Microbes and Origins of Life

Evolution has occurred almost
elusively in a microbial world !!!

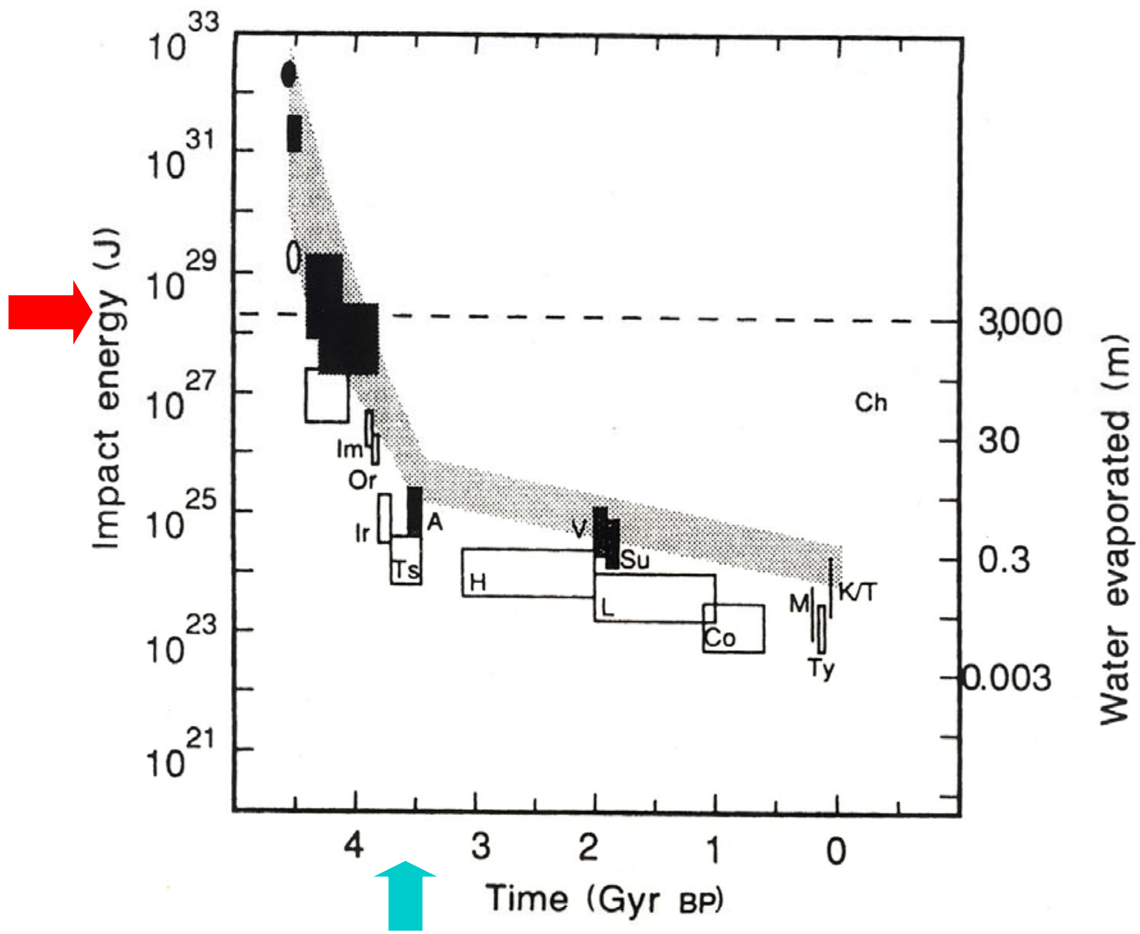
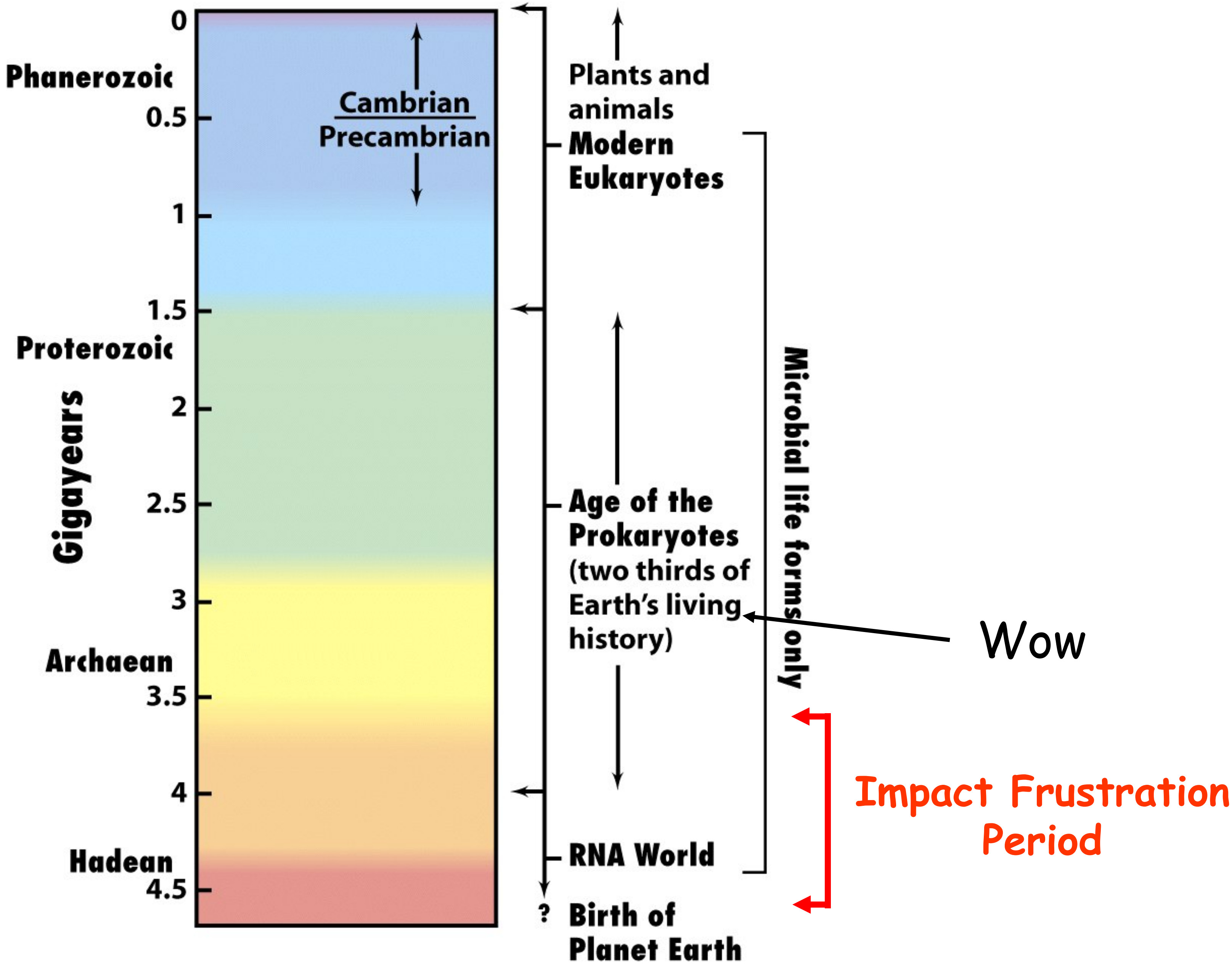


FIG. 1 The largest impacts on Earth and Moon. Open boxes are lunar, filled boxes terrestrial. Lunar craters are Tycho, Copernicus, Langrenus, Hausen, Tsiolkovski, Iridum, Orientale and Imbrium. Terrestrial events are the K/T impact, Manicougan, Sudbury, Vredevort and an impact energy corresponding to the thickness of Archaean spherule beds. Ovals are self energies of formation; the early box refers to a possible Moon-forming impact. Impact estimates between 3.8 and 4.4 Gyr are discussed in the text. The stippled region for Earth is inferred from these data. The depth of ocean vaporized by the impact is also given; the dashed line corresponds to an ocean-vaporizing impact. A possible but extremely unlikely collision with Chiron is placed safely in the future.

Impact Frustration period forces origins of life into a narrow time period to have gotten started!

Hydrothermal vents may have served as zones of refuge.


0
Phanerozoic
0.5
1
1.5
Proterozoic
2
2.5
3
Archaean
3.5
4
Hadean
4.5
Gigayears
Cambrian
Precambrian
Plants and animals
Modern Eukaryotes
Age of the Prokaryotes (two thirds of Earth's living history)
RNA World
? Birth of Planet Earth
Microbial life forms only
Wow
Impact Frustration Period

The Chemical Aspects of The Origin of Life

Life is the cumulative product of interactions among the many kinds of chemical substances that make up the cells of an organism.

The abiotic chemical evolution of life follows four major hurdles:

(1) The abiotic synthesis and accumulation of small organic molecules, or monomers, such as amino acids and nucleotides.
(2) The joining of these monomers into polymers, including proteins and nucleic acids.
(3) The aggregation of abiotically produced molecules into droplets, e.g., protobionts, that had chemical characteristics different from their surroundings.
(4) The origin of heredity or information transference.

To understand how the origin of life from abiotic material occurred, we have to consider <u>two critical concepts</u>:

(1) The extension of the idea of natural selection to the chemical level.

(2) The realization that the condition of the early Earth when life first arose must have been vastly different from present:

(a) Non-oxidizing atmosphere: present level of oxygen, which began to accumulate around 2.1 billion years ago with the presence of cyanobacteria, would have been lethal to primitive organisms

(b) Abundant resources produced non-biologically

(c) Long time scale without competition

Origins of Life Models

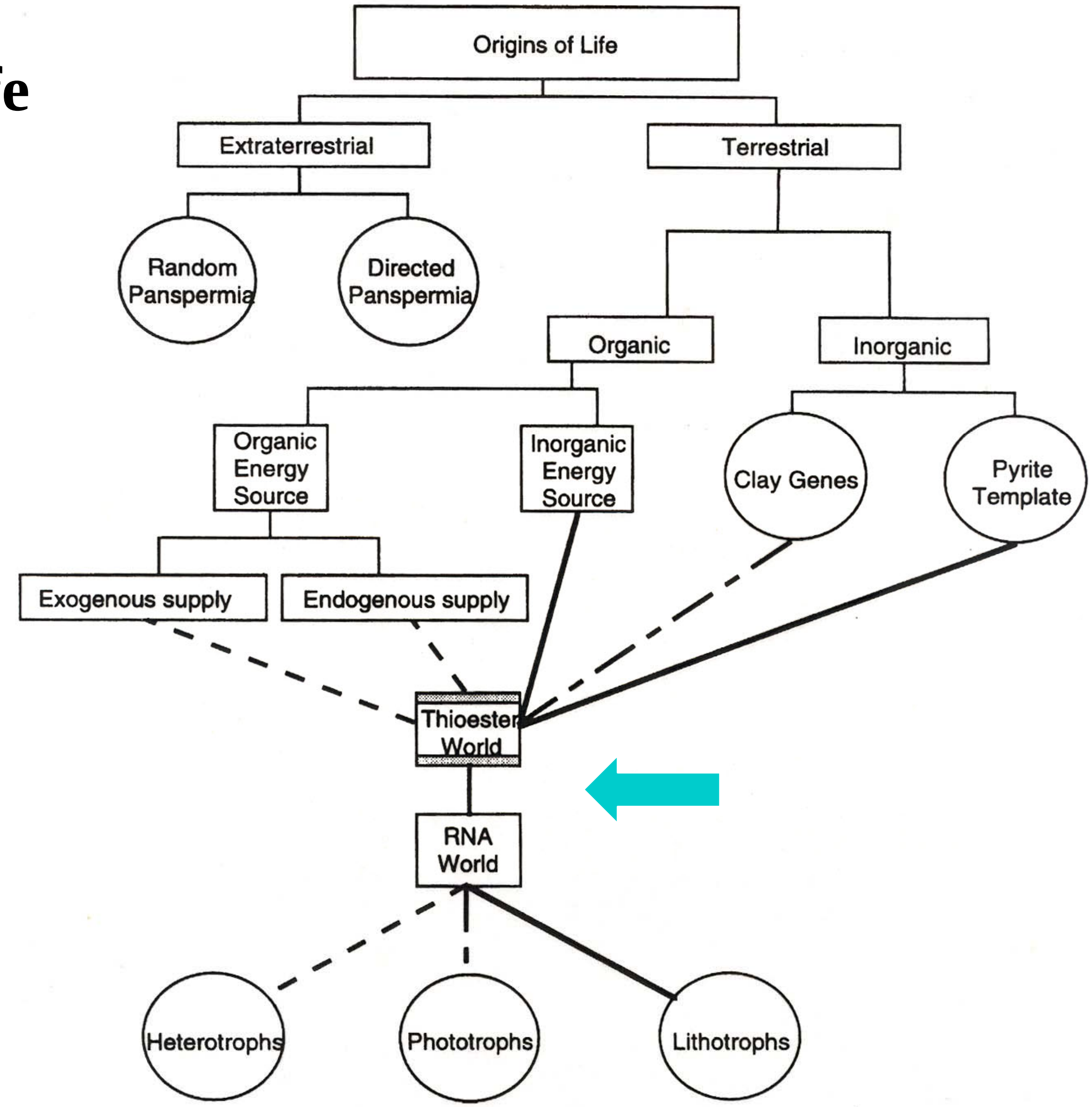


Figure 10.6 Relationships among various theoretical or conceptual models for the origins of life.[77] Dashed and solid lines at the bottom of the figure connect mechanisms with putative metabolic type of first organisms. The thioester world is proposed as an intermediate leading to an RNA world

Thioester World

Mechanisms of synthesis

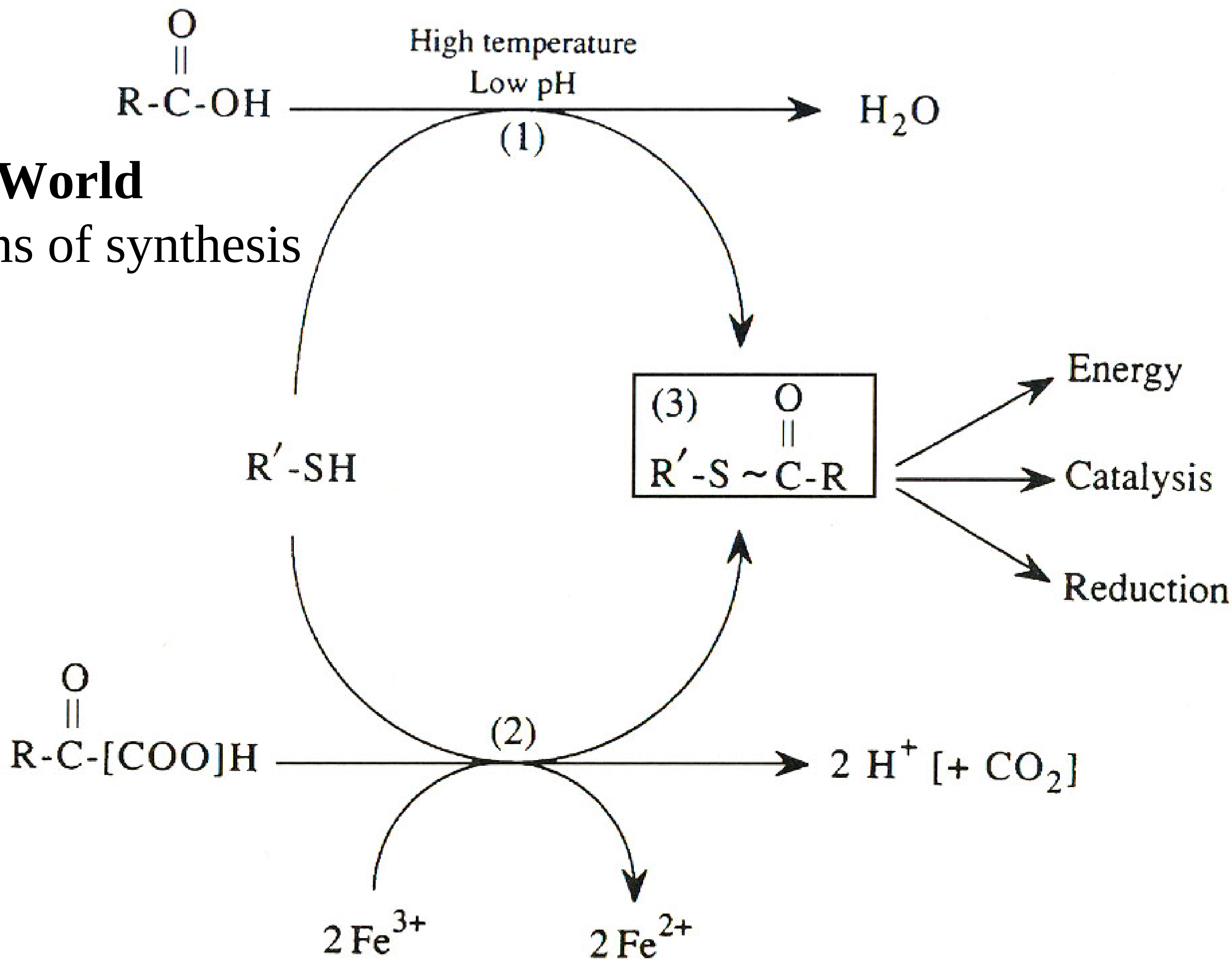


Figure 10.12 Mechanisms for synthesis of thioesters. (1) High temperature, low pH spontaneous synthesis from thiols and organic acids; (2) oxidative synthesis from thiols and α-keto organic acids based on ferric iron reduction[29]

Thioester World

Chemical Transformations

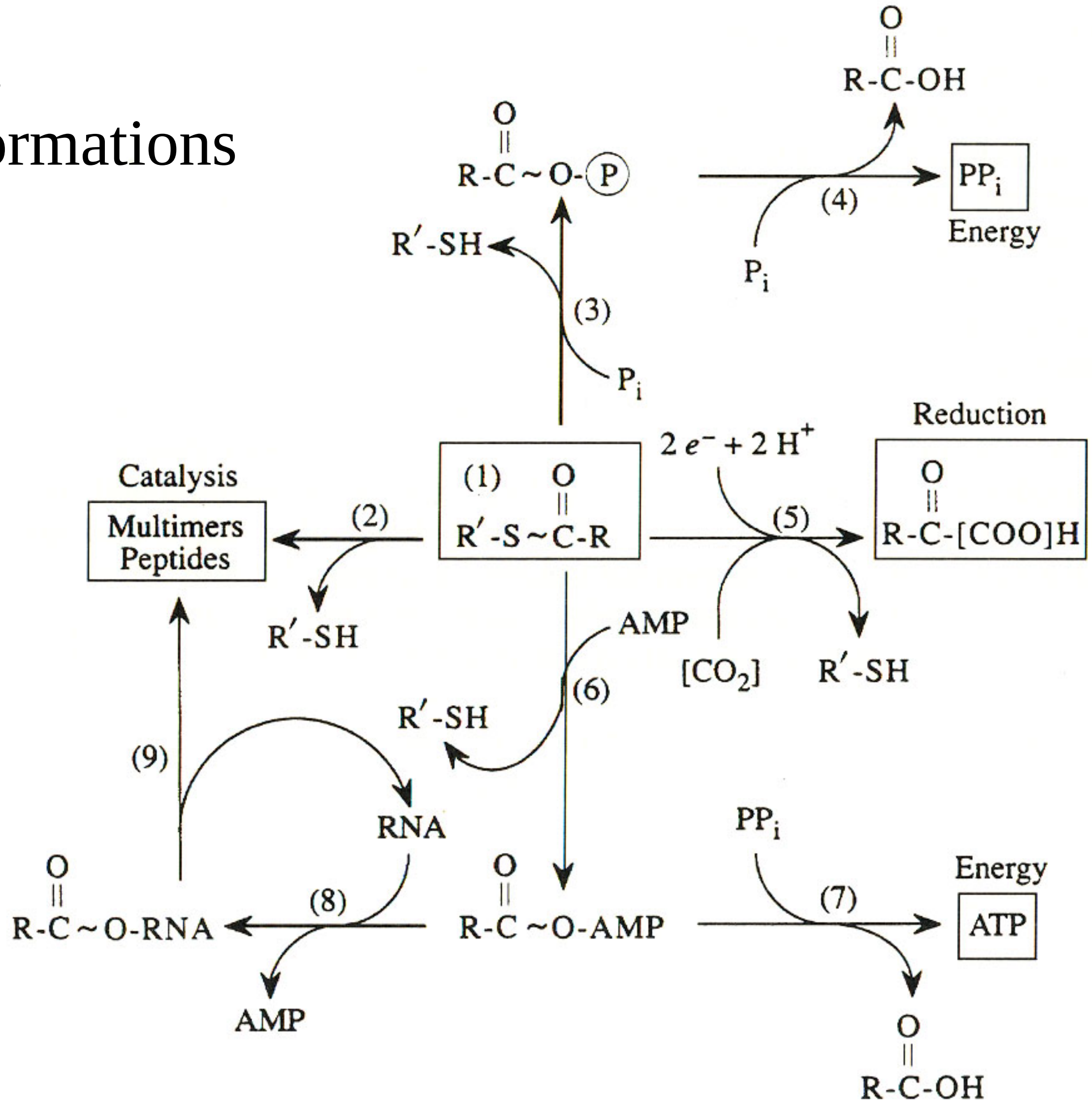


Figure 10.10 Synopsis of chemical transformations in the thioester world illustrating: (1) a pool of thioesters; (2) polymerisation of protoenzymes; (3) generation of high-energy phosphate esters; (4) generation of pyrophosphate, a primordial energy carrier; (5) thioester-based organic synthesis reactions; (6) formation of high-energy adenylate derivatives; (7) production of ATP; (8) generation of acyl-RNA complexes (e.g. amino-charged tRNA); (9) peptide formation[29]

The Molecular Clues to the Origin of Life on Earth

• Molecules of living organisms are rich in **hydrogen-containing carbon** compounds that are highly reduced. This suggests that there was little or no free molecular oxygen on early Earth.

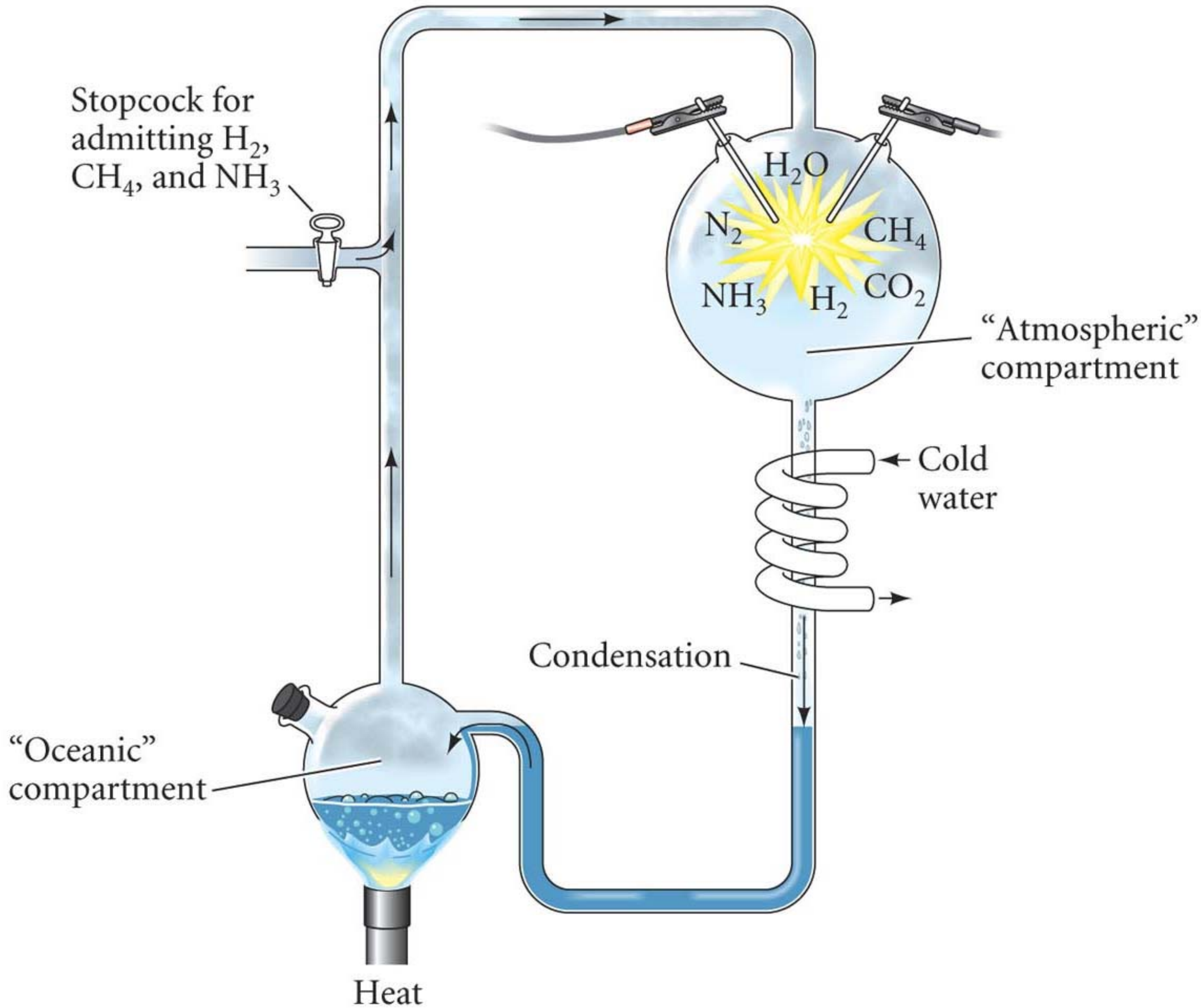
• All **amino acids** exist in both the right-handed and left-handed state. However, only 20 amino acids of the left-handed variety are used by living organisms in proteins. Therefore, suggesting there was a single origin of life.

• **DNA** & **RNA** are the universal informational basis of all life forms on Earth.

• **ATP** is the universal energy currency of all living organisms; suggesting a common origin of metabolism.

• In any cell, first steps of carbohydrate metabolism involve **fermentation**, with the last steps in aerobic organisms the usage of oxygen via **respiration** – suggesting that aerobic organisms evolved from anaerobic ones.

The apparatus Miller et al. (1950s) used to simulate the conditions of early Earth

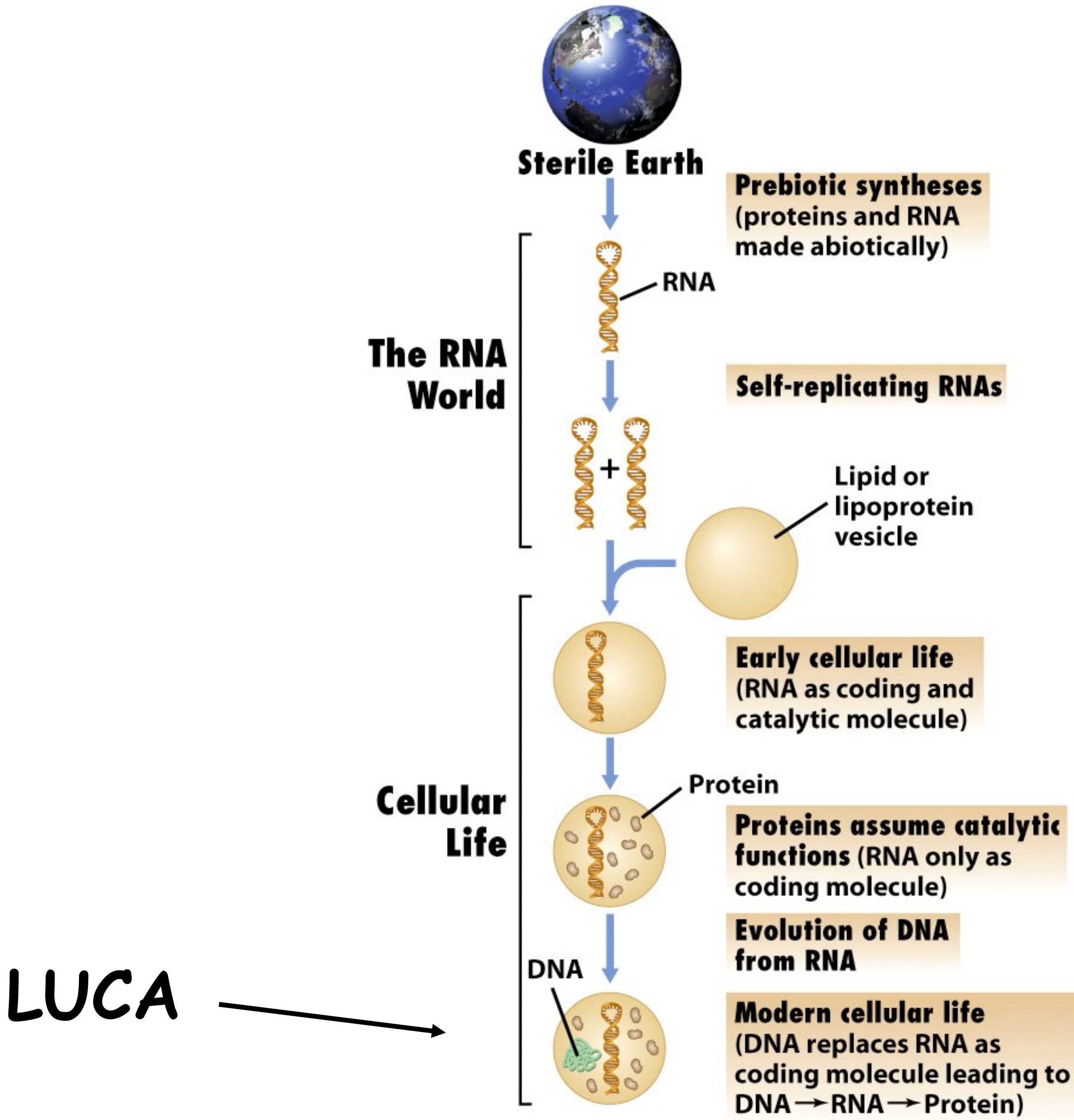


Necessary Conditions for the Origin of Life

- Before life appeared, polymerization reactions generated the carbohydrates, lipids, amino acids, and nucleic acids of which organisms are composed. These molecules accumulated in the oceans.

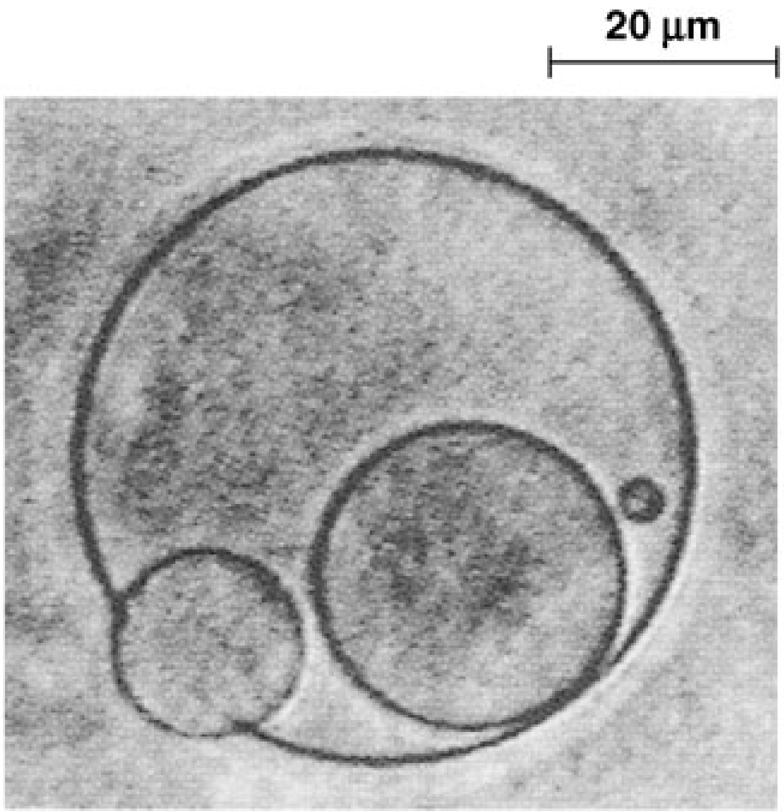
- Originally "Darwin's Warm Pond" Hypothesis

A painting of early Earth showing volcanic activity and photosynthetic prokaryotes in dense mats

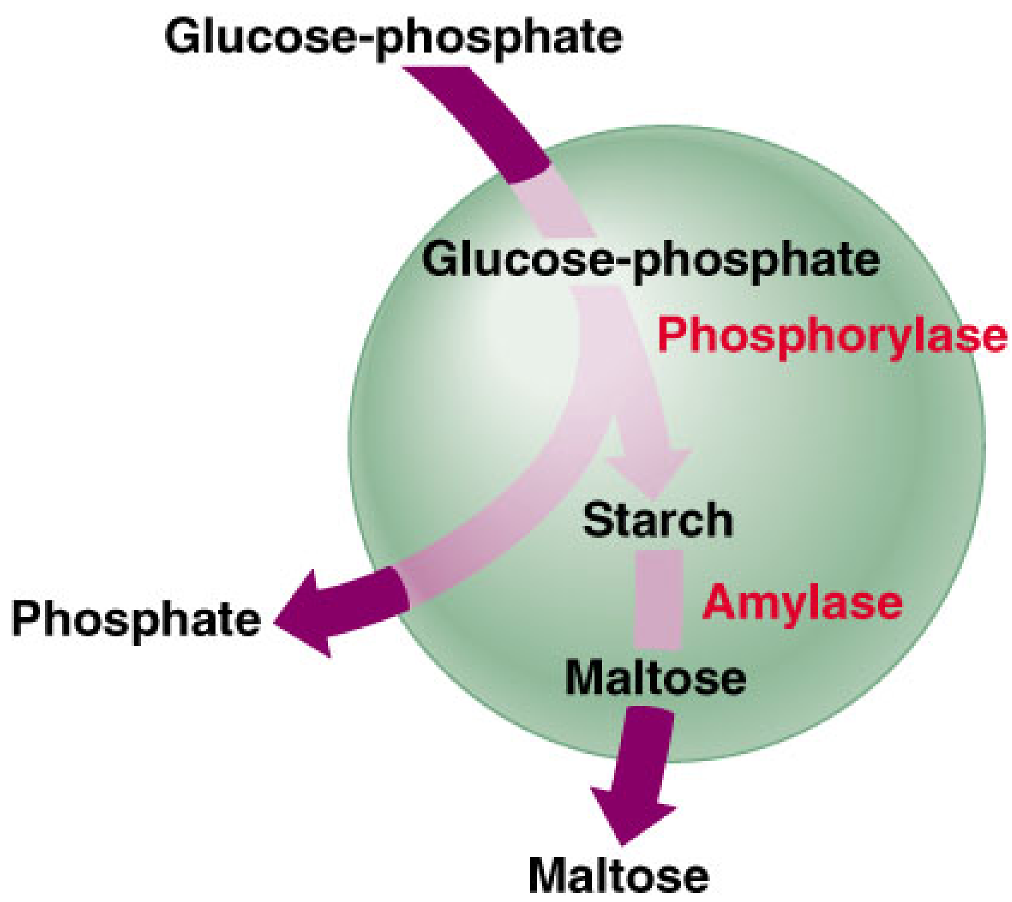


Sterile Earth
Prebiotic syntheses
(proteins and RNA
made abiotically)
RNA
The RNA
World
Self-replicating RNAs
Lipid or
lipoprotein
vesicle
Early cellular life
(RNA as coding and
catalytic molecule)
Protein
Cellular
Life
Proteins assume catalytic
functions (RNA only as
coding molecule)
Evolution of DNA
from RNA
DNA
Modern cellular life
(DNA replaces RNA as
coding molecule leading to
DNA → RNA → Protein)
LUCA

Laboratory versions of protobionts



(a) Simple reproduction

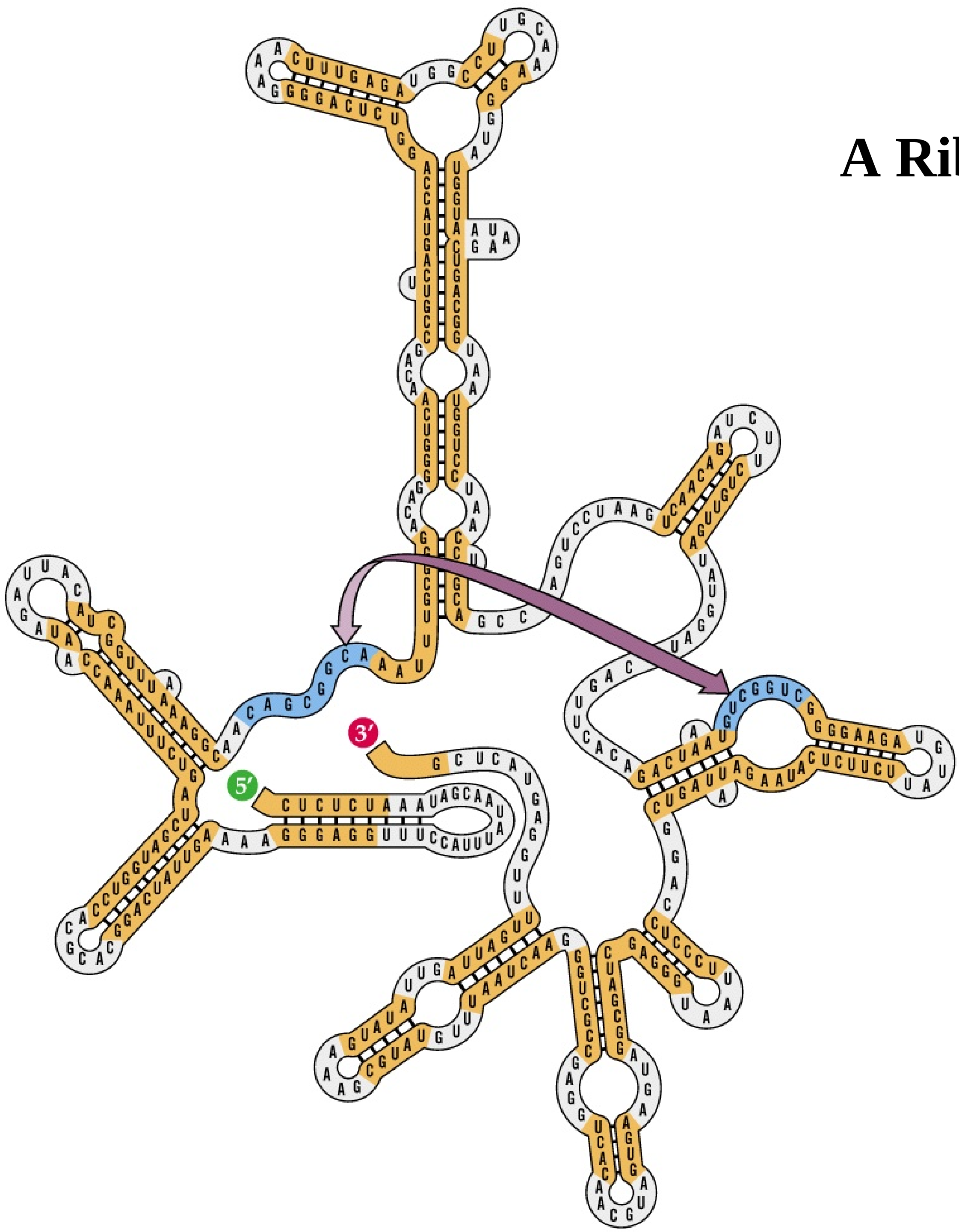


(b) Simple metabolism

Putative "Metabolism" of a Coacervate Drop

Protobionts: Enclosing Prebiotic Systems

- DNA probably evolved after RNA-based life became surrounded by membranes that provided an environment in which DNA was stable.



A Ribozyme from a Protist

Folding brings together complementary but distant base sequences allowing catalytic activity to occur

RNA World: Peptide Bond Formation

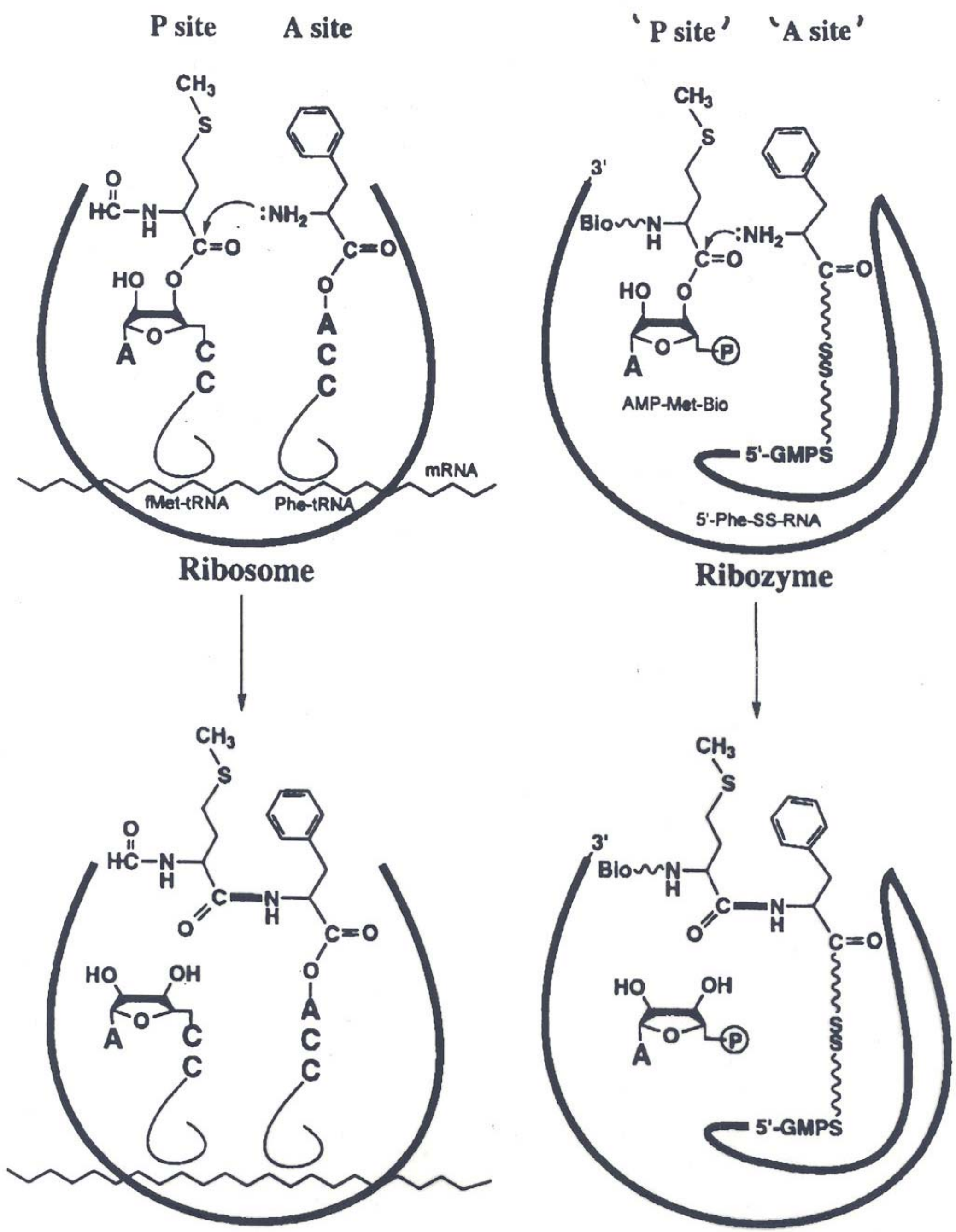
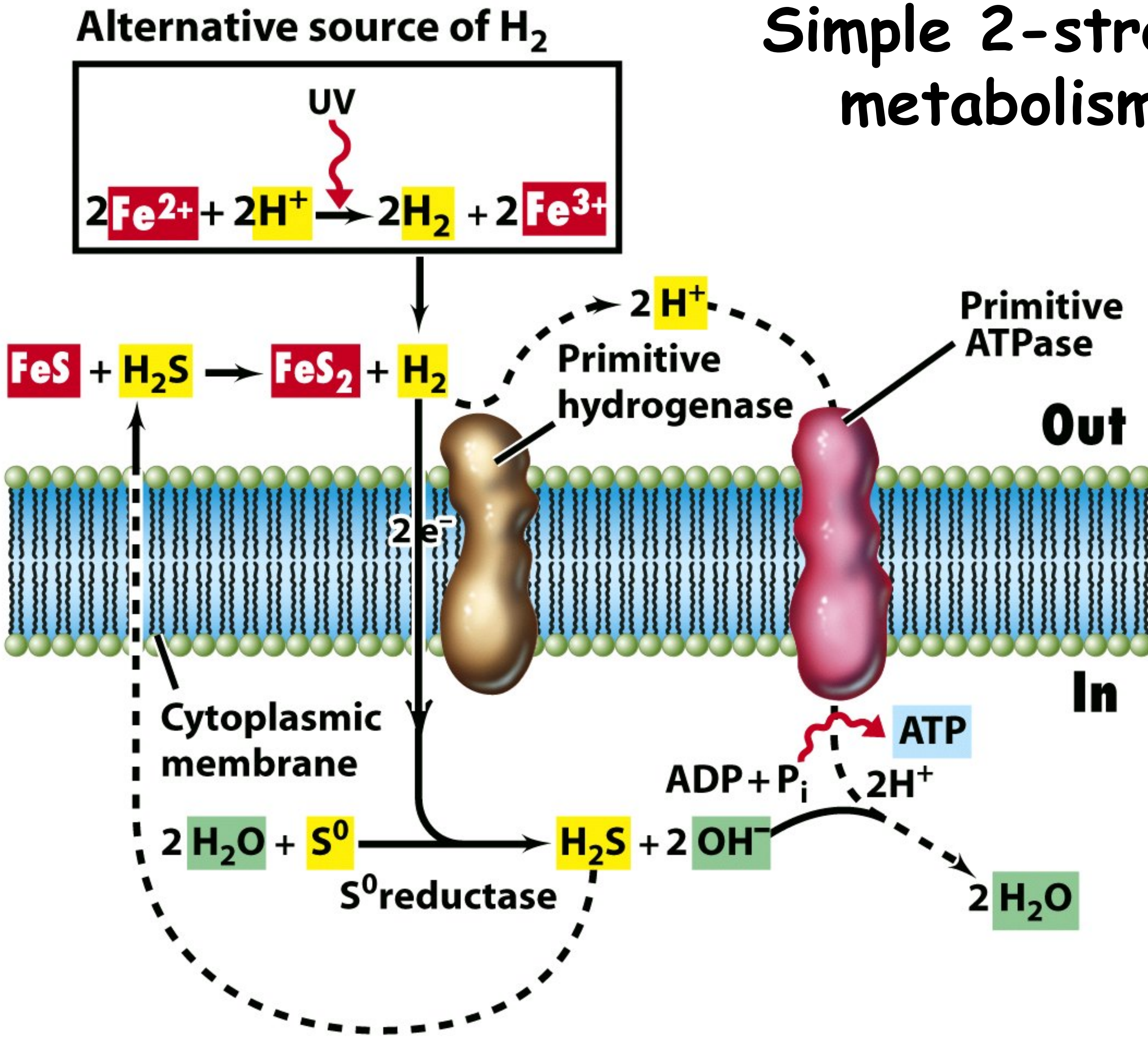


Figure 1 Peptide bond formation by a ribosome (left) and by a ribozyme (right).

Simple 2-stroke metabolism



Chemotrophy
or
Phototrophy???

Hydrogenase
or
Rhodopsin???

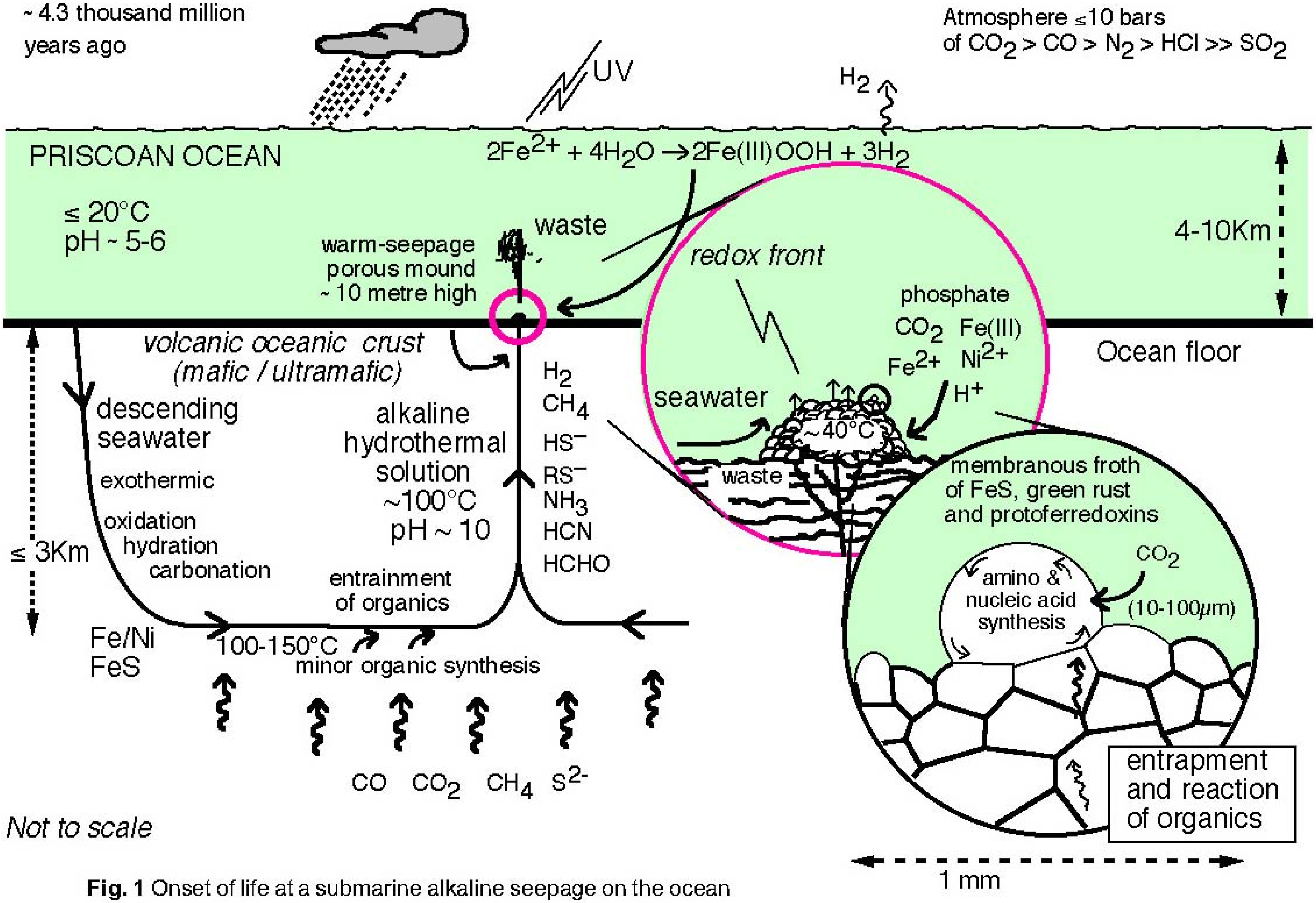


Fig. 1 Onset of life at a submarine alkaline seepage on the ocean floor (Russell et al. 2002).

Rocky roots of the Acetyl-CoA Pathway: CO_2 from volcanoes & H_2 from vents

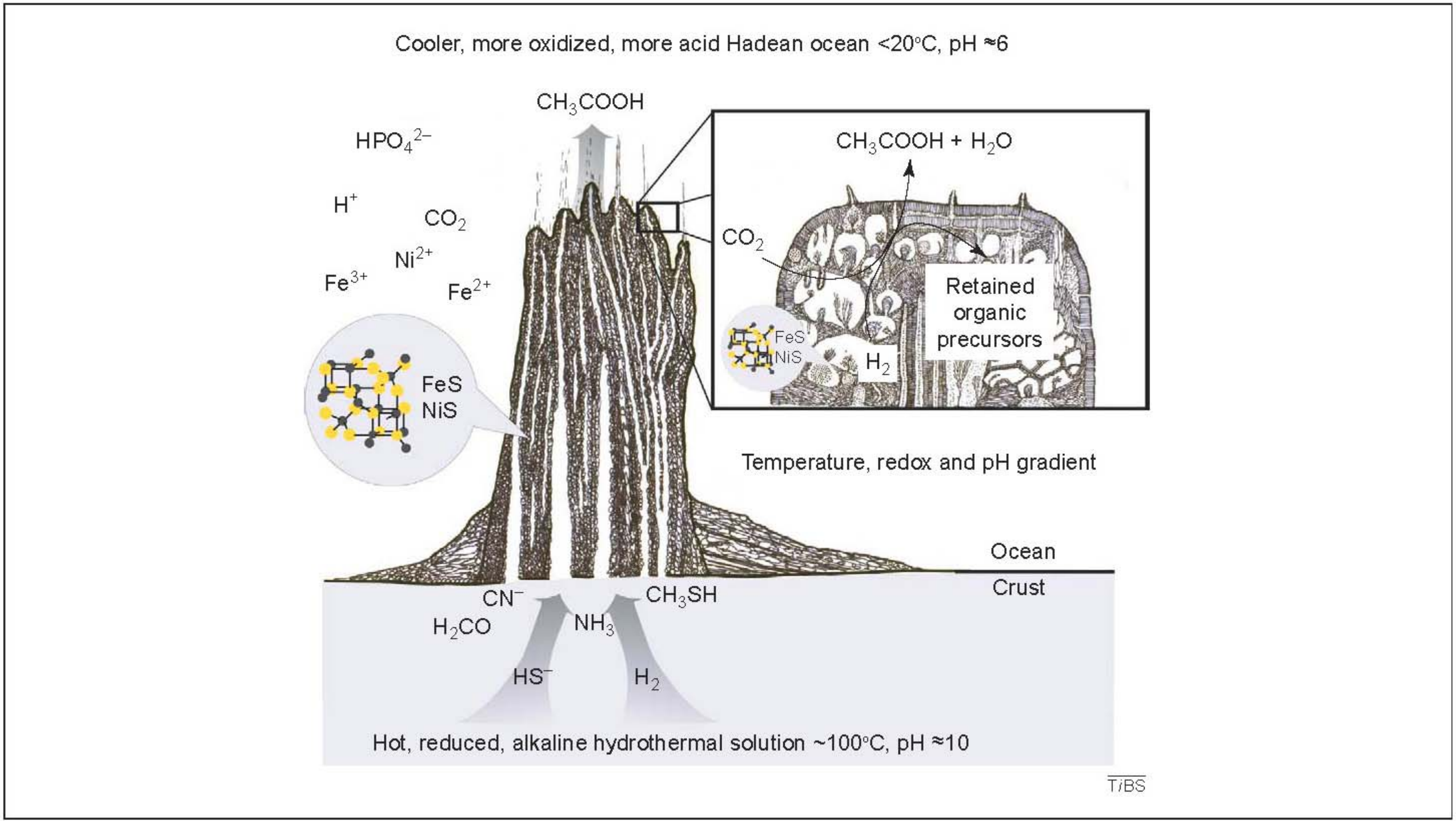
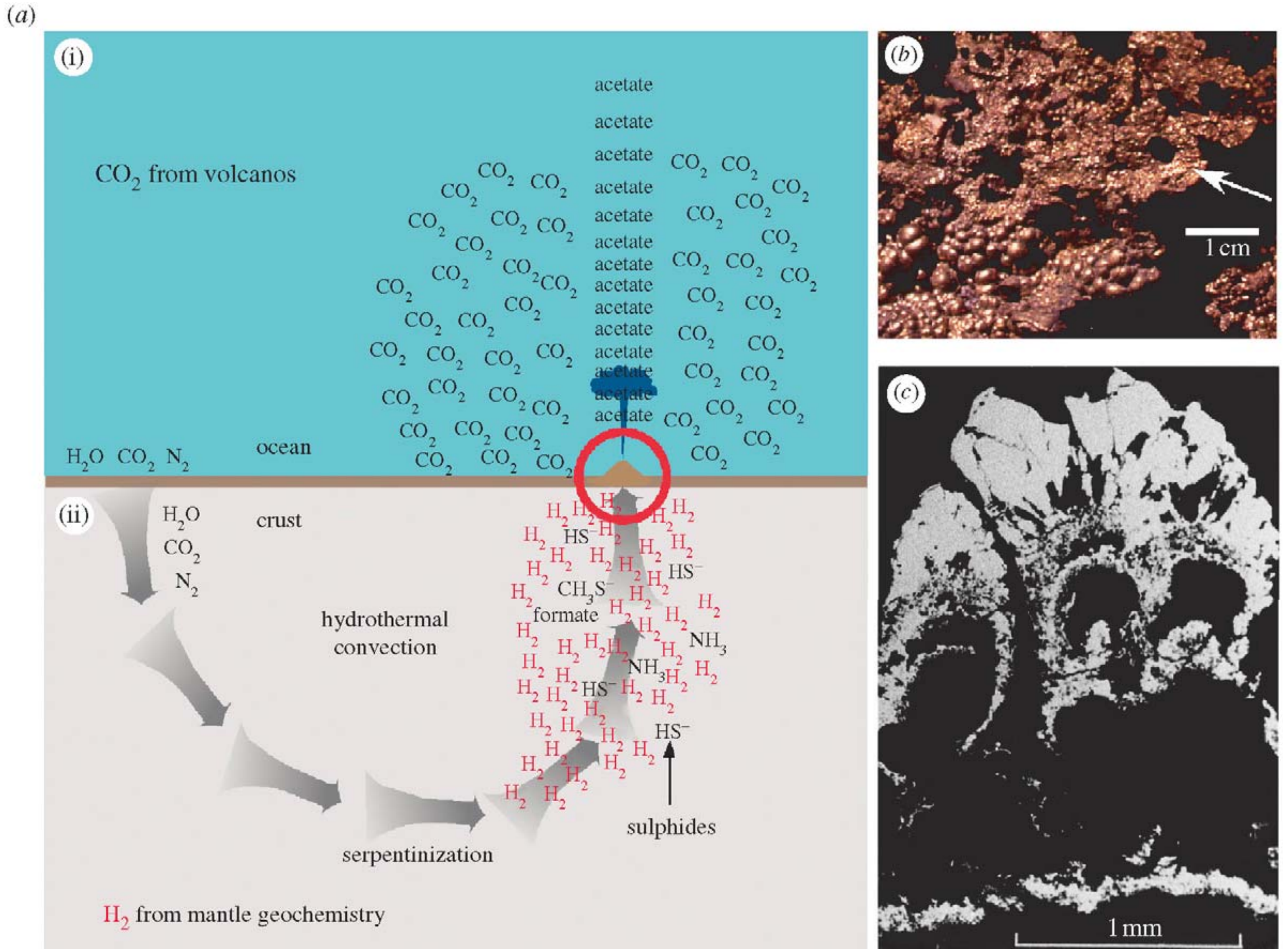


Figure 3. The kind of natural hydrothermal reactor developed at an alkaline submarine spring, proposed here to be the geological hatchery of life. Gradients in temperature (110 to 20 °C), pH (10 to 6) and redox (−600 mV to +100 mV) are steepest at the mound's exterior. The mound comprises carbonates, clays, iron oxyhydroxides and sulphides. Ionized and polar organic molecules are synthesized, concentrated, and ordered in the reactor [10,11]. Waste heat, water, unionized and nonpolar organic products, and much of the acetate are exhaled through self-forming chimneys. Inset shows an enlargement of one of the vents.

(Russell and Martin, 2004)



(Russell and Martin, 2006)

Cutting Loose

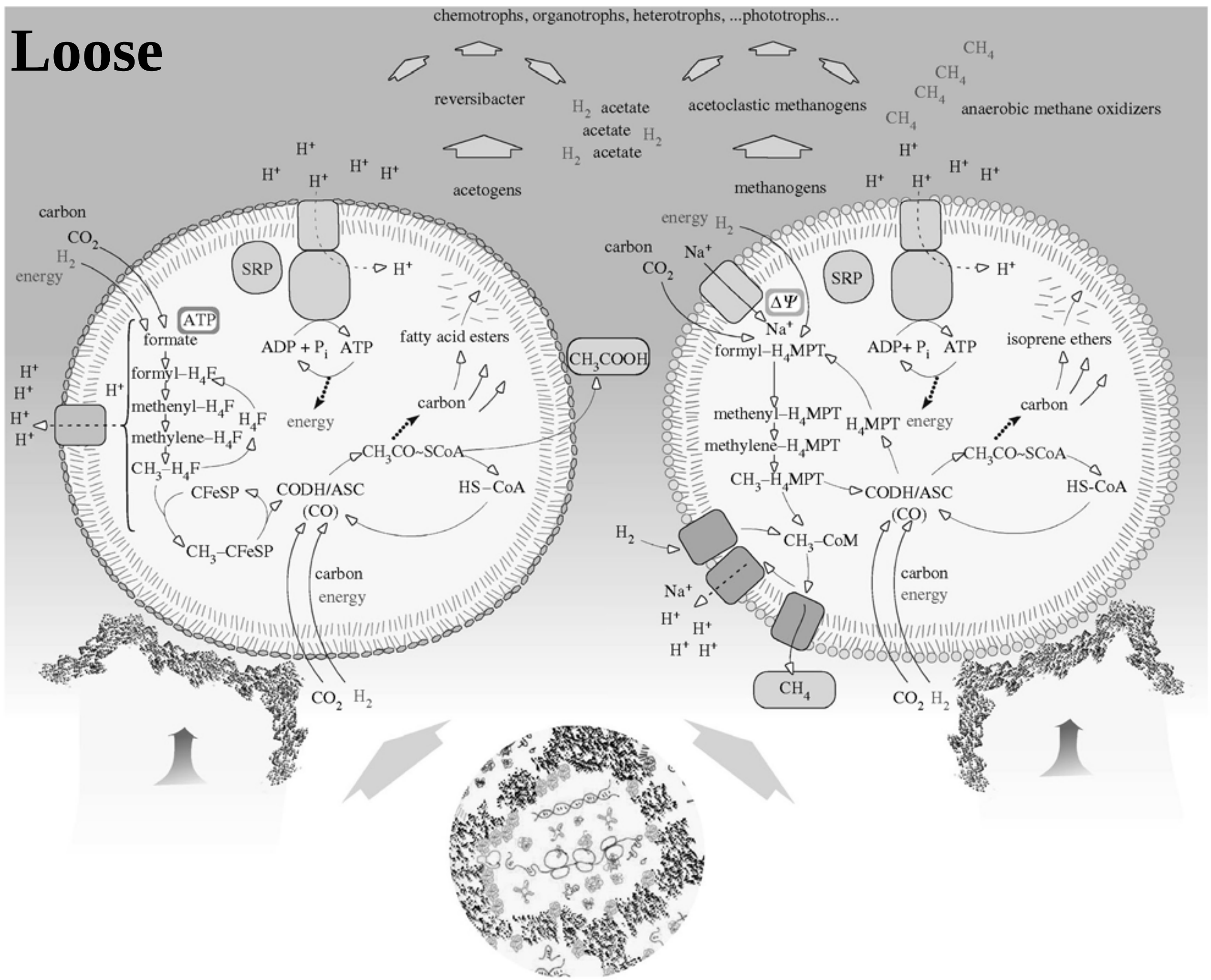
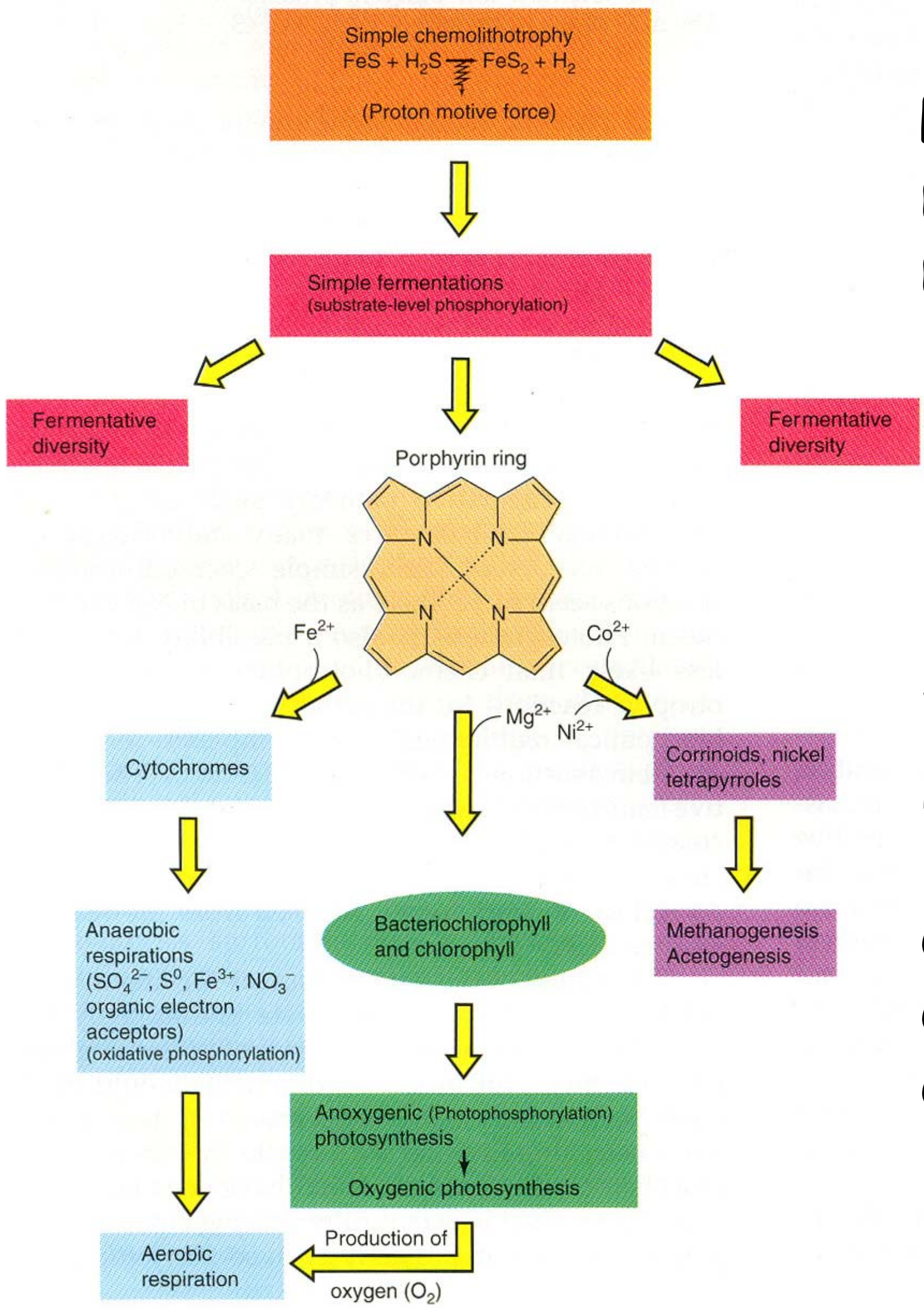


Figure 11. Cutting loose. Escape from the vent was only possible when genetically encoded lipid synthesis and cell wall synthesis had been achieved, and when autogenous formyl pterin synthesis as well as *ab initio* ion-pumping mechanisms had been developed for bioenergetic reasons relating to energy conservation efficiency (see text), but in independent lineages of energetically sustainable and genetically replicating ensembles within the network of FeS compartments (see also Russell & Hall 1997; Martin & Russell 2003; Koonin & Martin 2005). The ancestral state of eubacterial physiology would be acetogenesis and that of archaebacterial physiology would be methanogenesis, followed by anaerobic microbial communities (Schink 1997) utilizing H_2, acetate, methane and similar small organic compounds.

(Russell and Martin, 2006)



Porphyrin Ring opens many possibilities for metabolic pathways!!!

Which ones are **Domain specific**?

Cytochromes: Bacteria…
Chlorophyll: Bacteria…
Corrinoids: Archaea only

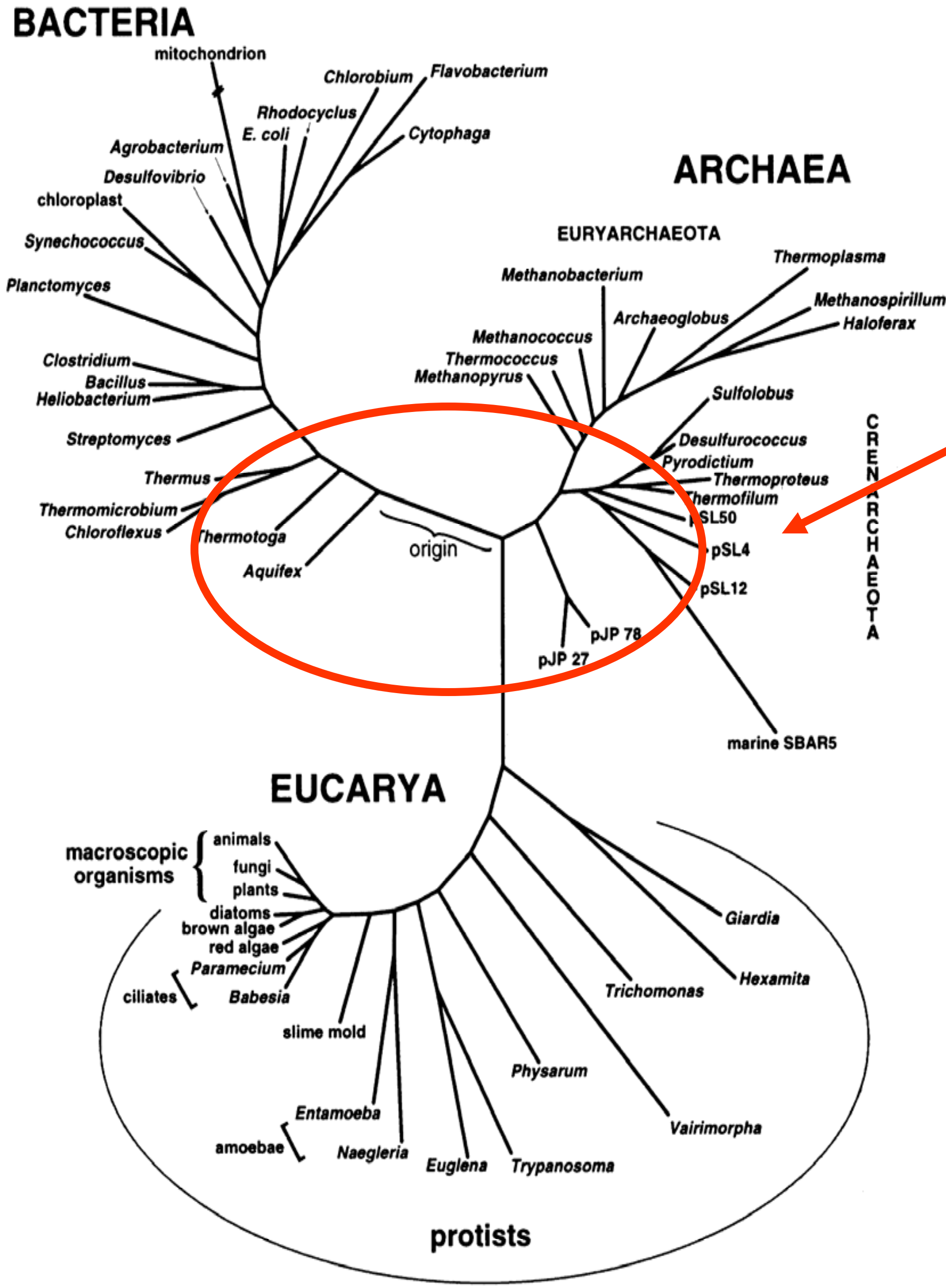


Figure 1. Diagrammatic "Universal" phylogenetic tree of life, based on small-subunit ribosomal RNA sequences. Based on analyses of Barns et al. (1996b), Olsen et al. (1994), and Sogin (1994).

Almost all are Thermophiles!

Hot Start Hypothesis

Some Lessons from the BIG TREE:
Map of the Biological Record

Single origin for all life on Earth...

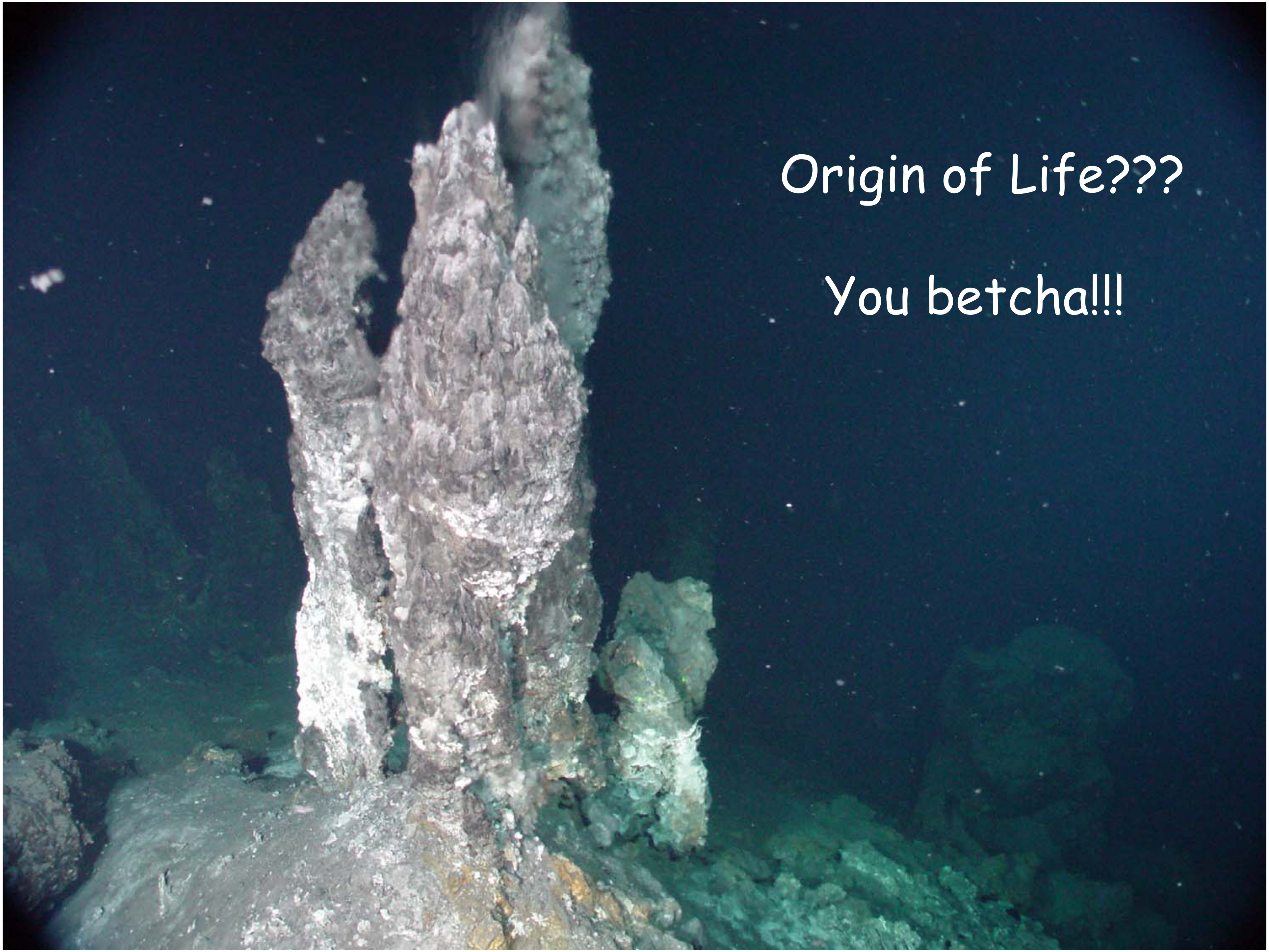
- Central Dogma intact
- ATP and PMF are universal themes
- Uniformity among chiral carbon compds (sugars & AAs)
- Hot start origin…

- Also Cyanobacteria did not arrive first on the scene!

Some Lessons from the BIG TREE:
Map of the Biological Record

General topology implies:

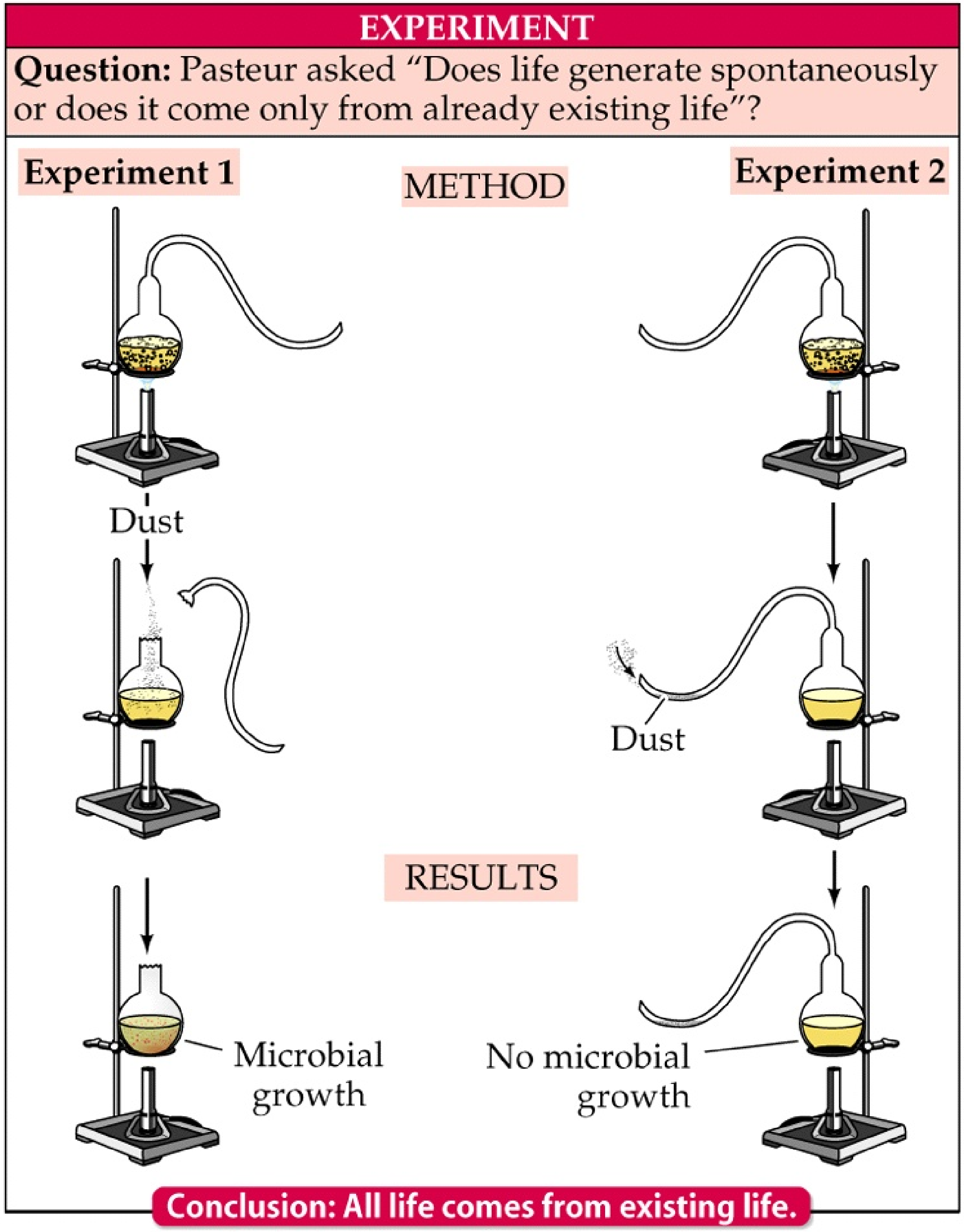
- Three "primary lines of evolutionary descent."
- The Eucarya *"nuclear"* lineage almost as old as the prokaryote lines.
- Prokaryotes split between *Bacteria* and *Archaea*.
- Mitochondria and chloroplasts proven to be of bacterial origin.


Origin of Life???
You betcha!!!

Is Life Evolving from Nonlife Today?

- Because most of the chemical reactions that gave rise to life occur readily under the conditions that prevailed on early Earth, life's evolution was "probably" inevitable.

- Experiments by Louis Pasteur and others convinced scientists that life does not come from nonlife on Earth today…..



Pasteur (1860s) was also the father of "origins of life" research

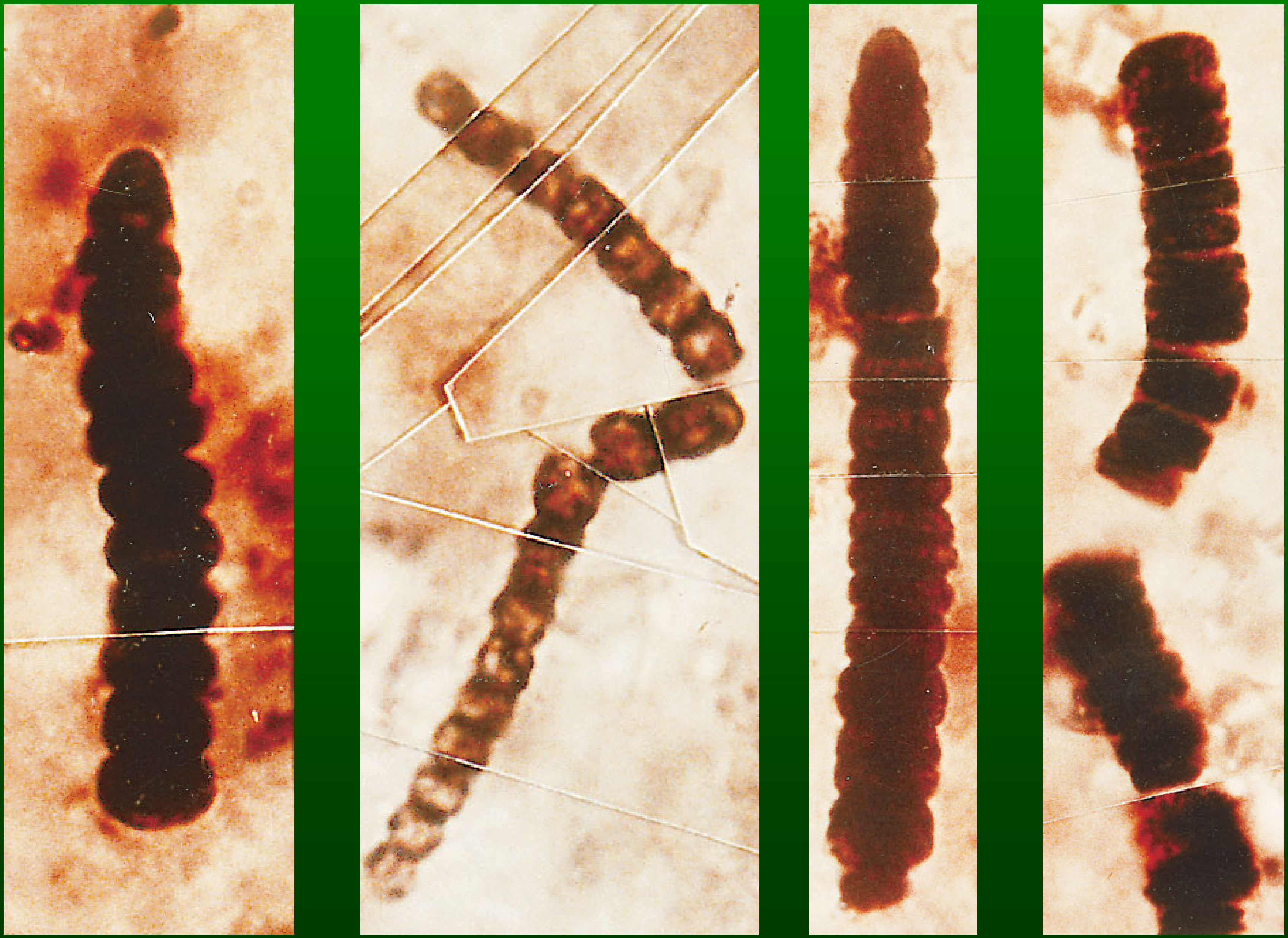
Is Life Evolving from Nonlife Today?

- New life is no longer being assembled from nonliving matter because simple biological molecules that form in today’s environment are oxidized or consumed by existing life.

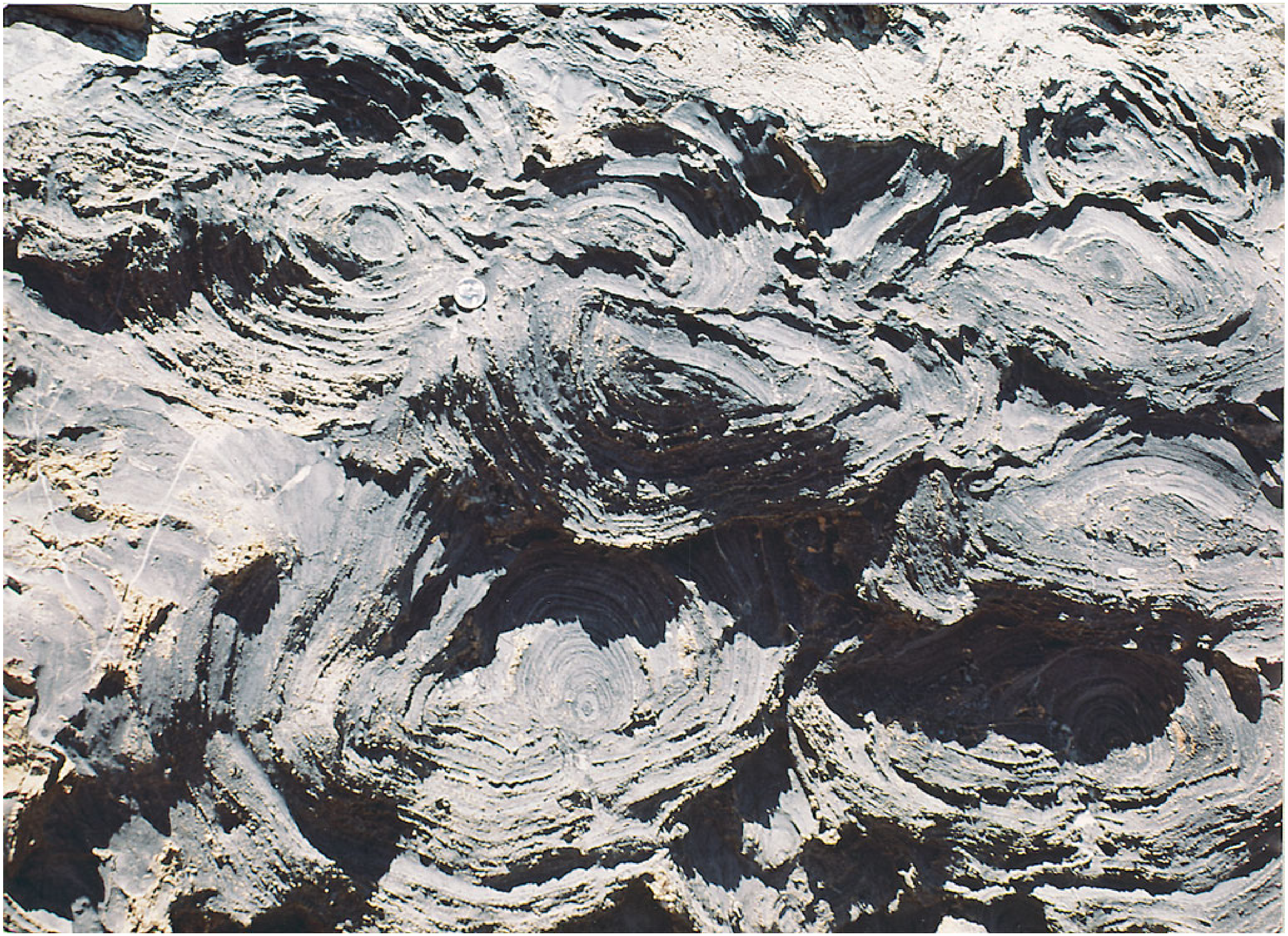
- Now we have competition & oxygen!

- Everywhere……?

Oldest Known Fossils of Living Organisms (~3500 Mya)



Fossil Stromatolites from Glacier Natl. Park



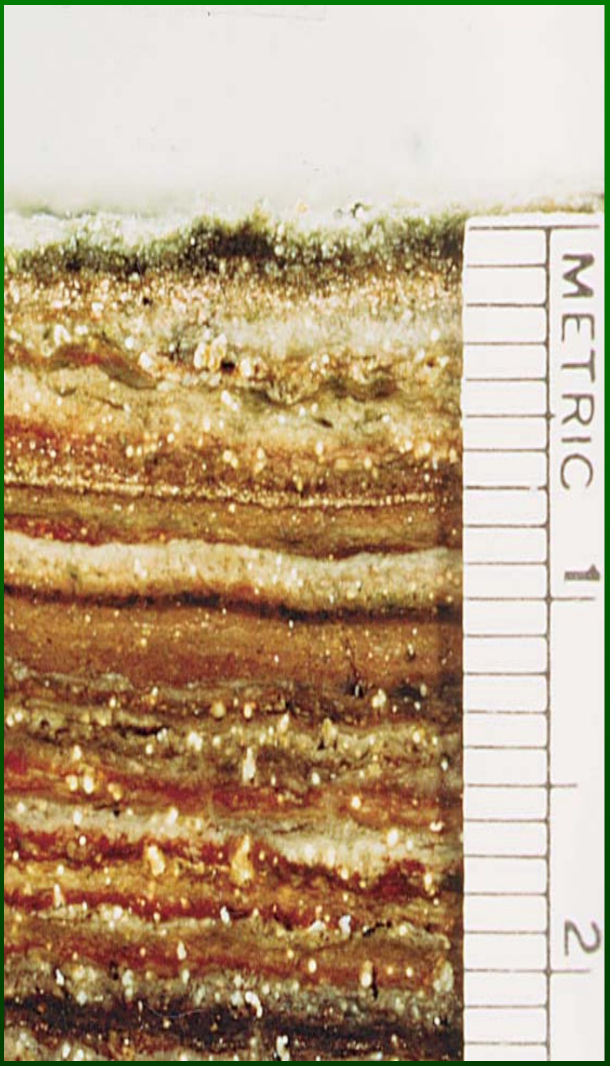
Living Columnar Stromatolites, Shark Bay, Western Australia

Modern Stromatolites from Yellowstone Natl. Park

Photosynthesis Is the Source of Atmospheric O_2

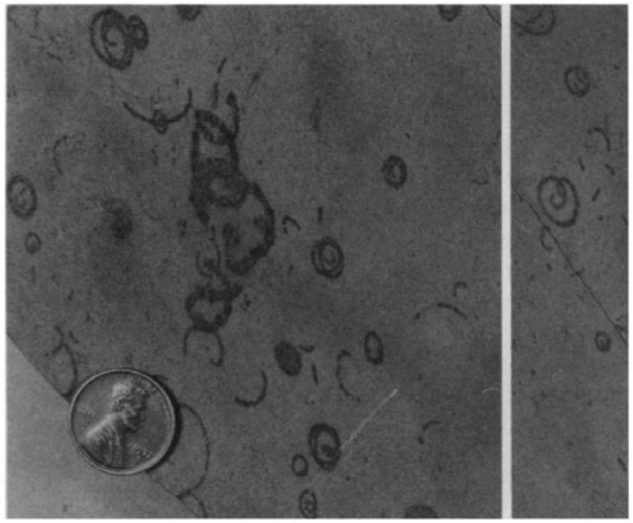
- Cyanobacteria, which evolved the ability to split water into hydrogen ions and O_2, created atmospheric O_2. Accumulation of free O_2 in the atmosphere made possible the evolution of aerobic metabolism.

Extant Microbial Mat Communities



First Eukaryotic Fossil: *Grypania* (~2100 Mya)

Fig. 1. Bed surface of Negaunee Iron-Formation with numerous fragments of *Grypania* and some thicker filaments. Line represents 2-cm-wide strip of unfossiliferous rock; coin is 18.5 mm in diameter.



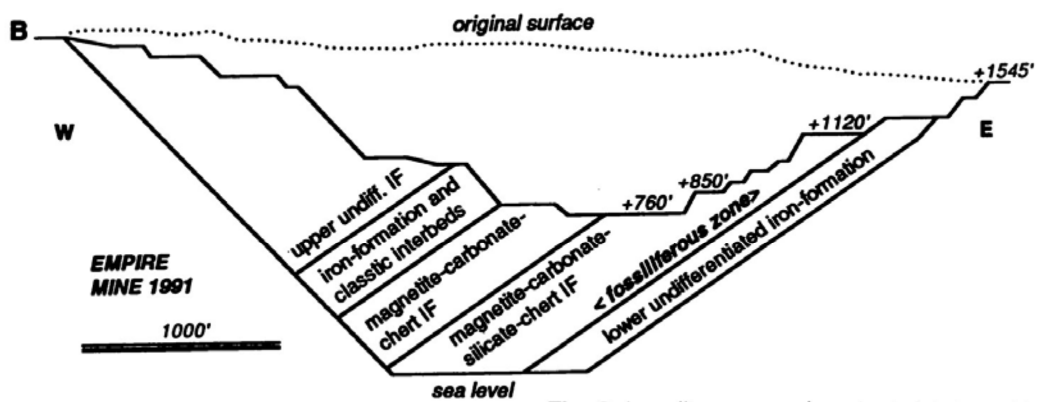
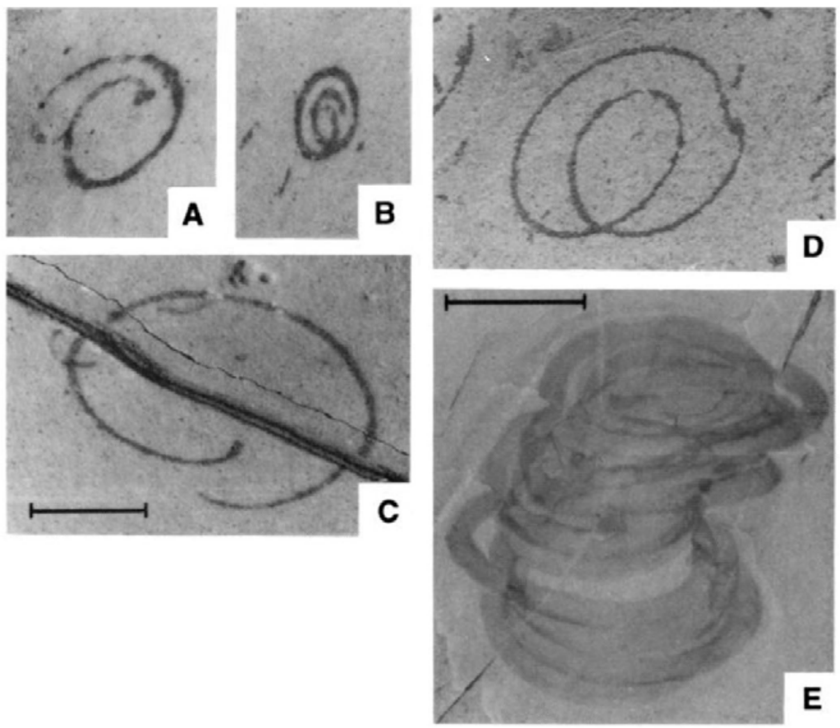


Fig. 2. Locality map and east-west cross section of the Empire Mine showing the 1991 and projected positions of the pit surface.

First Eukaryotic Fossil: *Grypania* (~2100 Mya)

~2.1 Bya

Fig. 3. (**A** to **D**) Specimens of *Grypania* from the Negaunee Iron-Formation, Empire Mine. (**E**) Large specimen of *Grypania spiralis*, about 1100 million years old, Rohtas Formation, Semri Group, Vindhyan Supergroup, central India. Scale bar in (C) (applies to A to D), 1 cm; scale bar in (E), 1 cm.



~1.1 Bya

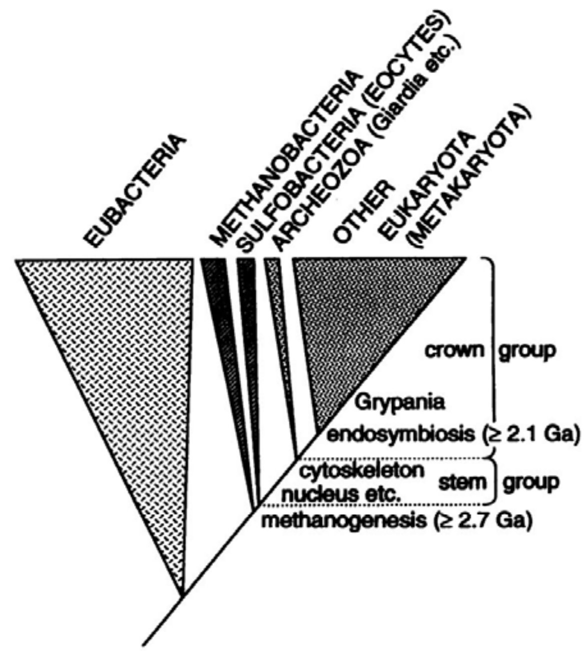
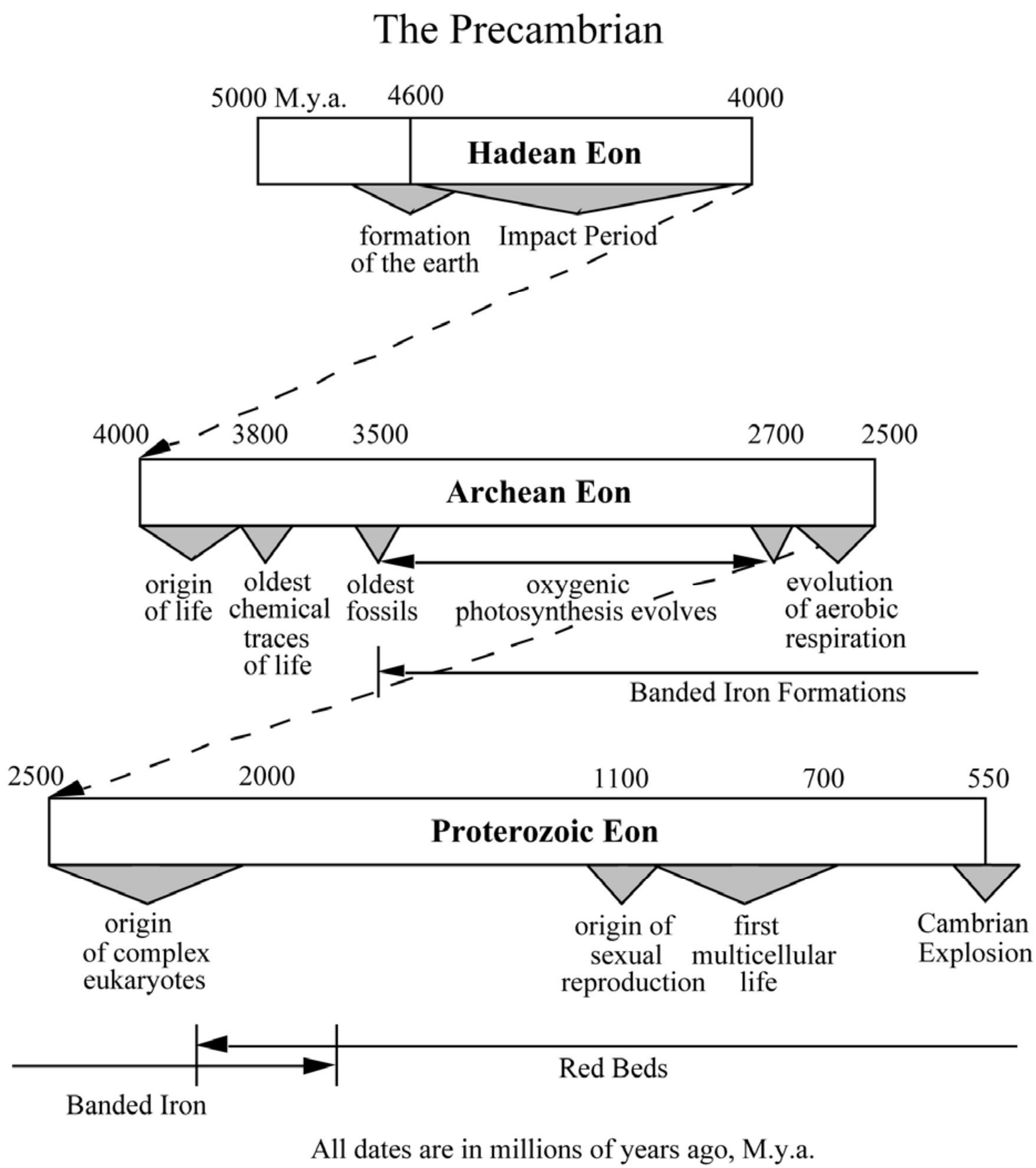


Fig. 5. Cartoon showing the major branches of the universal tree of life and the presumed position of *Grypania* in the tree.


The Precambrian
5000 M.y.a.
4600
4000
Hadean Eon
formation of the earth
Impact Period
4000
3800
3500
2700
2500
Archean Eon
origin of life
oldest chemical traces of life
oldest fossils
oxygenic photosynthesis evolves
evolution of aerobic respiration
Banded Iron Formations
2500
2000
1100
700
550
Proterozoic Eon
origin of complex eukaryotes
origin of sexual reproduction
first multicellular life
Cambrian Explosion
Red Beds
Banded Iron
All dates are in millions of years ago, M.y.a.

Rust the Crust

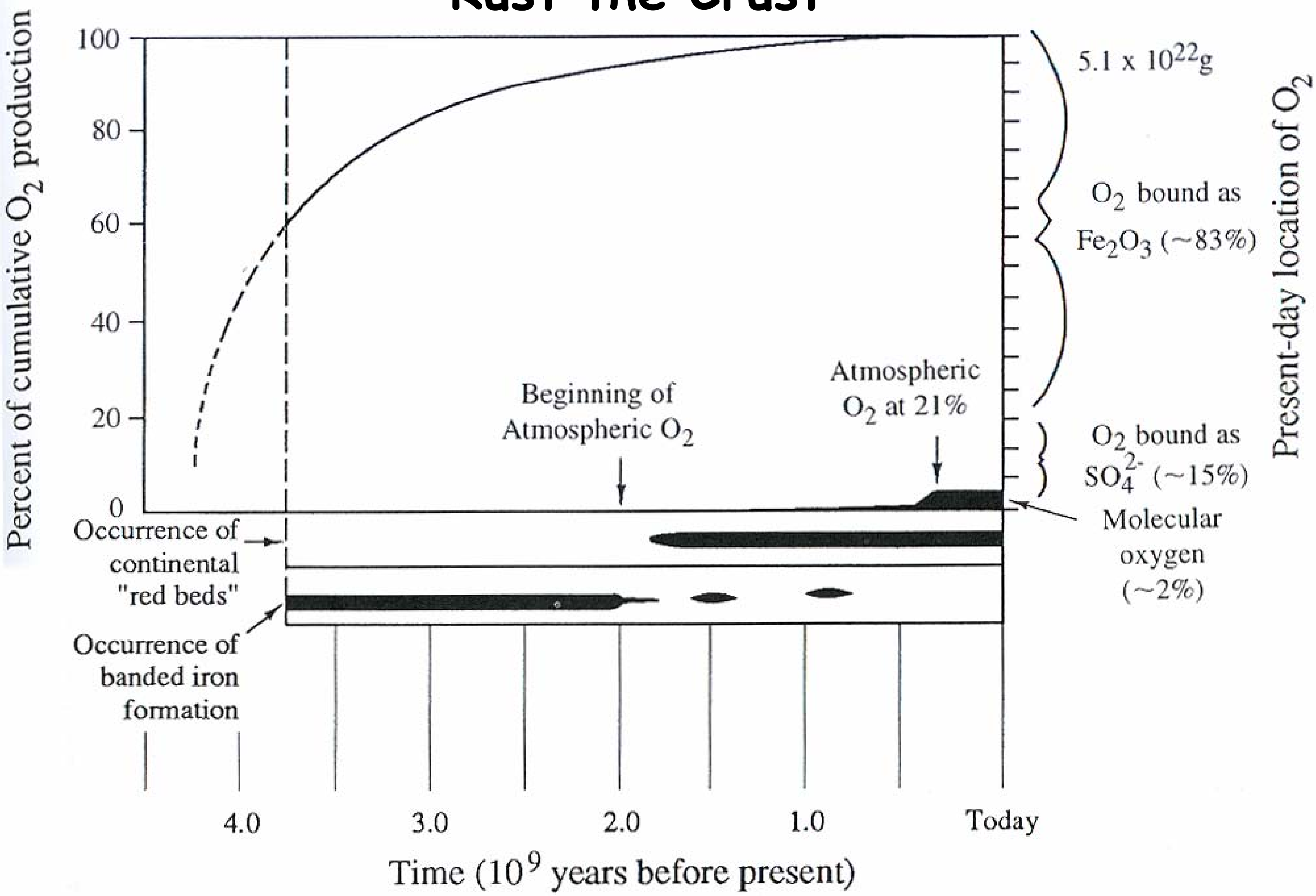
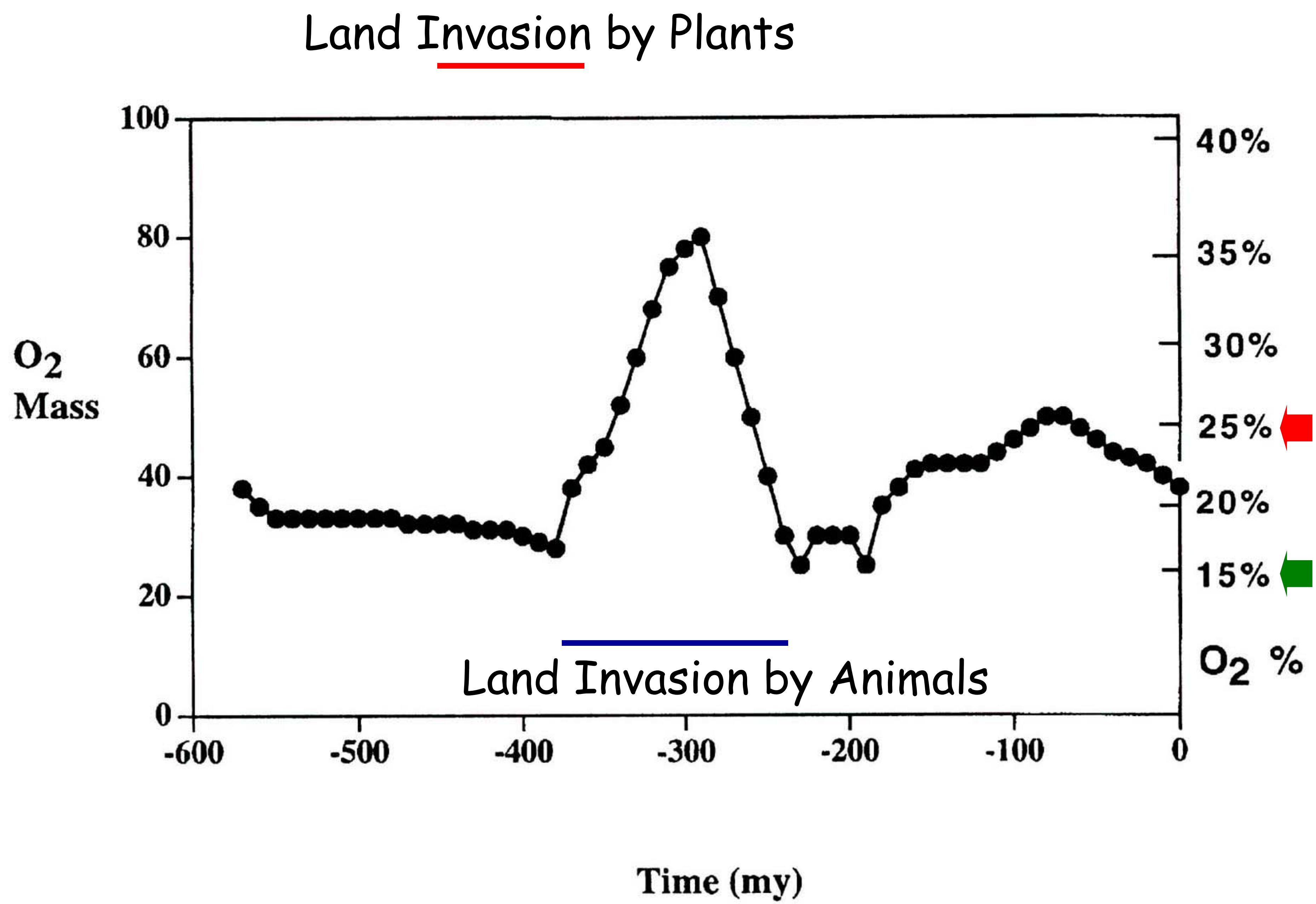


Figure 2.7 Cumulative history of O_2 released by photosynthesis through geologic time. Of more than 5.1×10^{22} g of O_2 released, about 98% is contained in seawater and sedimentary rocks, beginning with the occurrence of Banded Iron Formations at least 3.5 billion years ago (bya). Although O_2 was released to the atmosphere beginning about 2.0 bya, it was consumed in terrestrial weathering processes to form Red Beds, so that the accumulation of O_2 to present levels in the atmosphere was delayed to 400 mya. Modified from Schidlowski (1980).

Banded iron formations are evidence of oxygenic photosynthesis

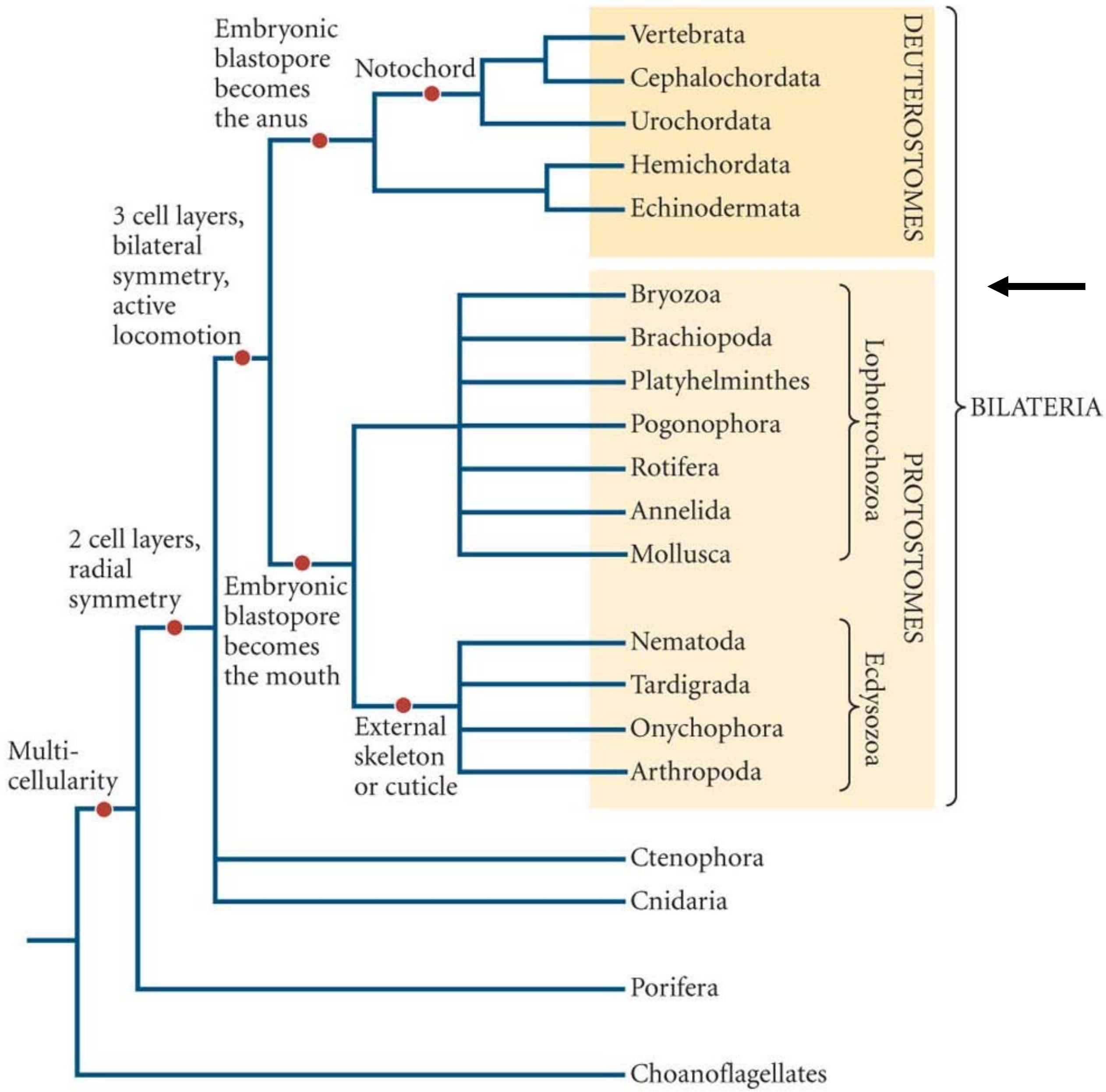


Land Invasion by Plants
100
80
60
40
20
0
O_2 Mass
40%
35%
30%
25%
20%
15%
O_2 %
Land Invasion by Animals
-600
-500
-400
-300
-200
-100
0
Time (my)

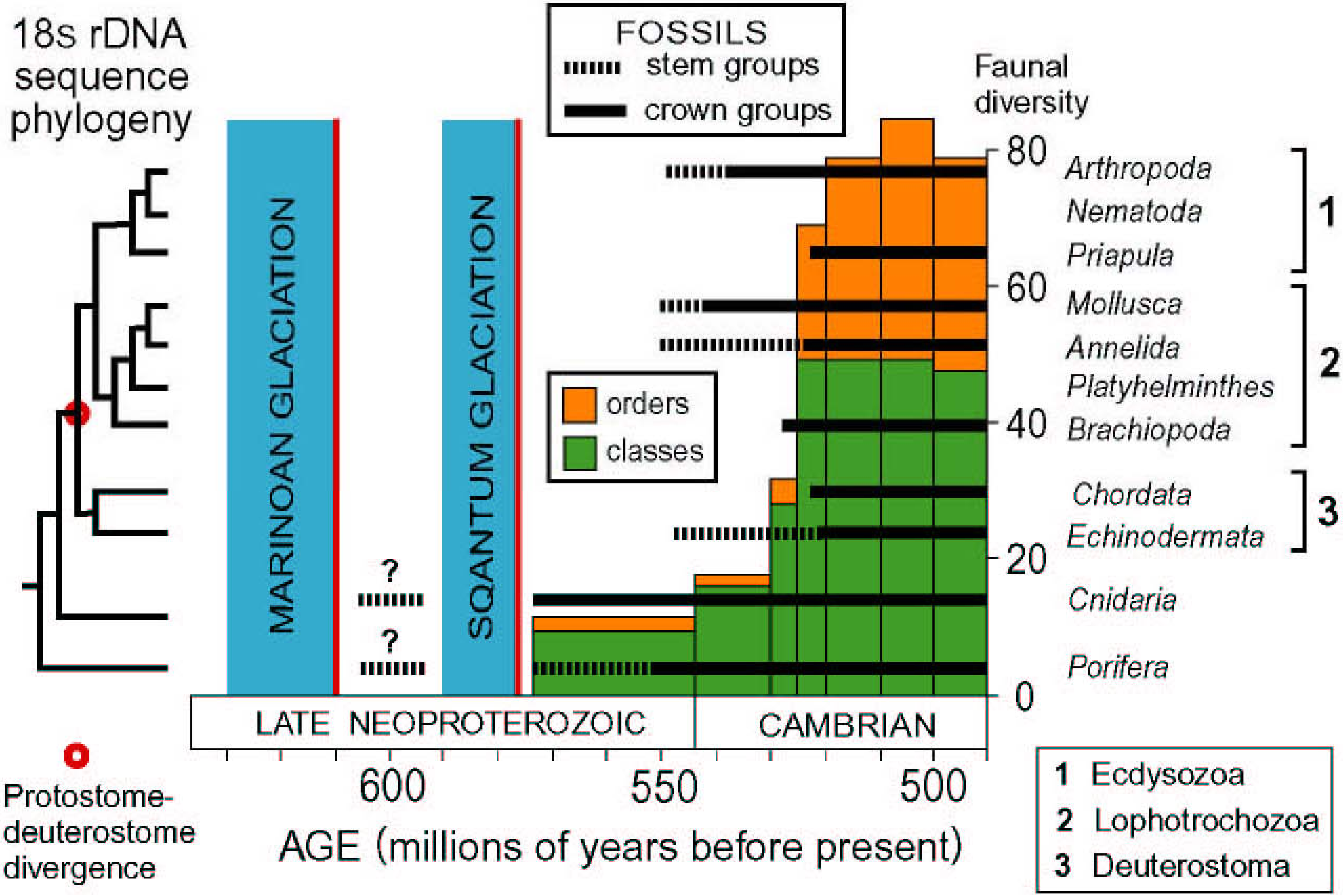
Patterns of Evolutionary Change

- Multicellularity requires atmospheric oxygen and aerobic respiration (i.e., **mitochondria**)!
  - This gave rise to the **Cambrian Explosion**
- The Oxygen "Blip" @ ~300 Mya resulted from the invasion of land by plants!
  - This gave rise to:
    - **Gigantic Insects**
    - **Origin of Flight by Dragonflies**
    - **Invasion of land by Vertebrate Animals**

A recent estimate of relationships among animal phyla

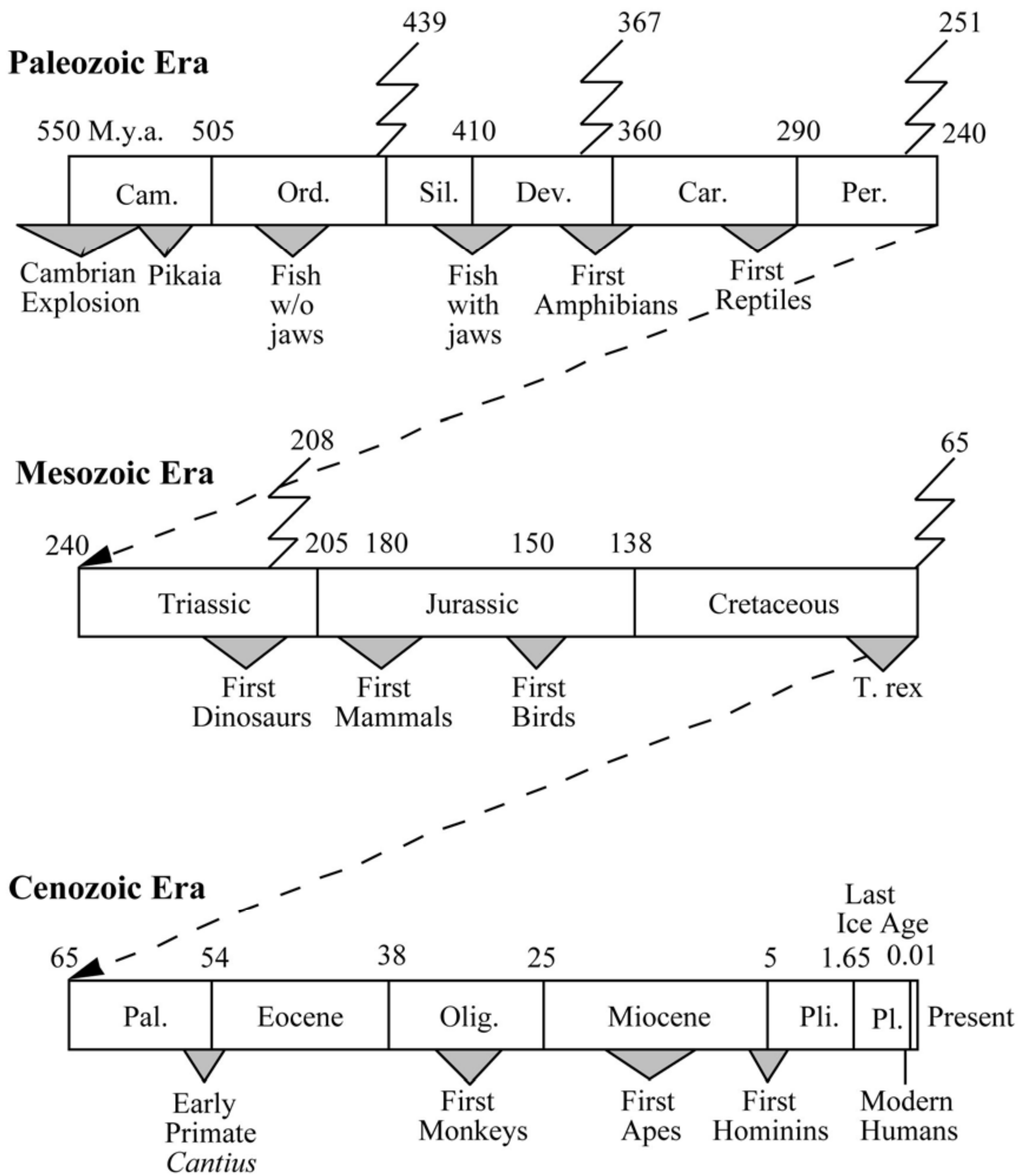


Last One!



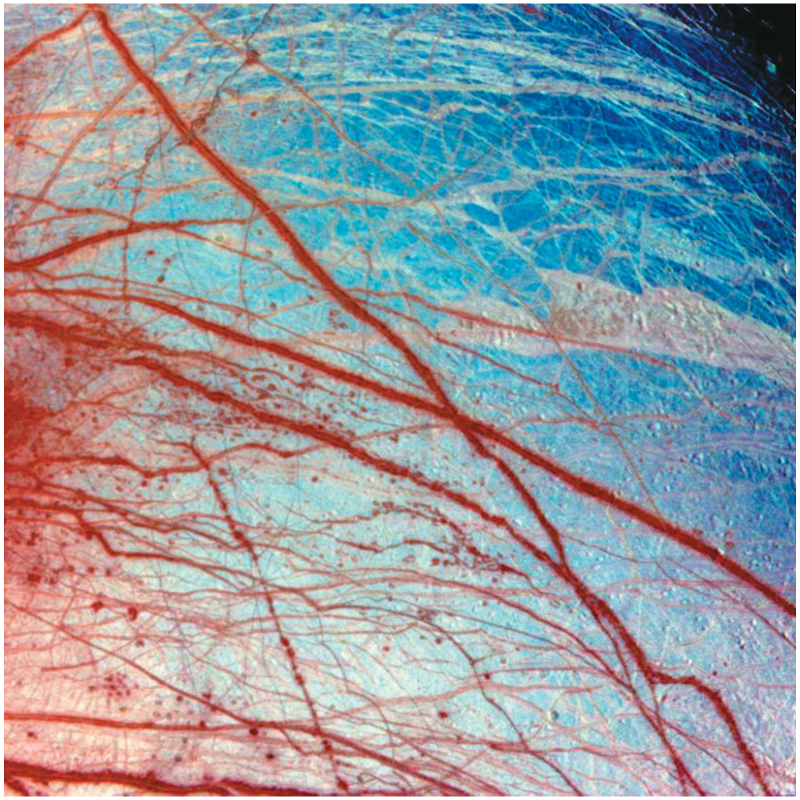
THE METAZOAN EXPLOSION

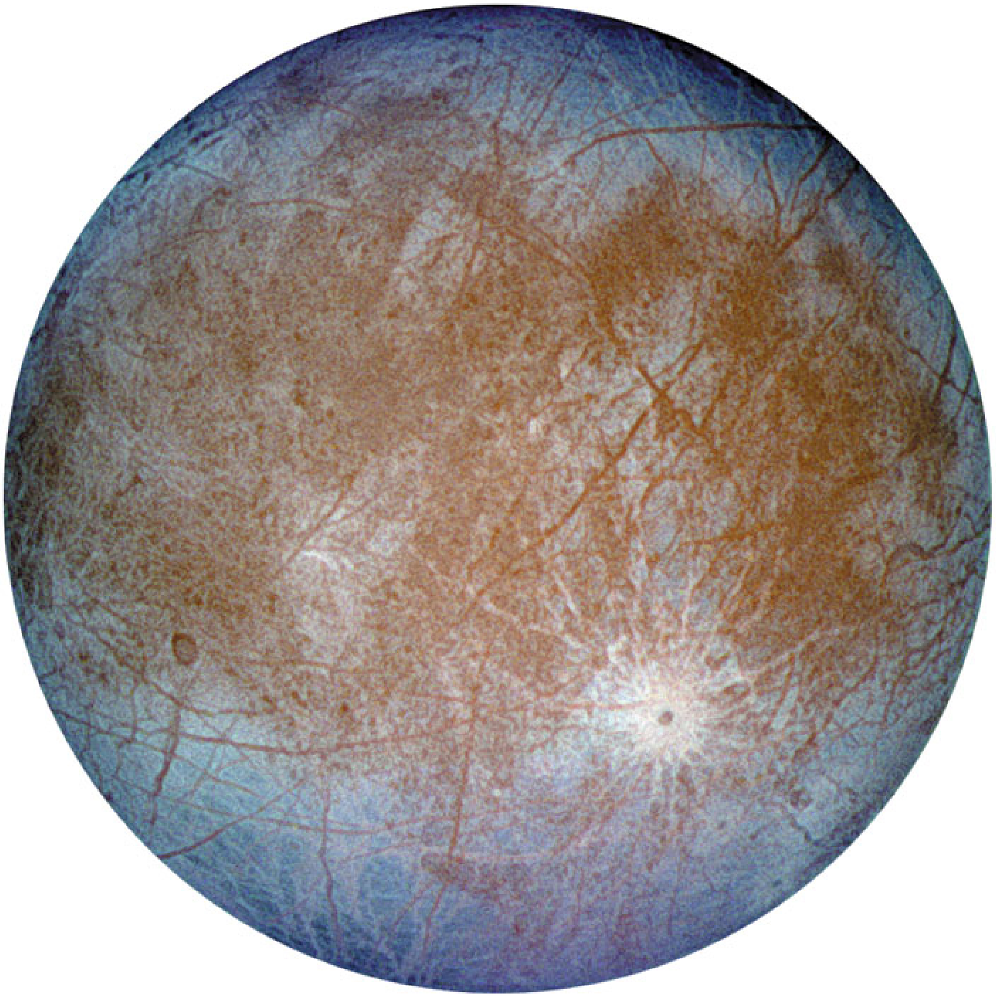
The Phanerozoic Eon



All dates are in millions of years ago, M.y.a.

Europa, Jupiter's moon: Astrobiology???





Does Life Exist Elsewhere in the Universe?

- Conditions that permit the evolution and maintenance of simple bacterial life may be widespread in the universe, but multicellular life has more stringent requirements.
    - a planet with a relatively circular orbit
    - a rapid rate of spin
    - nearby planets that intercept impacts
    - a large moon that stabilizes the planet’s orbit
    - a magnetic field

Such conditions may be very rare.