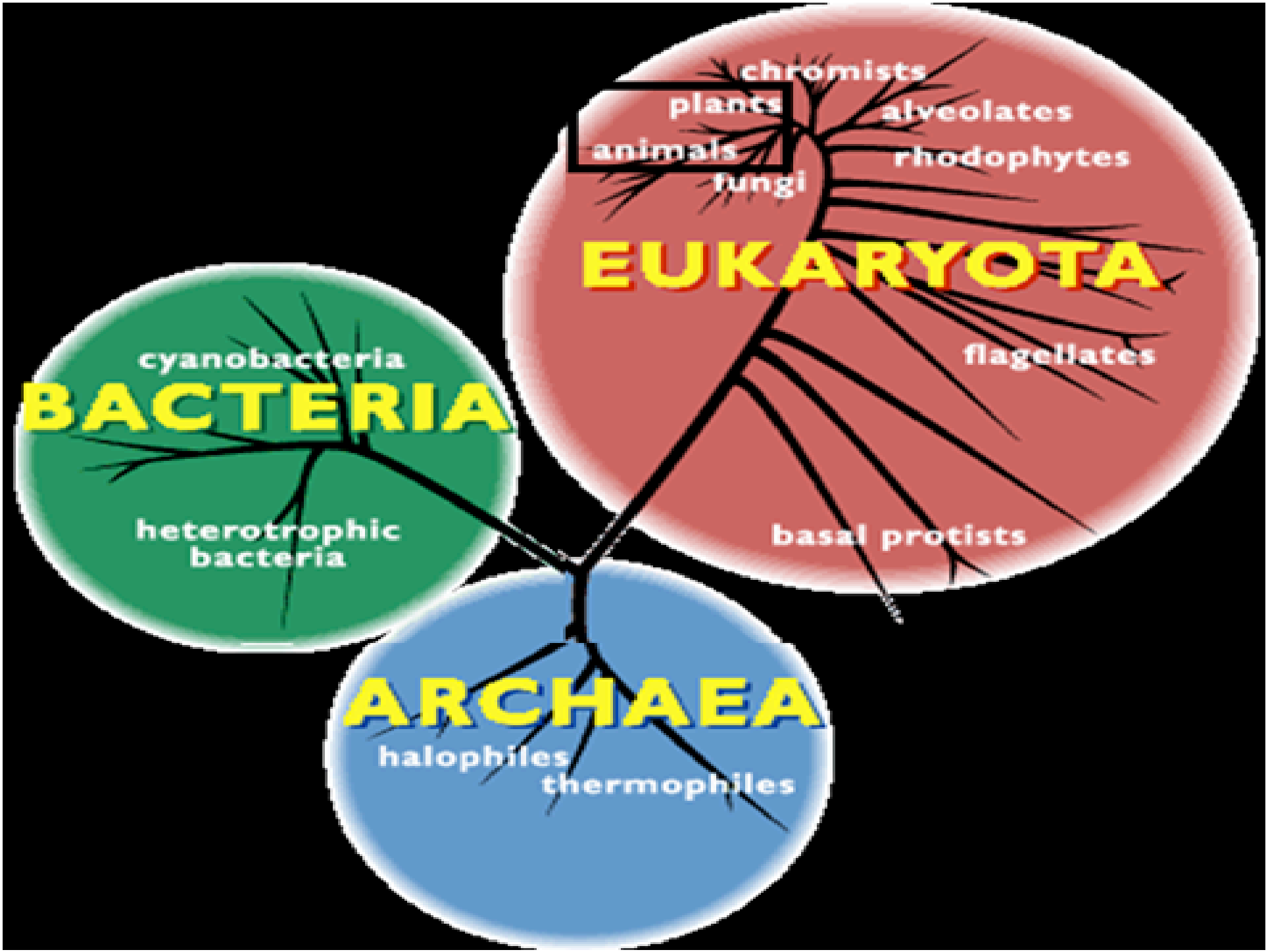
- Starfish
- Crinoid-like creatures
- Deep sea octopus
- Predatory fish

- All have physiological adaptations to deal with H_2S

Archaea



- Prokaryotes
- Similar in morphology to bacteria
  - Rods, cocci, etc…


chromists
plants
alveolates
animals
rhodophytes
fungi
EUKARYOTA
flagellates
cyanobacteria
BACTERIA
heterotrophic
bacteria
basal protists
ARCHAEA
halophiles
thermophiles

Archaea

- Similar in physical appearance and ecology to Bacteria
- Have strikingly similar cellular processes to eukaryotes

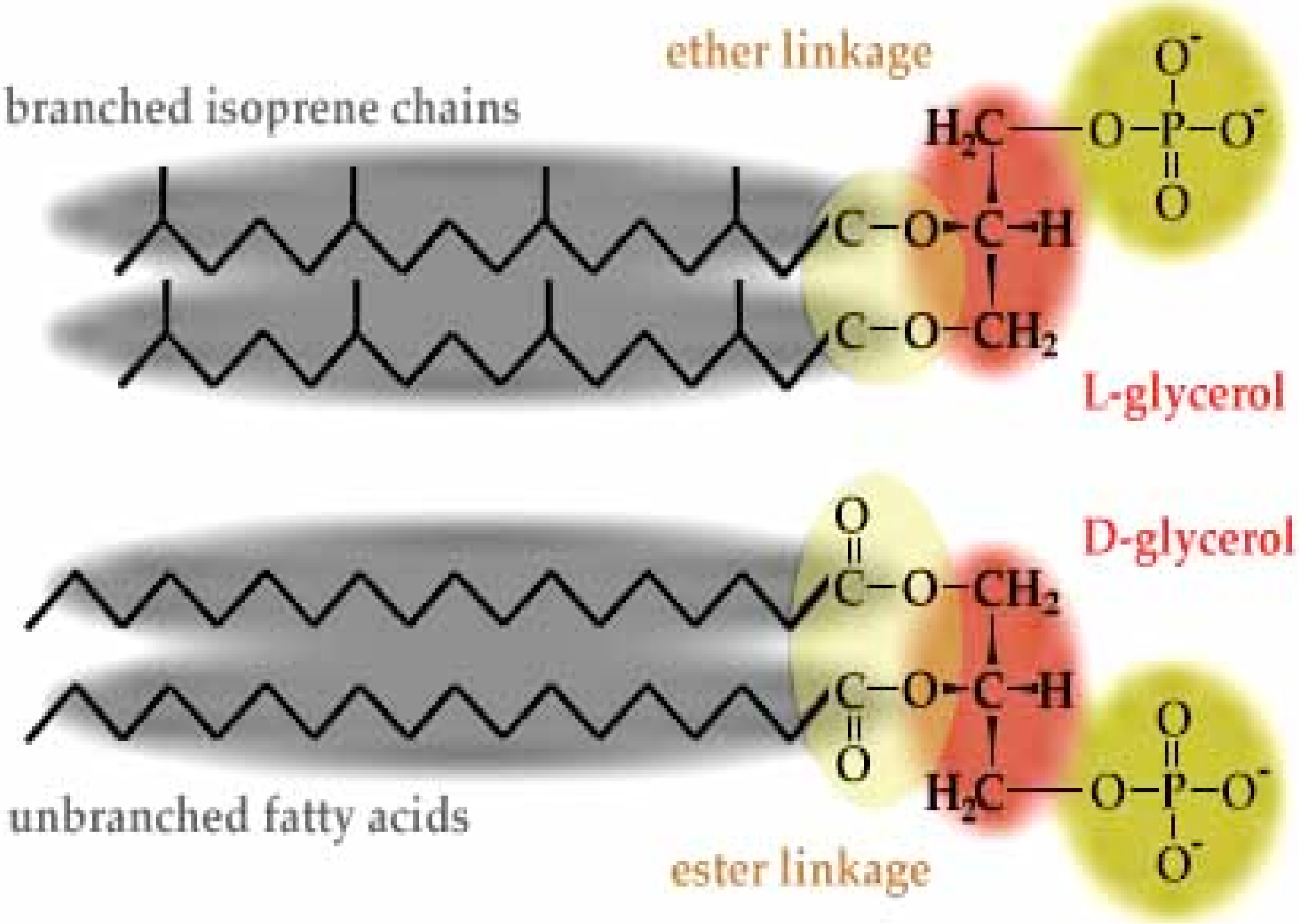
  RNA Metabolism

  Amino acid sequences

  Succeptable to viral infection

Unique traits to Arachaea

- Most are “Extremophiles”
- Many are thermophiles and hyperthermophiles
- Halophiles -- driest, saltiest locations
- Completely different cell membrane structure


ether linkage
branched isoprene chains
L-glycerol
D-glycerol
unbranched fatty acids
ester linkage

Why study extremophiles?

- Unique abilities to withstand temperatures and pressures
- Novel enzymes and chemicals for use in industry
  - Taq Polymerase
  - Anti-freeze chemicals
  - Unique enzymes capable of breaking down recalicitrant chemicals

Enzymes in Industry

- *Taq Polymerase*: used in *every* microbiology, genetics, molecular, immunology, and pharmecutical lab.
- Bioremediation: organisms capable of degrading long-chain hydrocarbons
- Oxidizing heavy metal contaminants, including Uranium

Biomedical Research

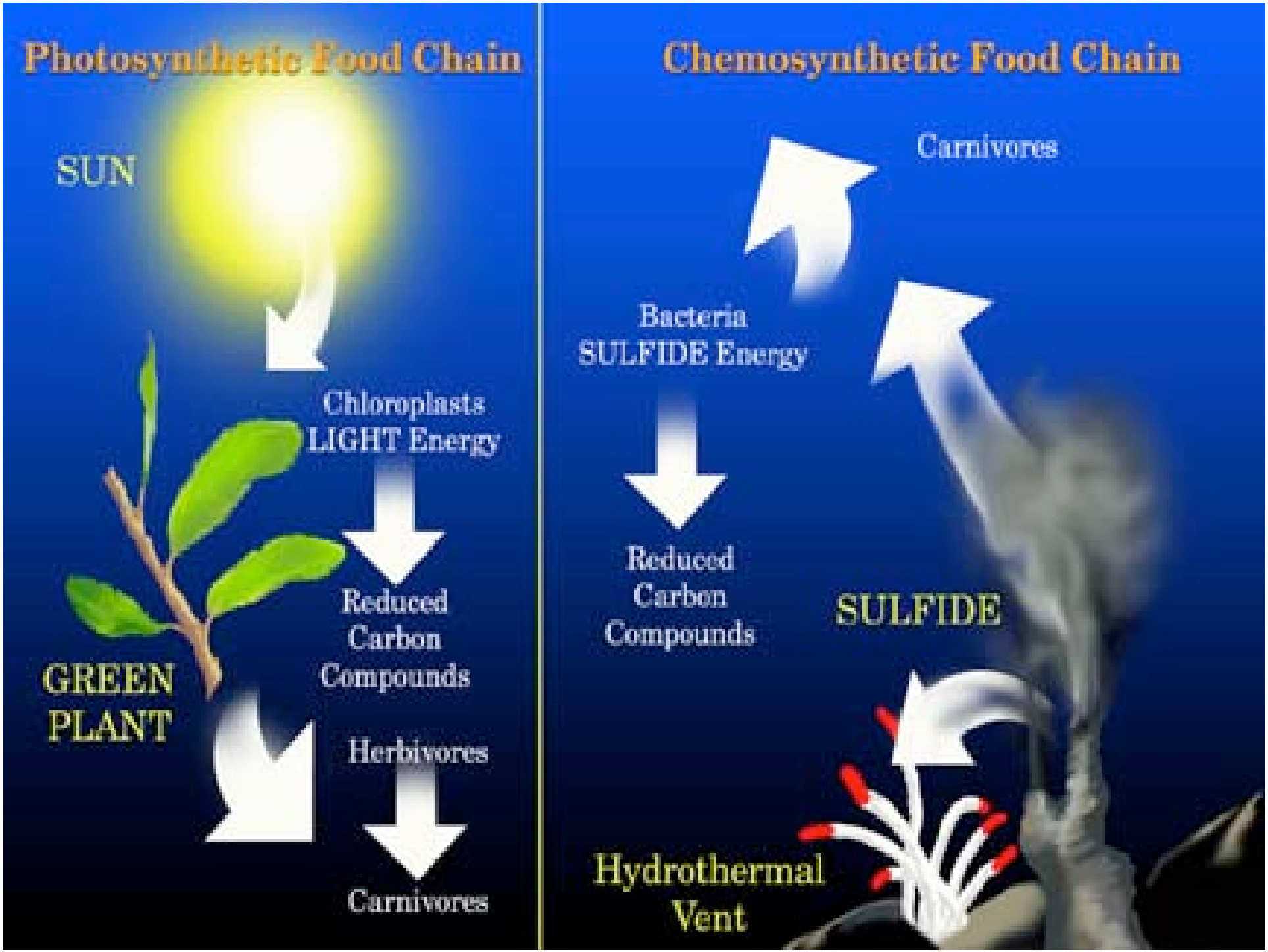
- Archaea share many metabolic similarities to eukaryotes (i.e. humans).
- More simple systems to study
- RNA metabolism-- RNA diseases
- Viral infections-- retroviruses
- Antibiotics

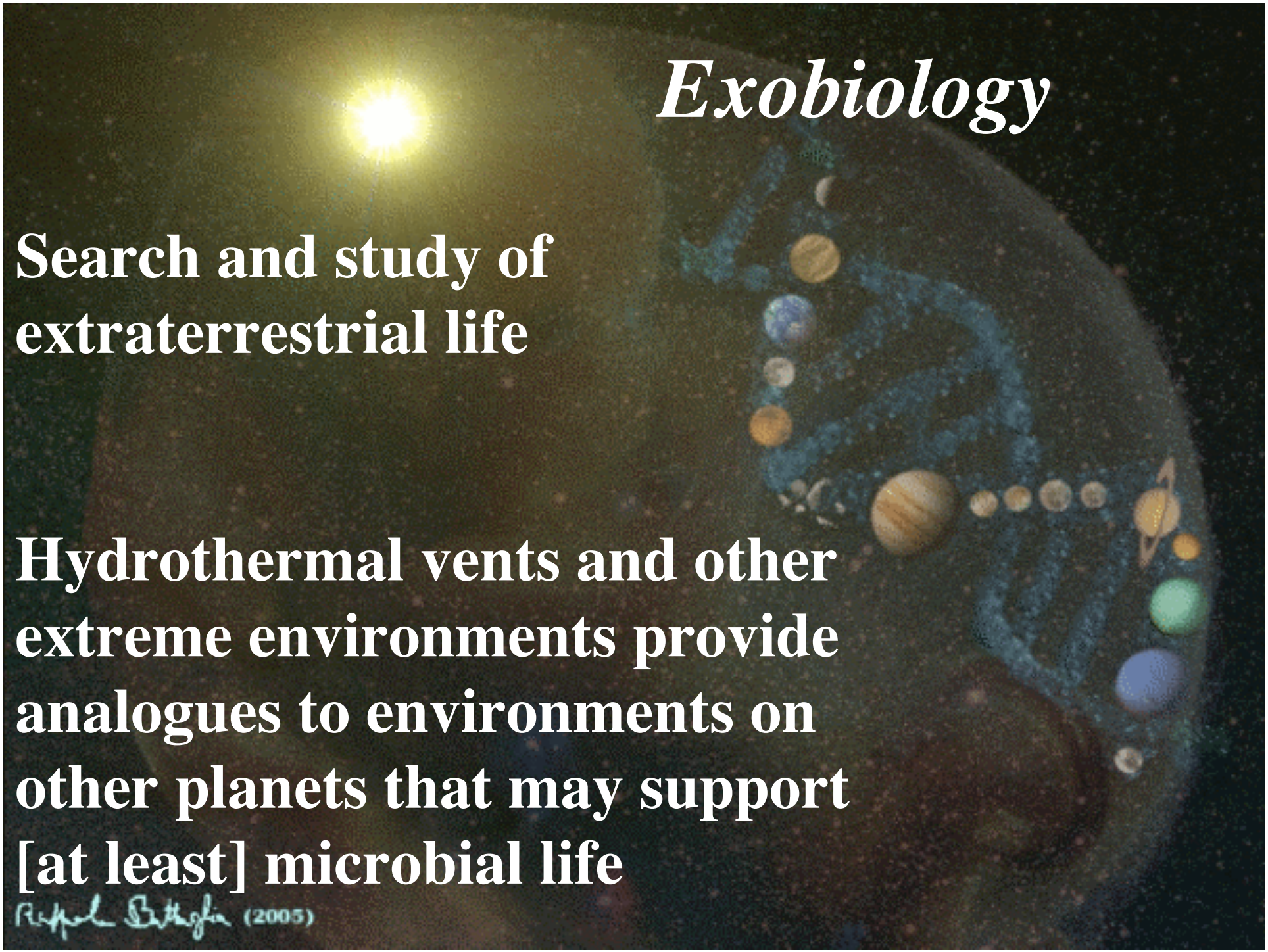
Chemosynthetic ecosystems

- Not discovered until the late 1970's
- Remain poorly understood

- How do they become colonized?
- How long do the ecosystems thrive?

ONE MAJOR DIFFERENCE TO ALL OTHER ECOSYSTEMS ON EARTH

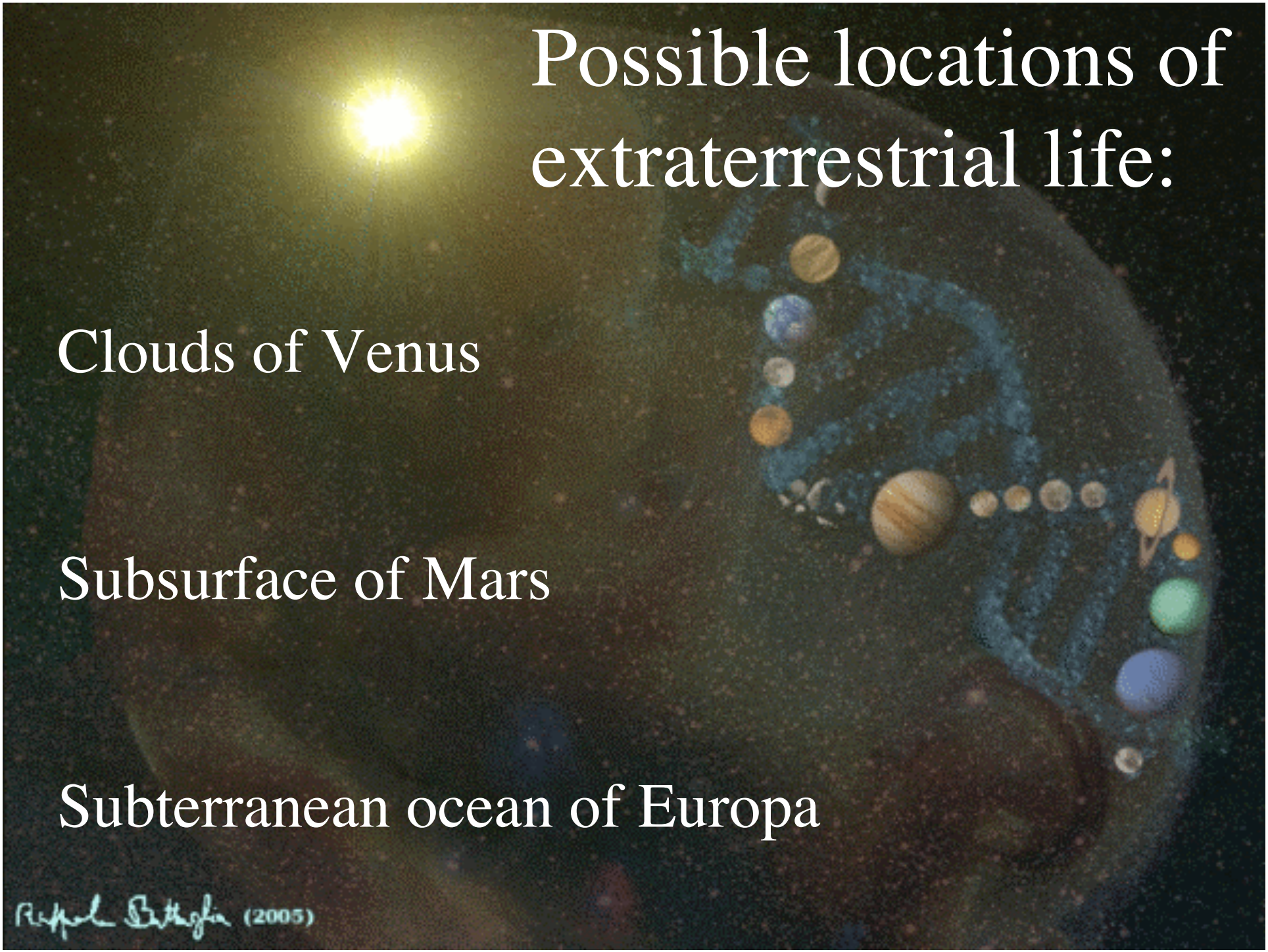

Photosynthetic Food Chain
SUN
Chloroplasts
LIGHT Energy
Reduced
Carbon
Compounds
GREEN
PLANT
Herbivores
Carnivores
Chemosynthetic Food Chain
Carnivores
Bacteria
SULFIDE Energy
Reduced
Carbon
Compounds
SULFIDE
Hydrothermal
Vent

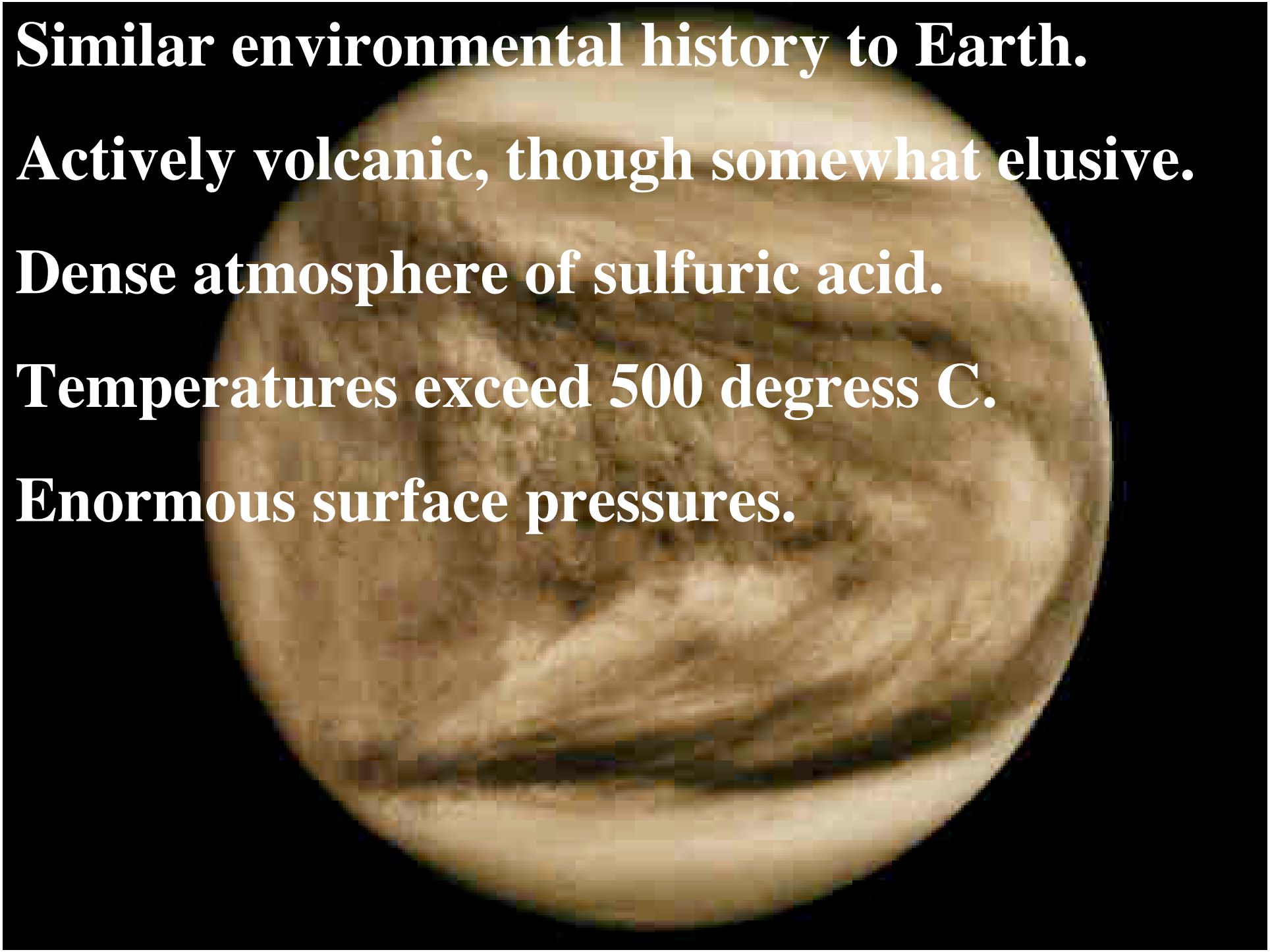


Exobiology

Search and study of extraterrestrial life

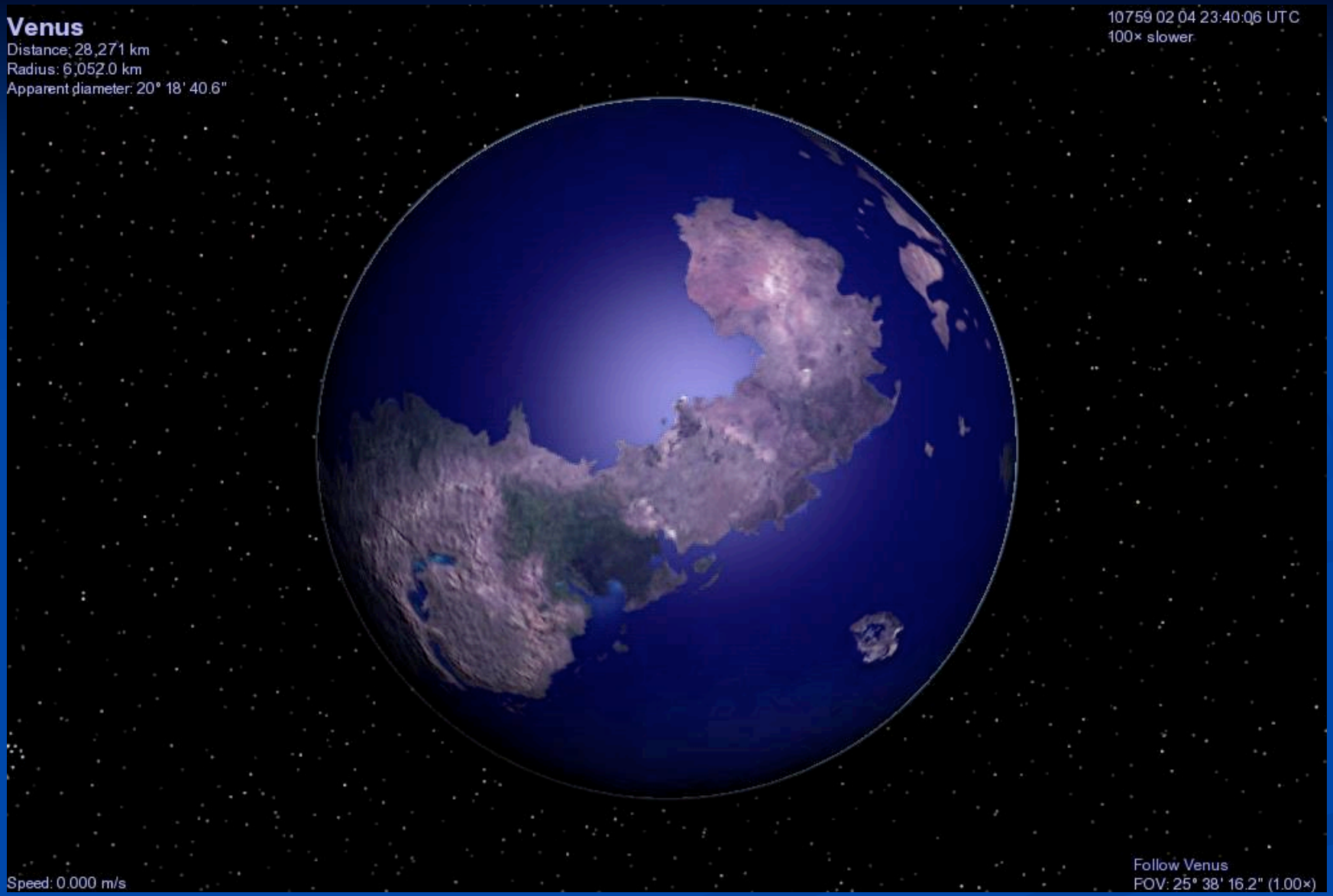
Hydrothermal vents and other extreme environments provide analogues to environments on other planets that may support [at least] microbial life


Possible locations of extraterrestrial life:
Clouds of Venus
Subsurface of Mars
Subterranean ocean of Europa
(2005)


Similar environmental history to Earth.
Actively volcanic, though somewhat elusive.
Dense atmosphere of sulfuric acid.
Temperatures exceed 500 degress C.
Enormous surface pressures.

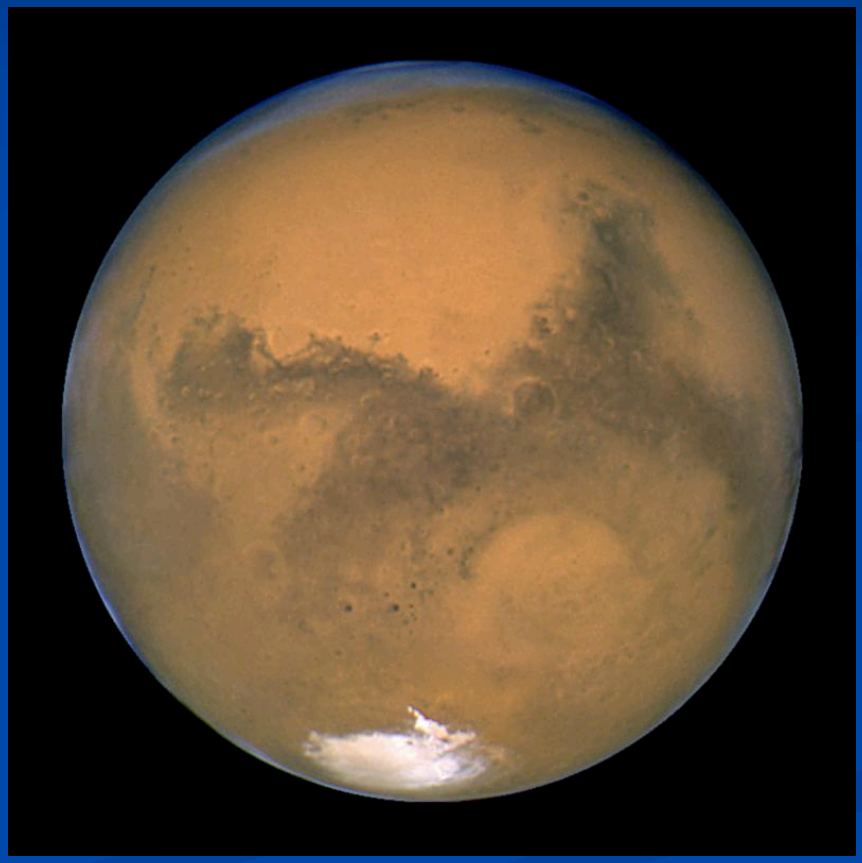
Venusian Life?

- Thin layer 3 - 5km above surface
- Maybe liquid water
- Low enough T and P
- Sulfur bacteria/archaea?


Venus
Distance: 28,271 km
Radius: 6,052.0 km
Apparent diameter: 20° 18' 40.6"
10759 02 04 23:40:06 UTC
100× slower
Speed: 0.000 m/s
Follow Venus
FOV: 25° 38' 16.2" (1.00×)

Mars

- Lots of Mythology surrounds Mars
- H.G. Wells
- Schiaparelli, 19th Century

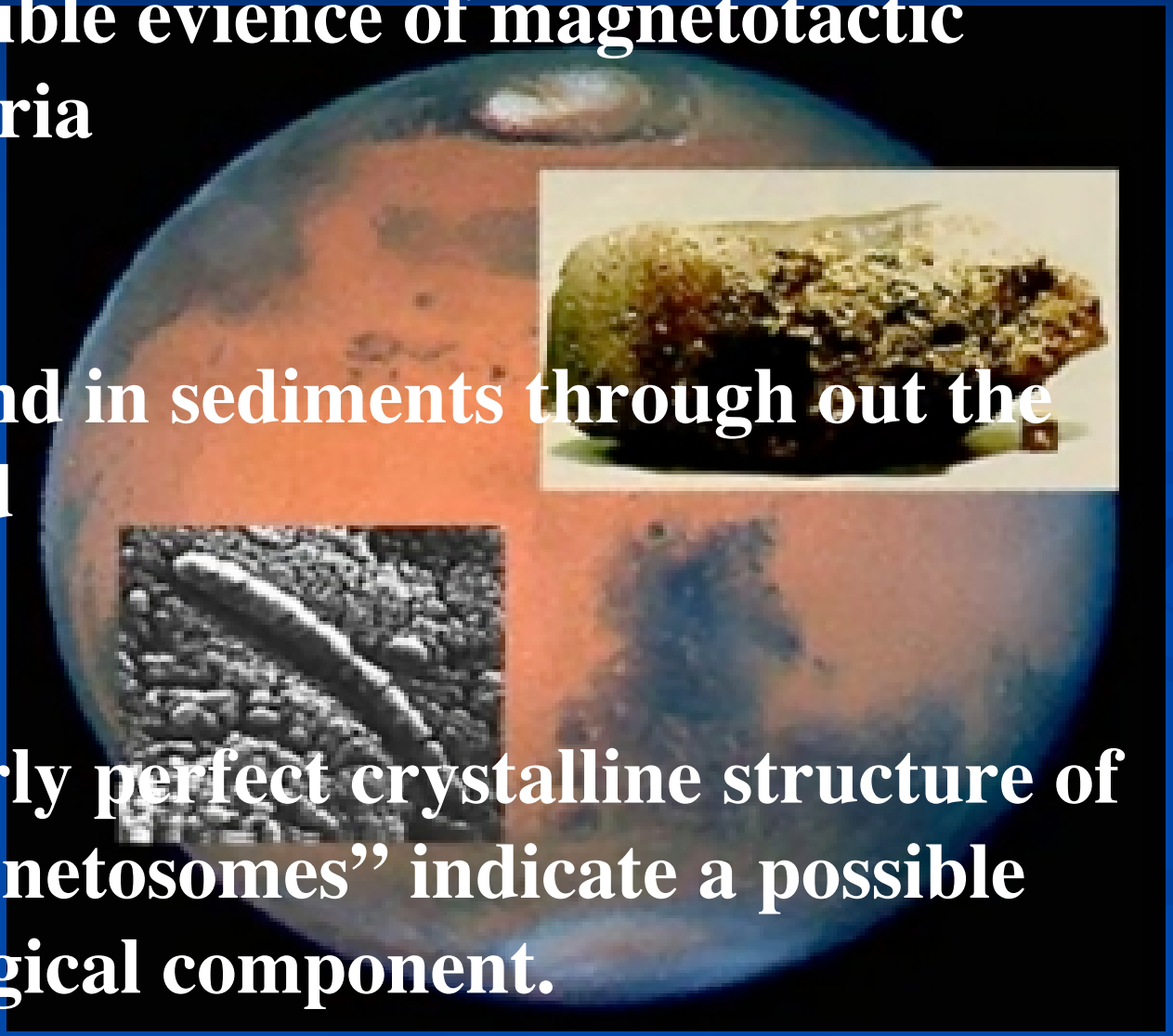


Little Green Men?

- Possible resevoirs of SALTY water in low lands.
- Extremely salty water within pores of glaciers
  - Remember Halophiles?
- Subsurface, warm, wet lithotrophic environment
  - Remember thermophiles and barophiles?

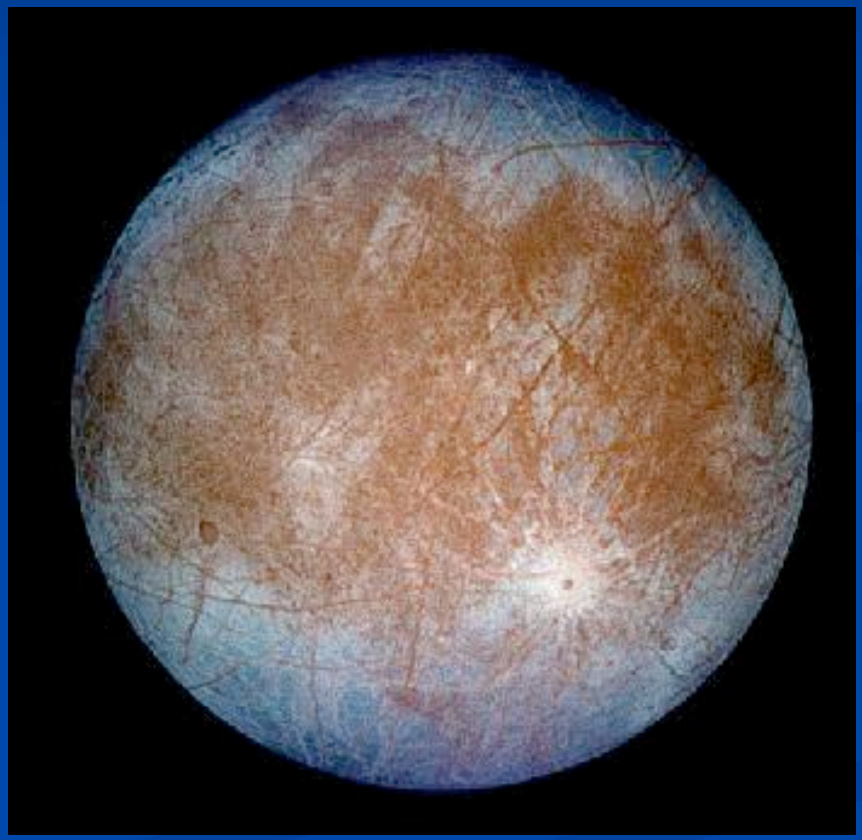
ALH84001

- Possible evience of magnetotactic bacteria
- Found in sediments through out the world
- Nearly perfect crystalline structure of "magnetosomes" indicate a possible biological component.



Europa

- Jovian satellite
- Frozen surface
- Liquid water ocean, more than twice the volume of Earth's
- Subsurface volcanism
- Radiation supplied to surface



Why Life on Europa?

- Water + volcanism + energy source + plate tectonics = recipe for life
- Everywhere on Earth that we find water, we find LIFE