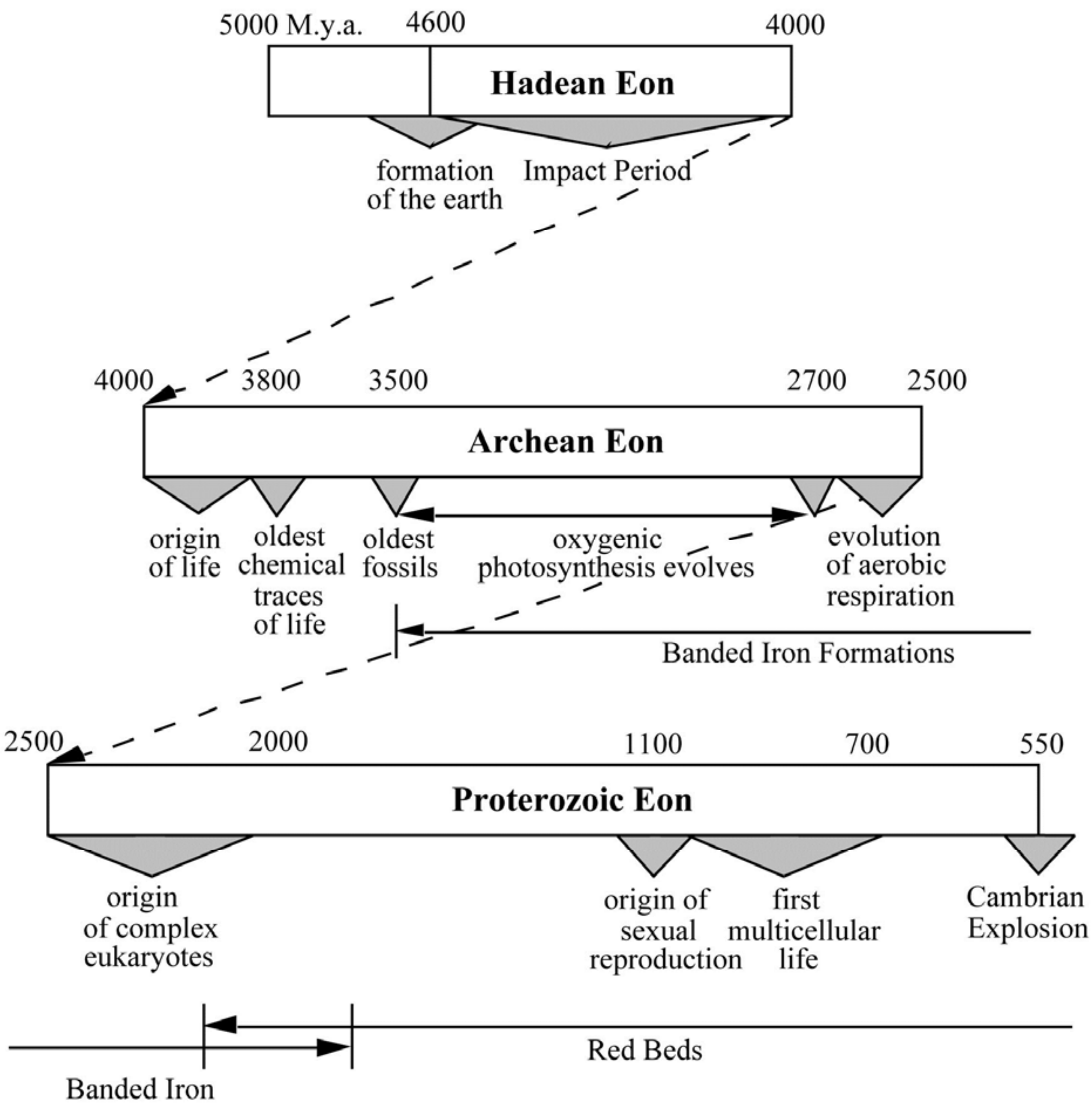
Origins of Life & the Cambrian Explosion

The Precambrian



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

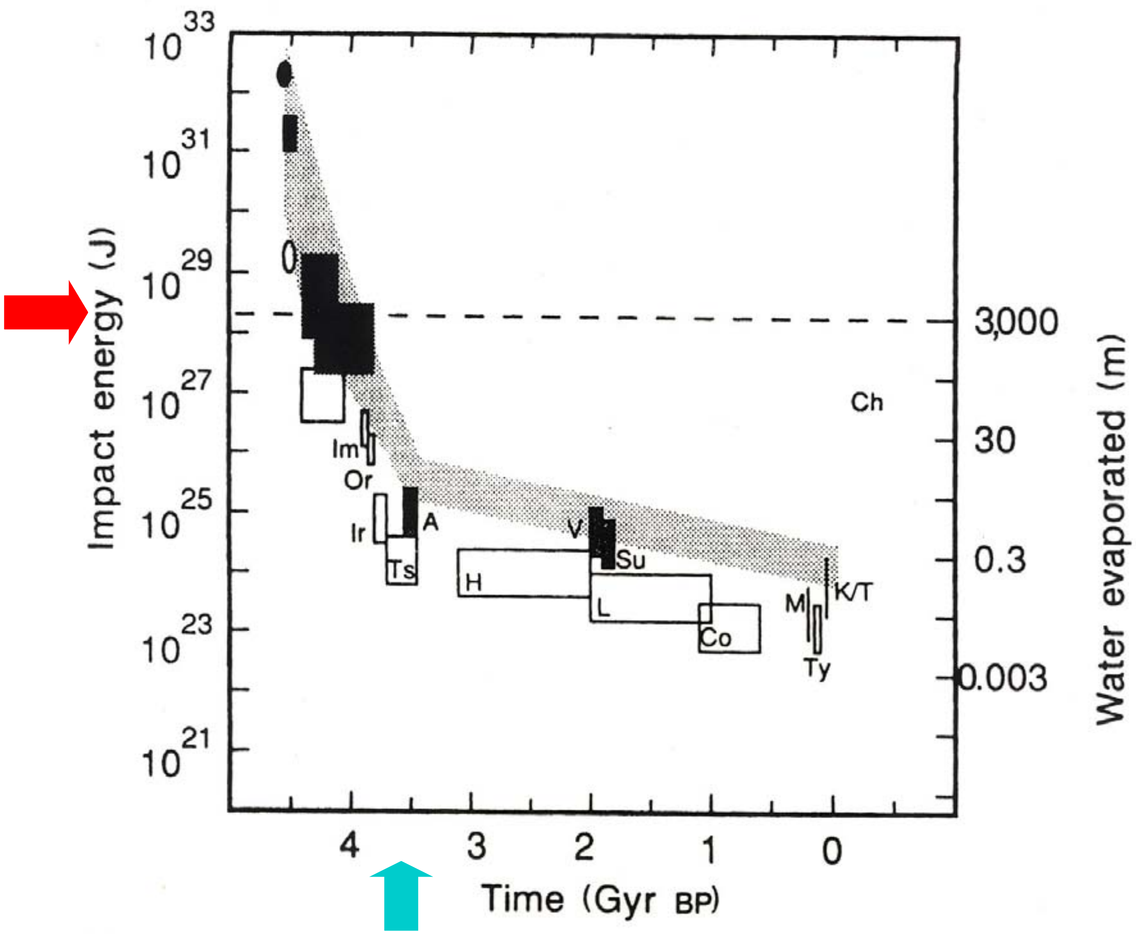
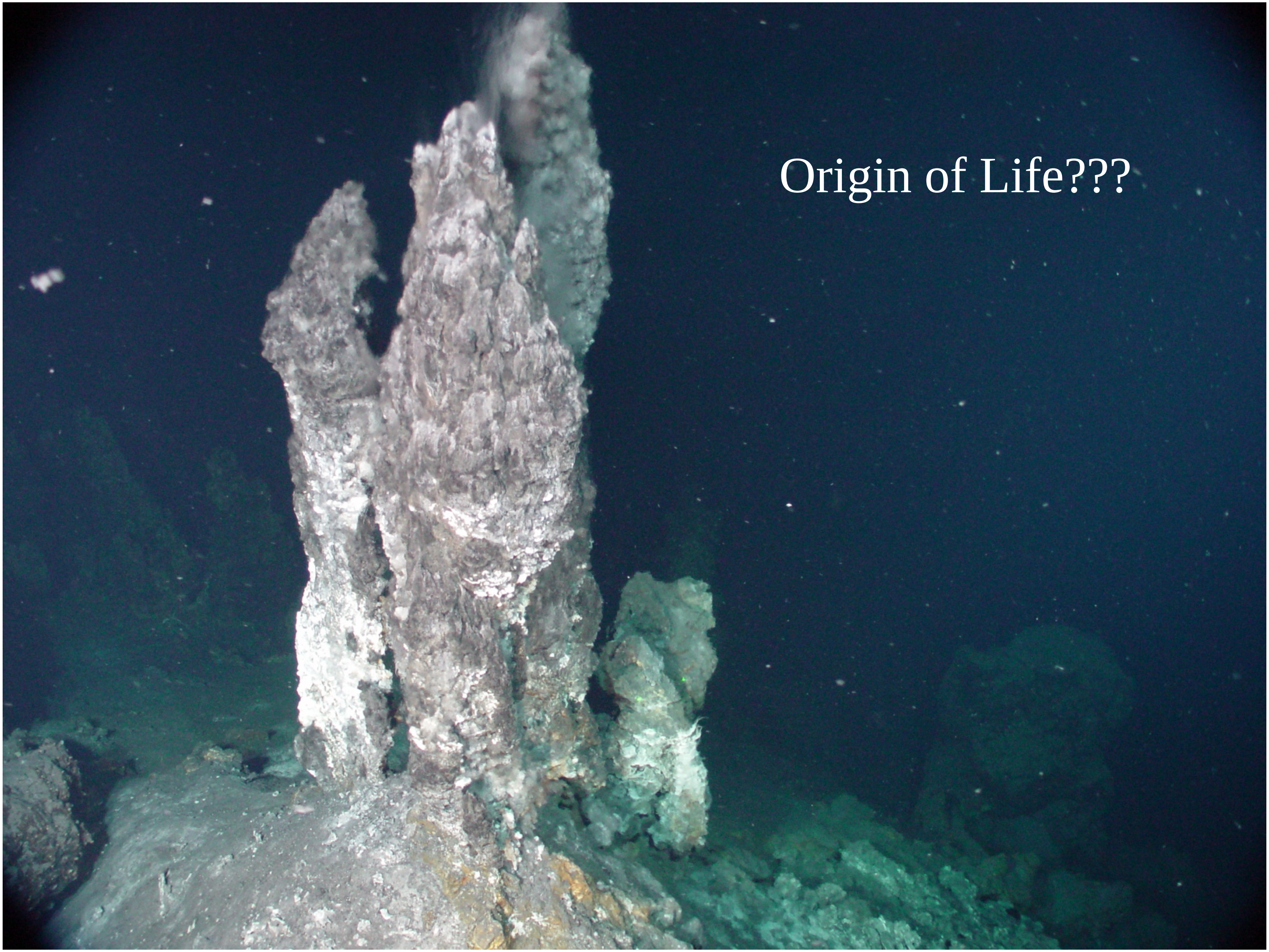


FIG. 1 The largest impacts on Earth and Moon. Open boxes are lunar, filled boxes terrestrial. Lunar craters are Tycho, Copernicus, Langrenus, Hausen, Tsiolkovski, Iridum, Orientale and Imbrium. Terrestrial events are the K/T impact, Manicougan, Sudbury, Vredevort and an impact energy corresponding to 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.


Origin of Life???

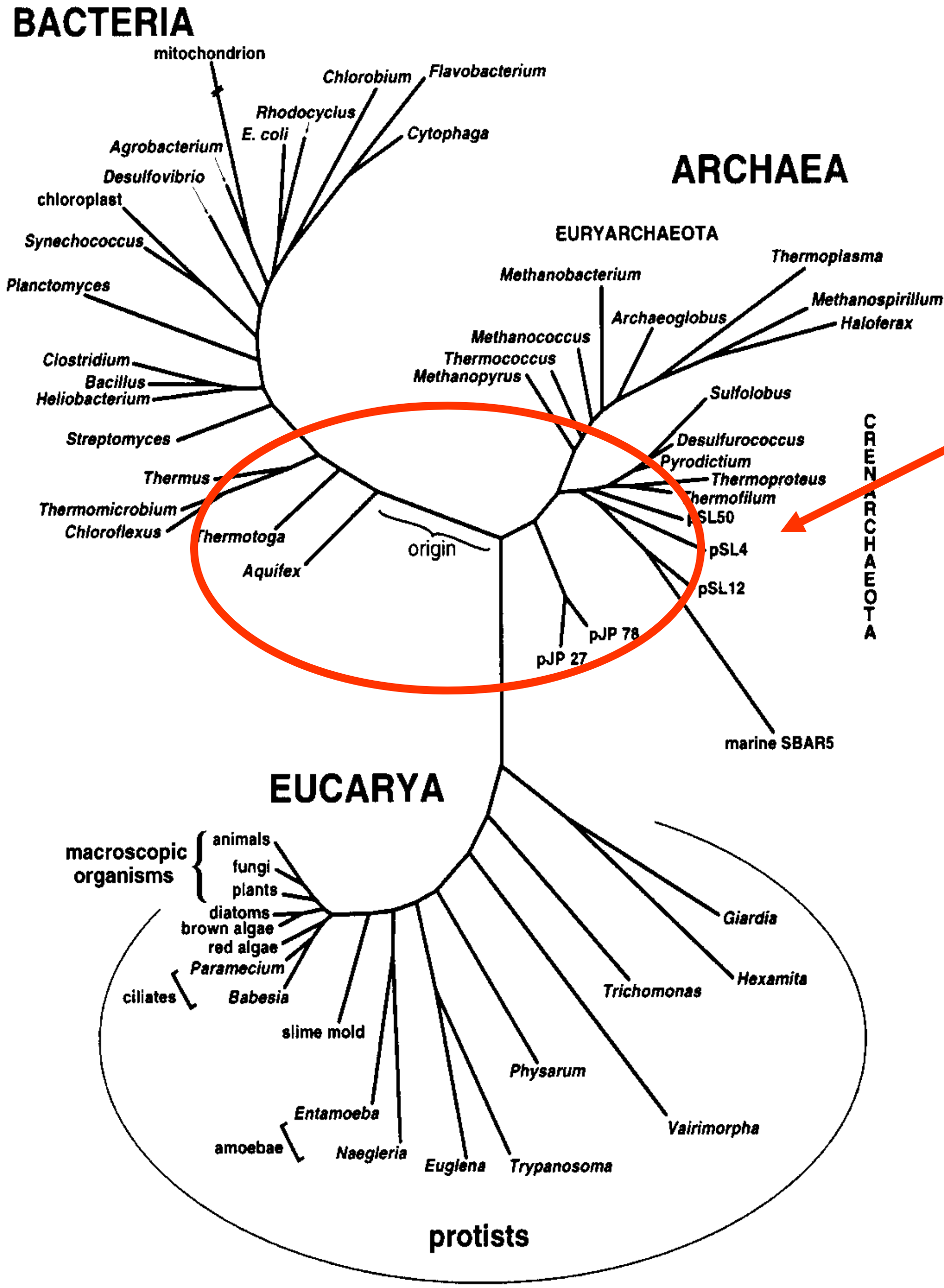


Figure 1. Diagrammatic "Universal" phylogenetic tree of life, based on small-subunit ribosomal RNA sequences. Based on analyses of Barns et al. (1996b), Olsen et al. (1994), and Sogin (1994).

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...

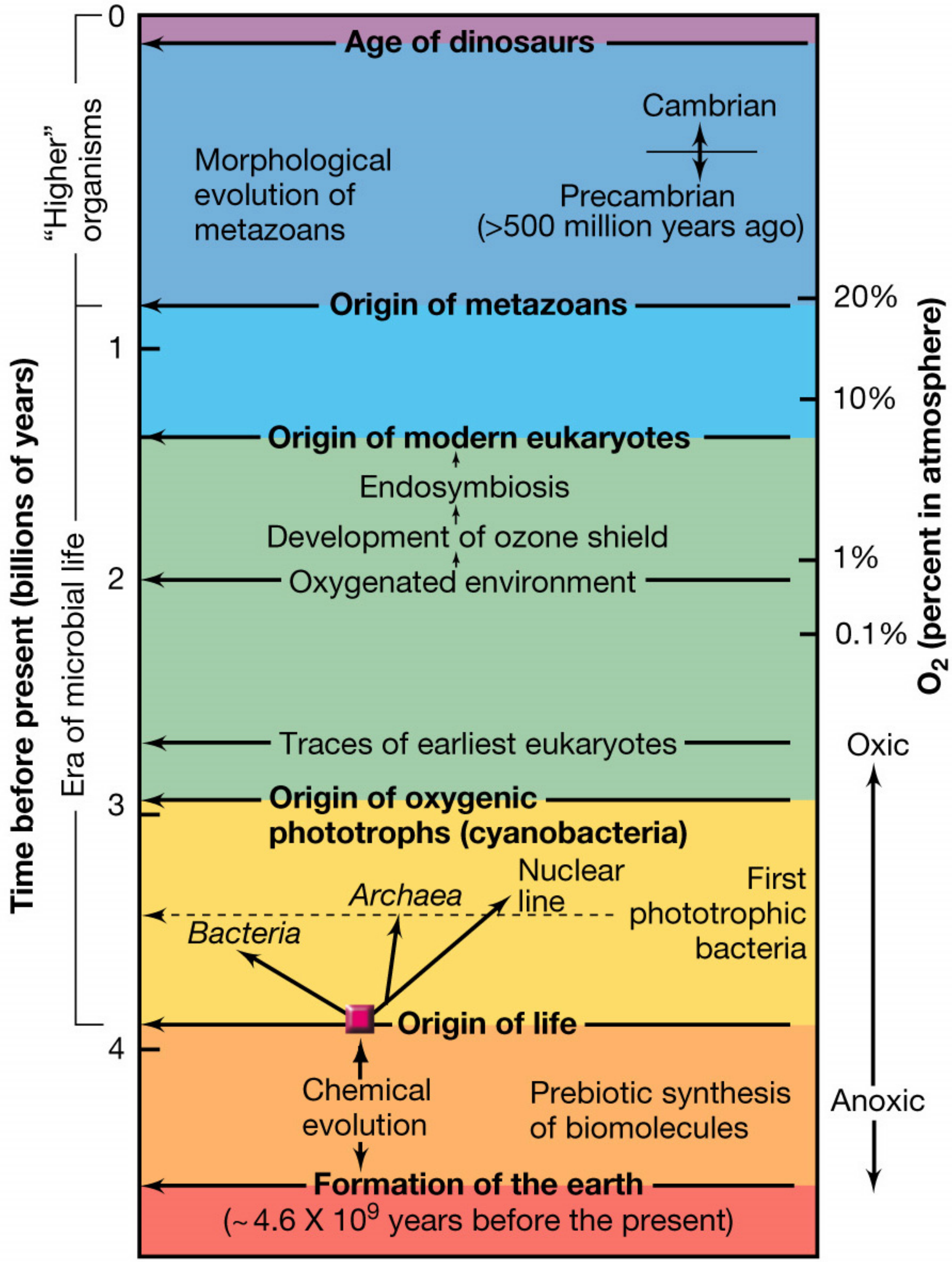
- Central Dogma intact
- ATP and PMF are universal themes
- Uniformity among chiral carbon compds (sugars & AAs)
- Hot start origin…

- 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.



Time before present (billions of years)
0
1
2
3
4
"Higher" organisms
Era of microbial life
Age of dinosaurs
Cambrian
Precambrian
(>500 million years ago)
Morphological evolution of metazoans
Origin of metazoans
Origin of modern eukaryotes
Endosymbiosis
Development of ozone shield
Oxygenated environment
Traces of earliest eukaryotes
Origin of oxygenic phototrophs (cyanobacteria)
Archaea
Nuclear line
Bacteria
First phototrophic bacteria
Origin of life
Chemical evolution
Prebiotic synthesis of biomolecules
Formation of the earth
(~4.6 X 10^9 years before the present)
20%
10%
1%
0.1%
O2 (percent in atmosphere)
Oxic
Anoxic

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 two critical concepts:

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 simpler organisms

(b) Abundant resources produced non-biologically

(c) Long time scale without competition

Thioester World

Chemical Transformations

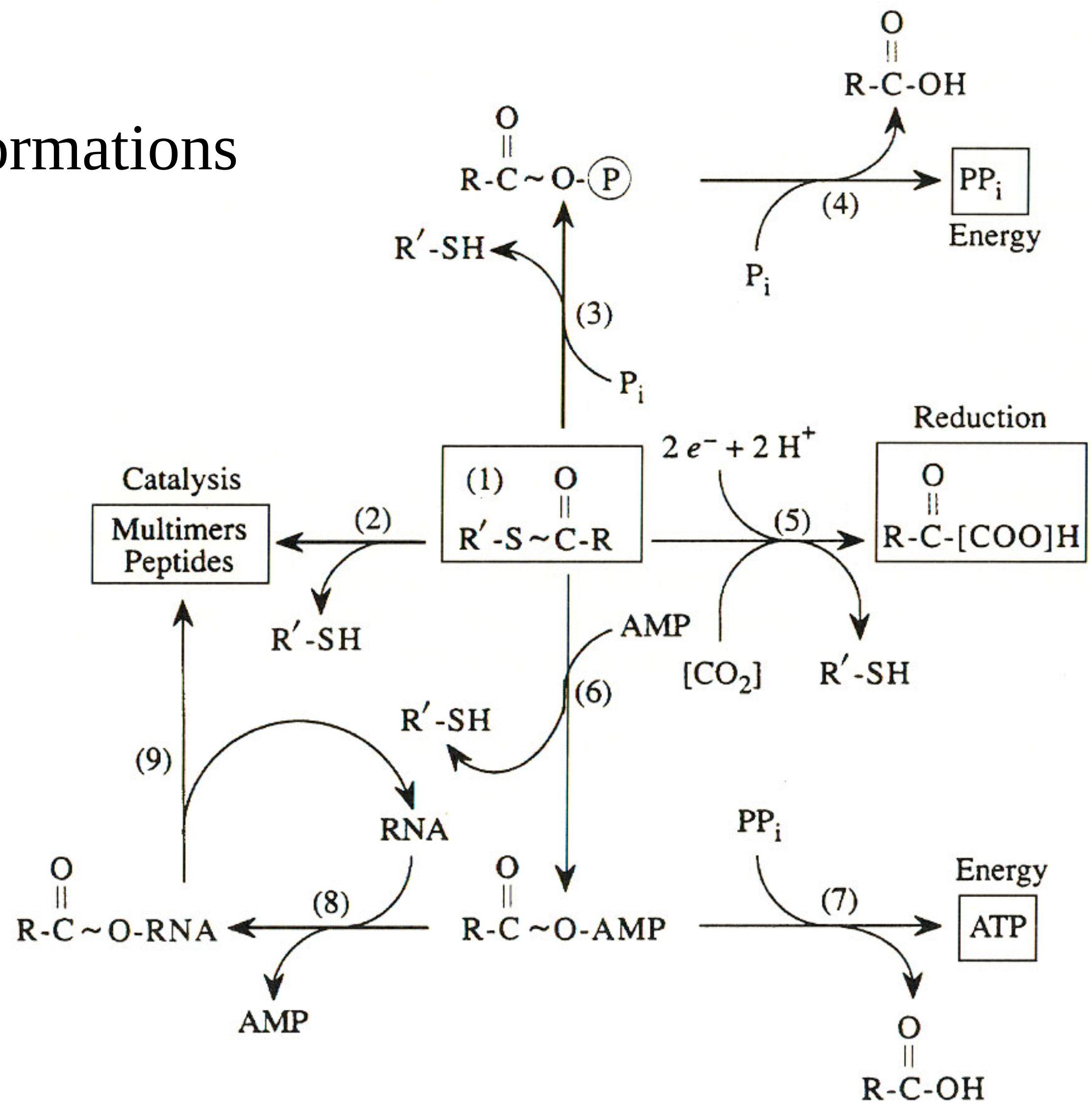


Figure 10.10 Synopsis of chemical transformations in the thioester world illustrating: (1) a pool of thioesters; (2) polymerisation of protoenzymes; (3) generation of high-energy phosphate esters; (4) generation of pyrophosphate, a primordial energy carrier; (5) thioester-based organic synthesis reactions; (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]

Thioester World

Mechanisms of synthesis

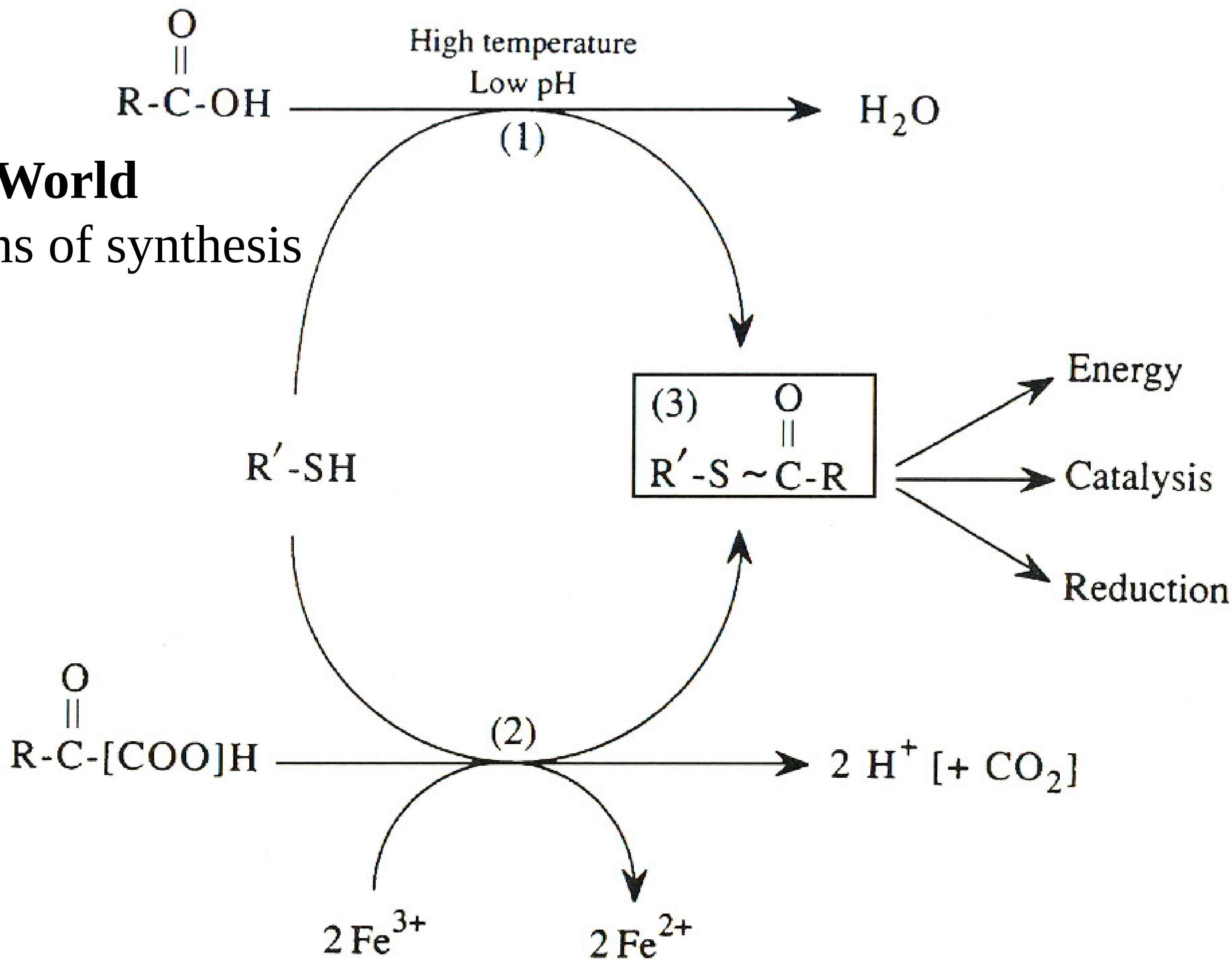


Figure 10.12 Mechanisms for synthesis of thioesters. (1) High temperature, low pH spontaneous synthesis from thiols and organic acids; (2) oxidative synthesis from thiols and α-keto organic acids based on ferric iron reduction[29]

Origins of Life Models

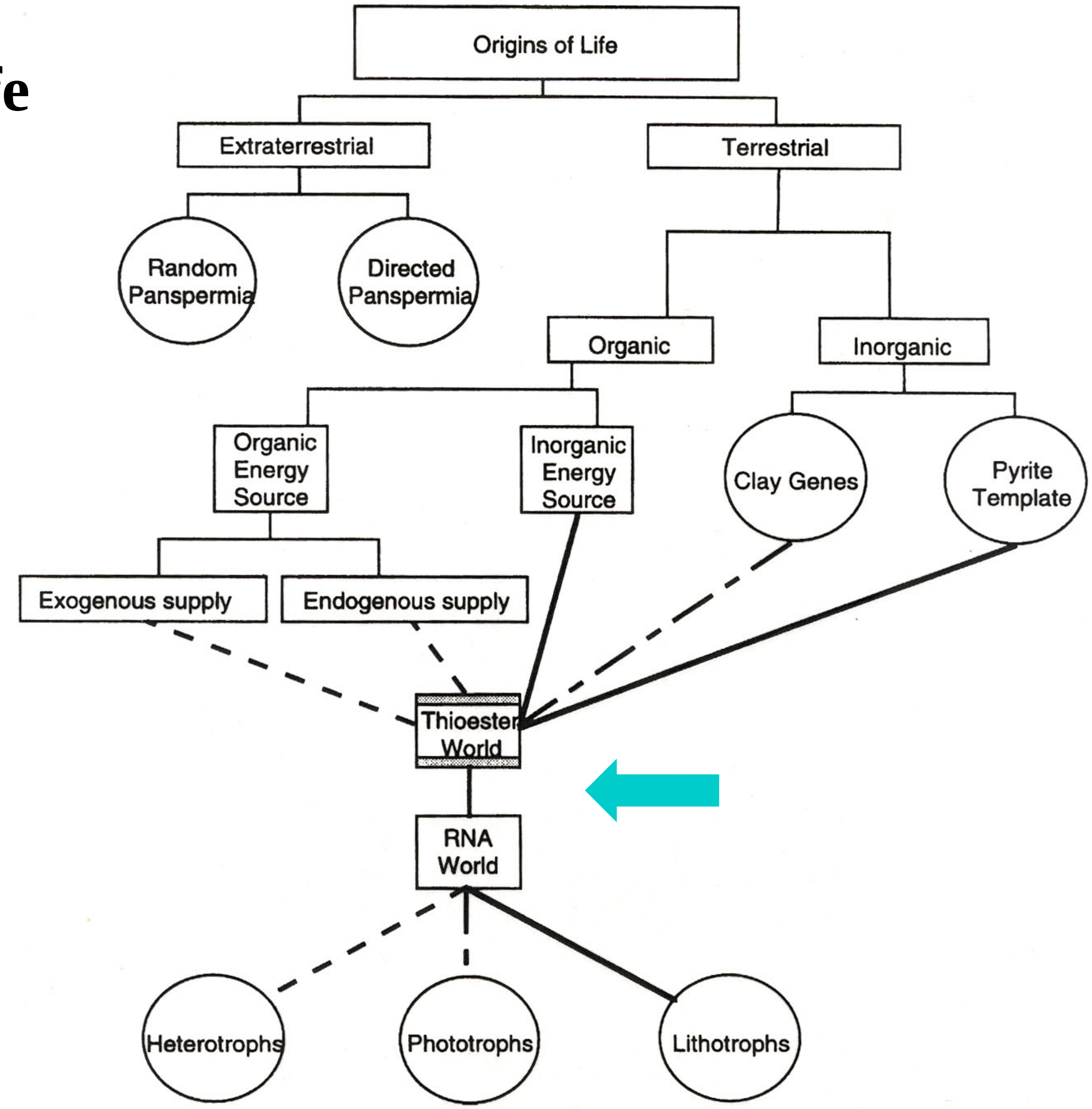


Figure 10.6 Relationships among various theoretical or conceptual models for the origins of life.[77] Dashed and solid lines at the bottom of the figure connect mechanisms with putative metabolic type of first organisms. The thioester world is proposed as an intermediate leading to an RNA world

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.

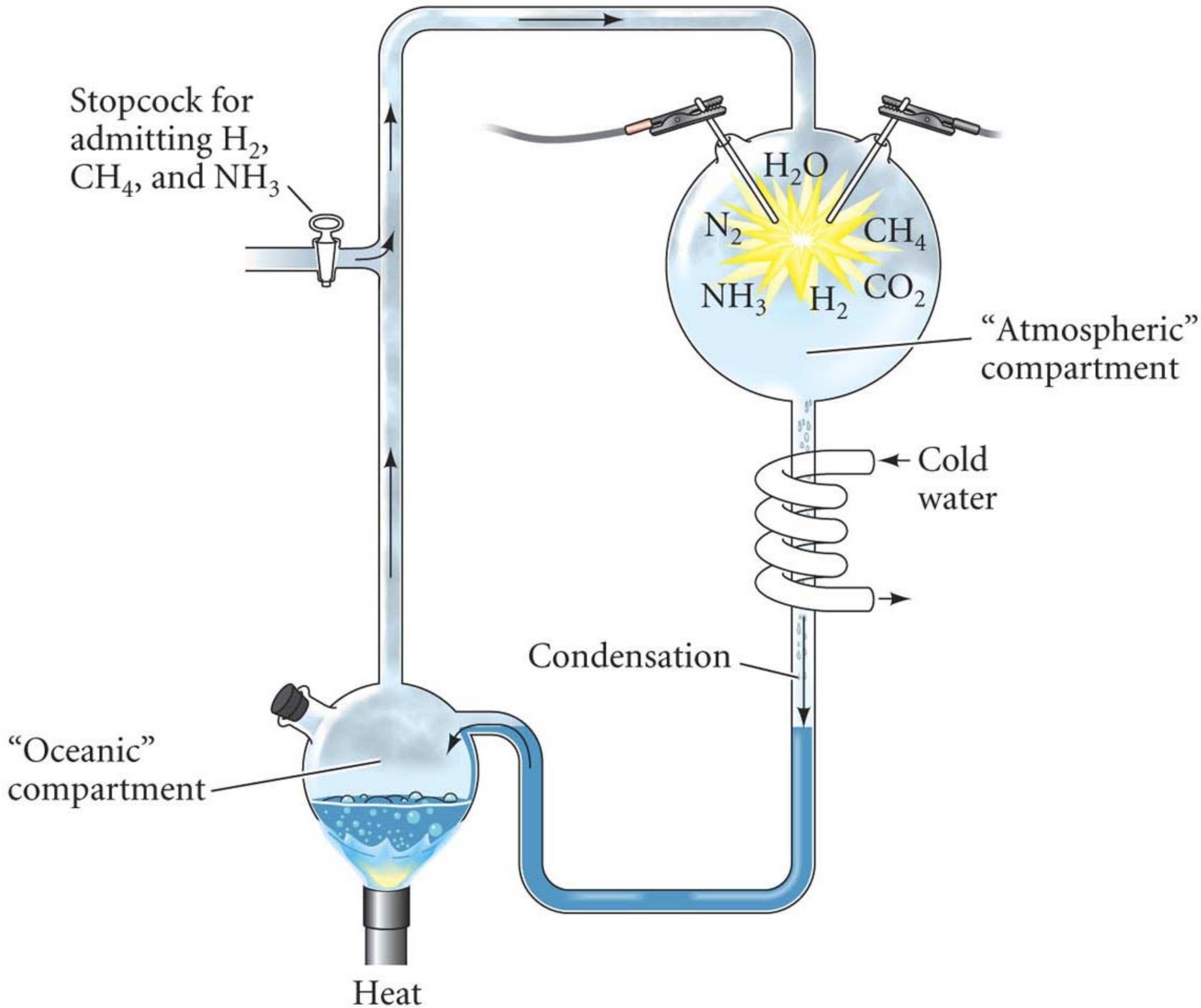
• All **amino acids** exist in both the right-handed and left-handed state. However, only 20 amino acids of the left-handed variety are used by living organisms in proteins. Therefore, suggesting there was a single origin of life.

• **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

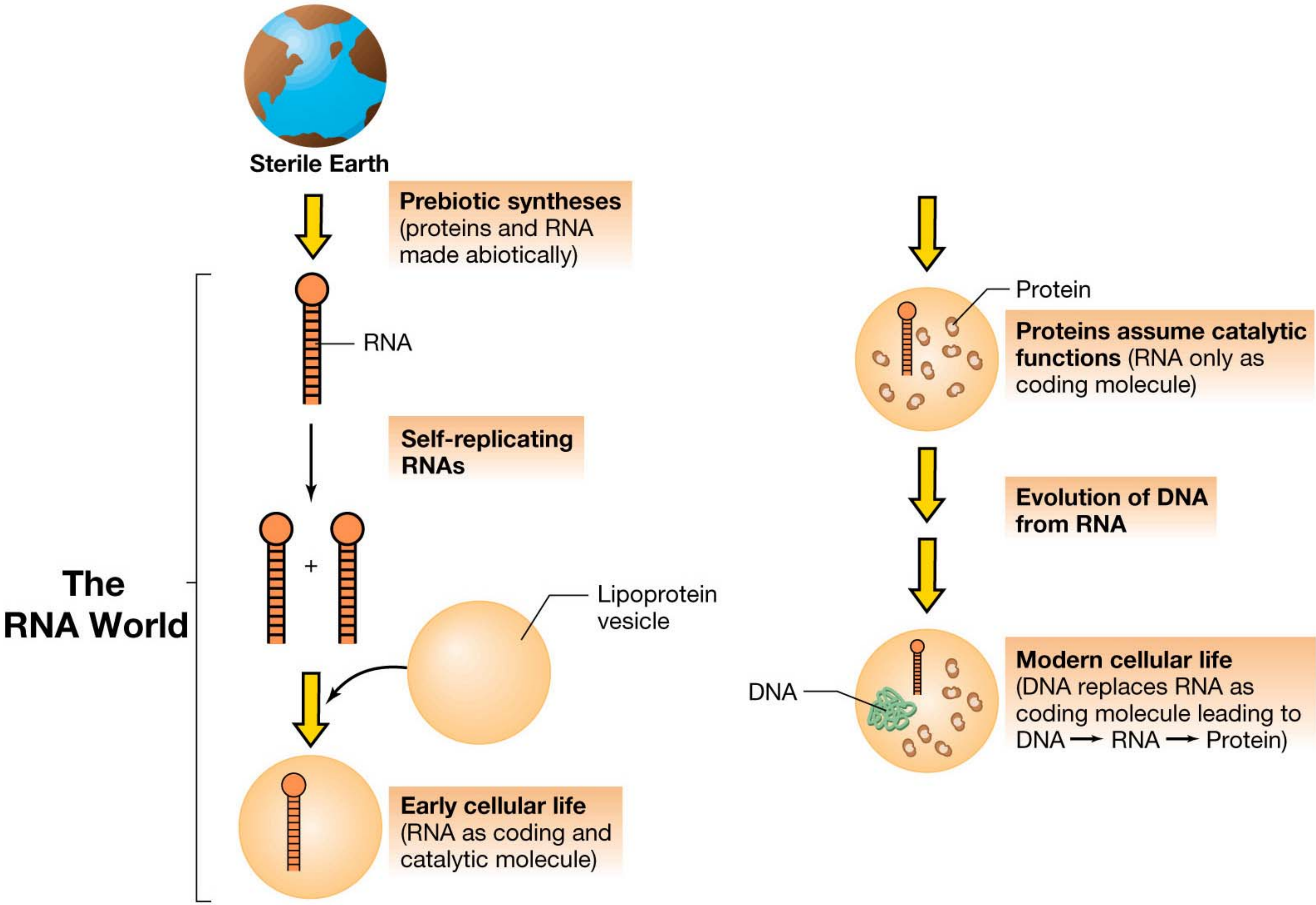


Necessary Conditions for the Origin of Life

- 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.

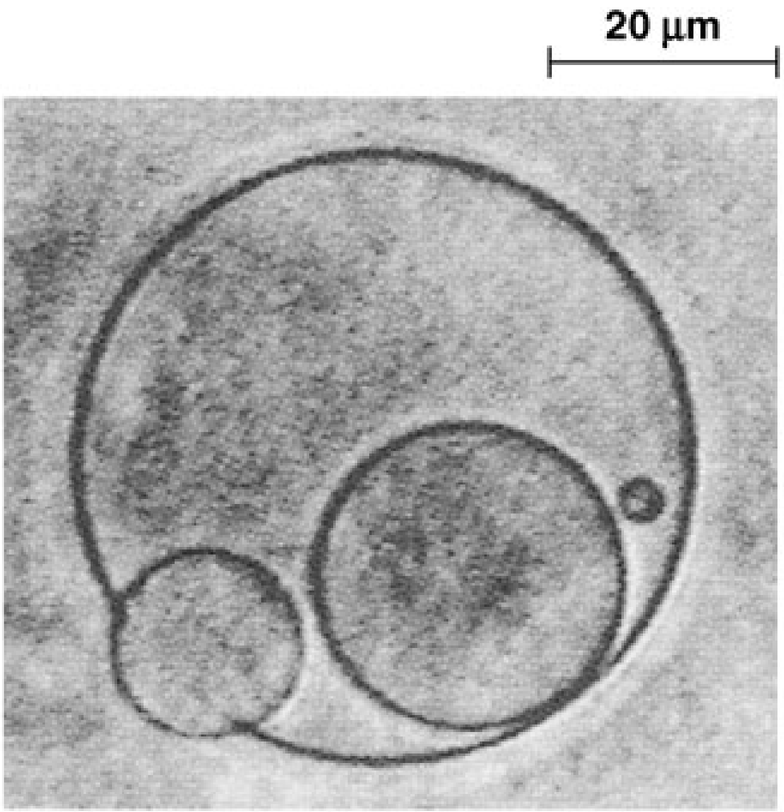
- Originally "Darwin's Warm Pond" Hypothesis

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

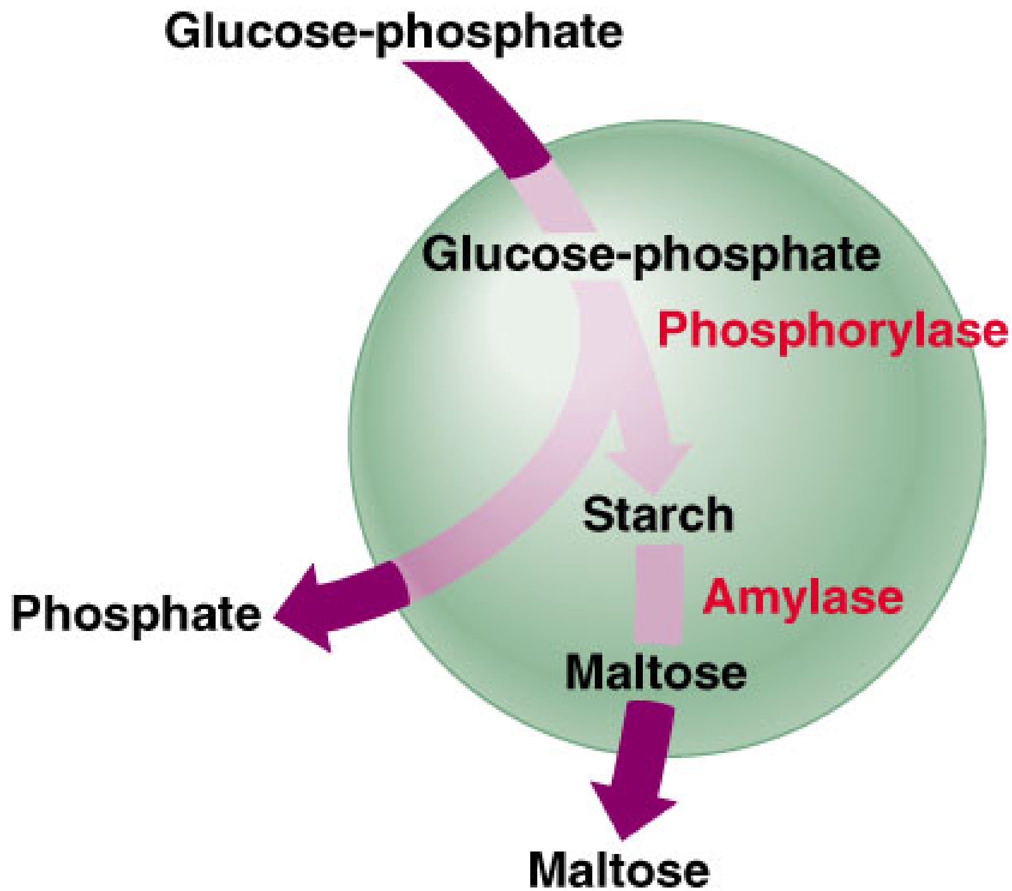


Sterile Earth
Prebiotic syntheses (proteins and RNA made abiotically)
RNA
Self-replicating RNAs
+
The RNA World
Lipoprotein vesicle
Early cellular life (RNA as coding and catalytic molecule)
Protein
Proteins assume catalytic functions (RNA only as coding molecule)
Evolution of DNA from RNA
DNA
Modern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

Laboratory versions of protobionts



(a) Simple reproduction

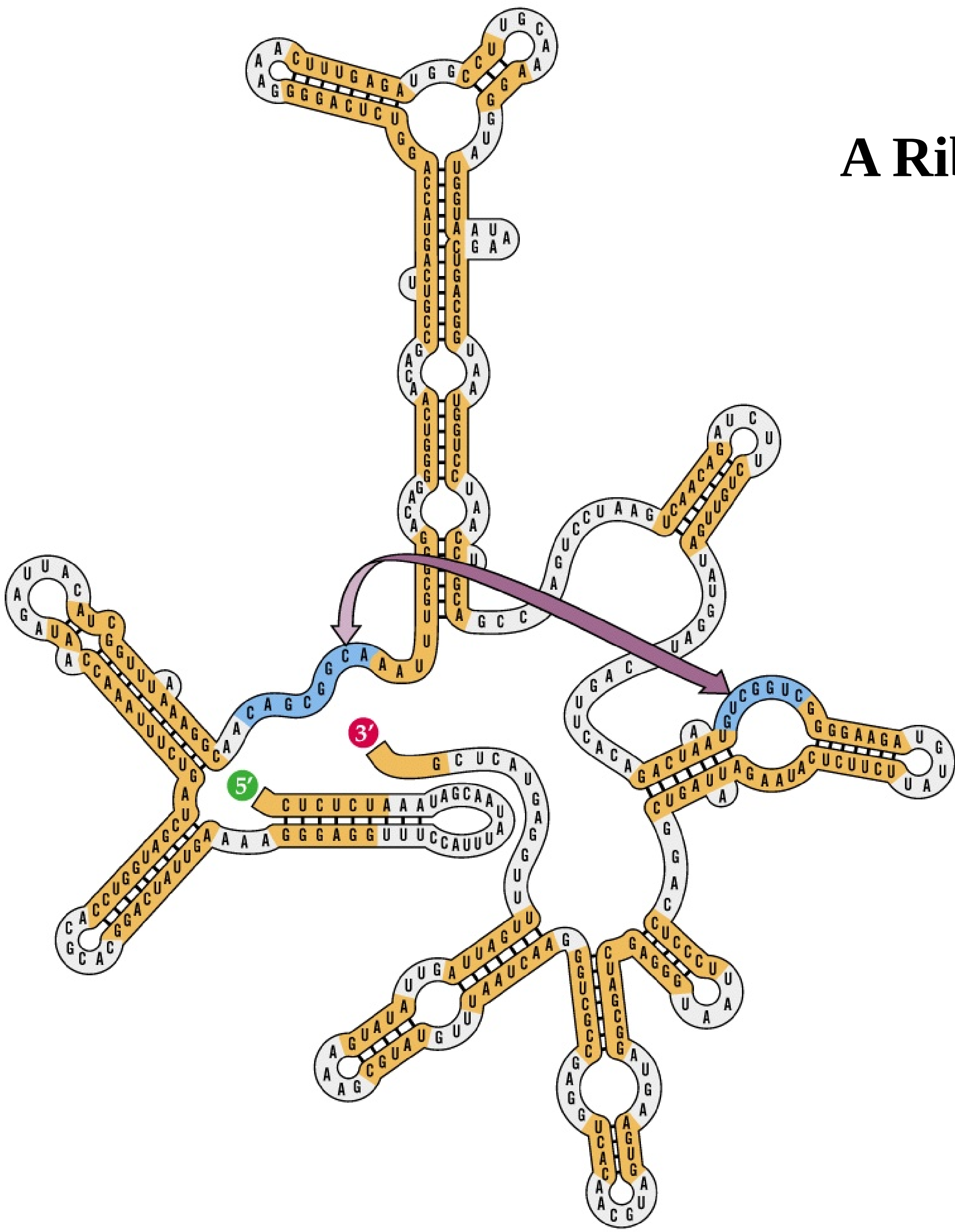


(b) Simple metabolism

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

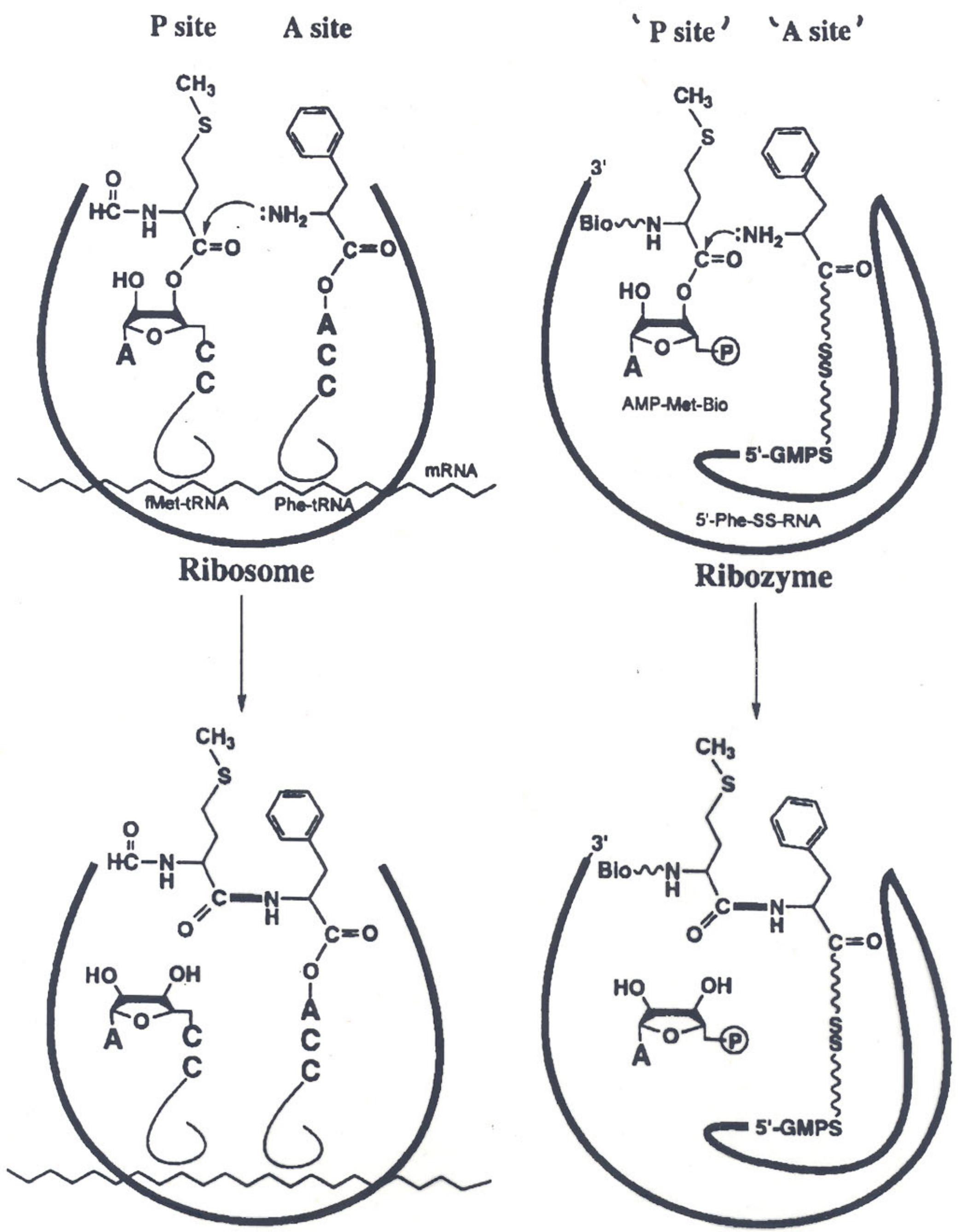
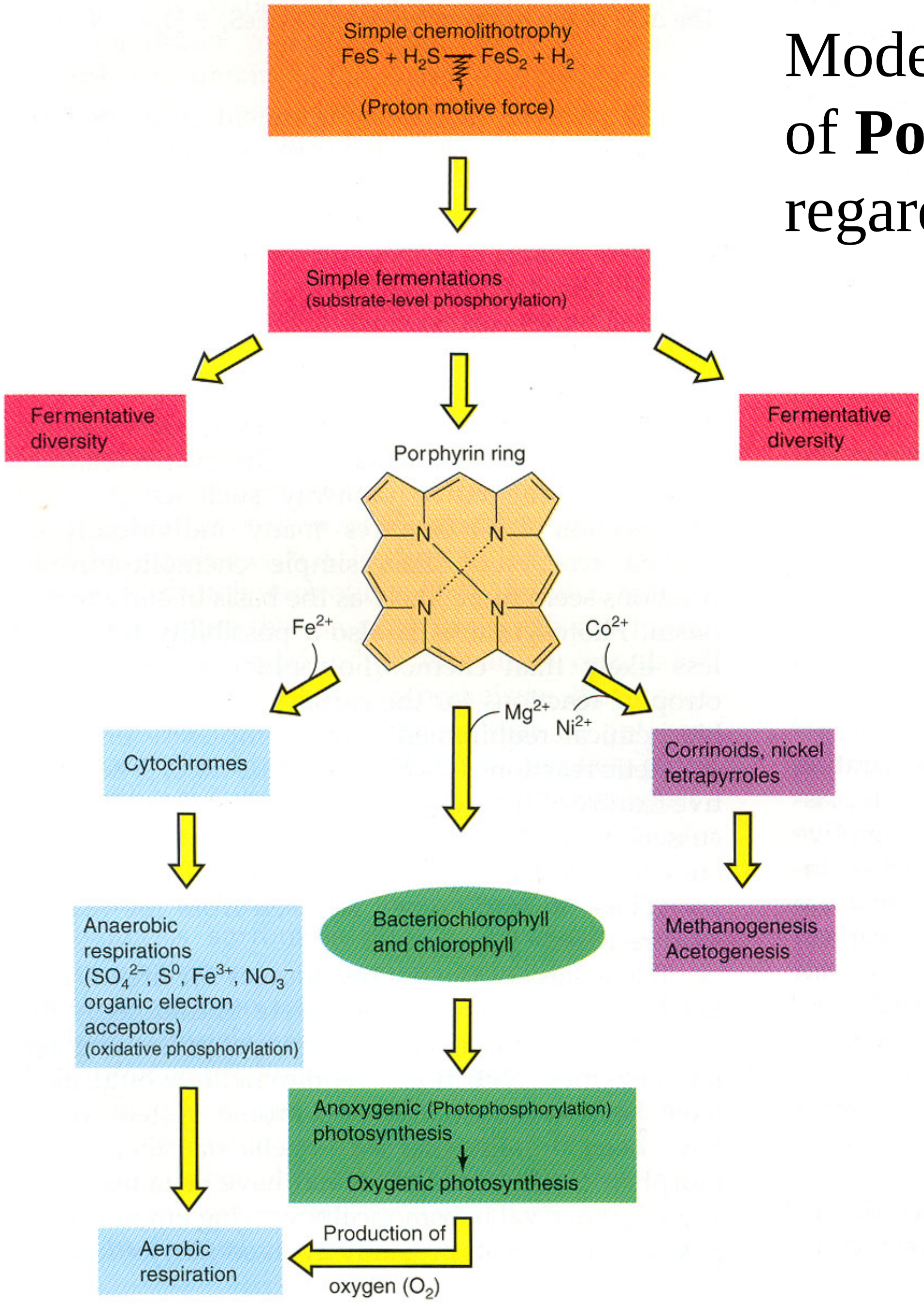


Figure 1 Peptide bond formation by a ribosome (left) and by a ribozyme (right).

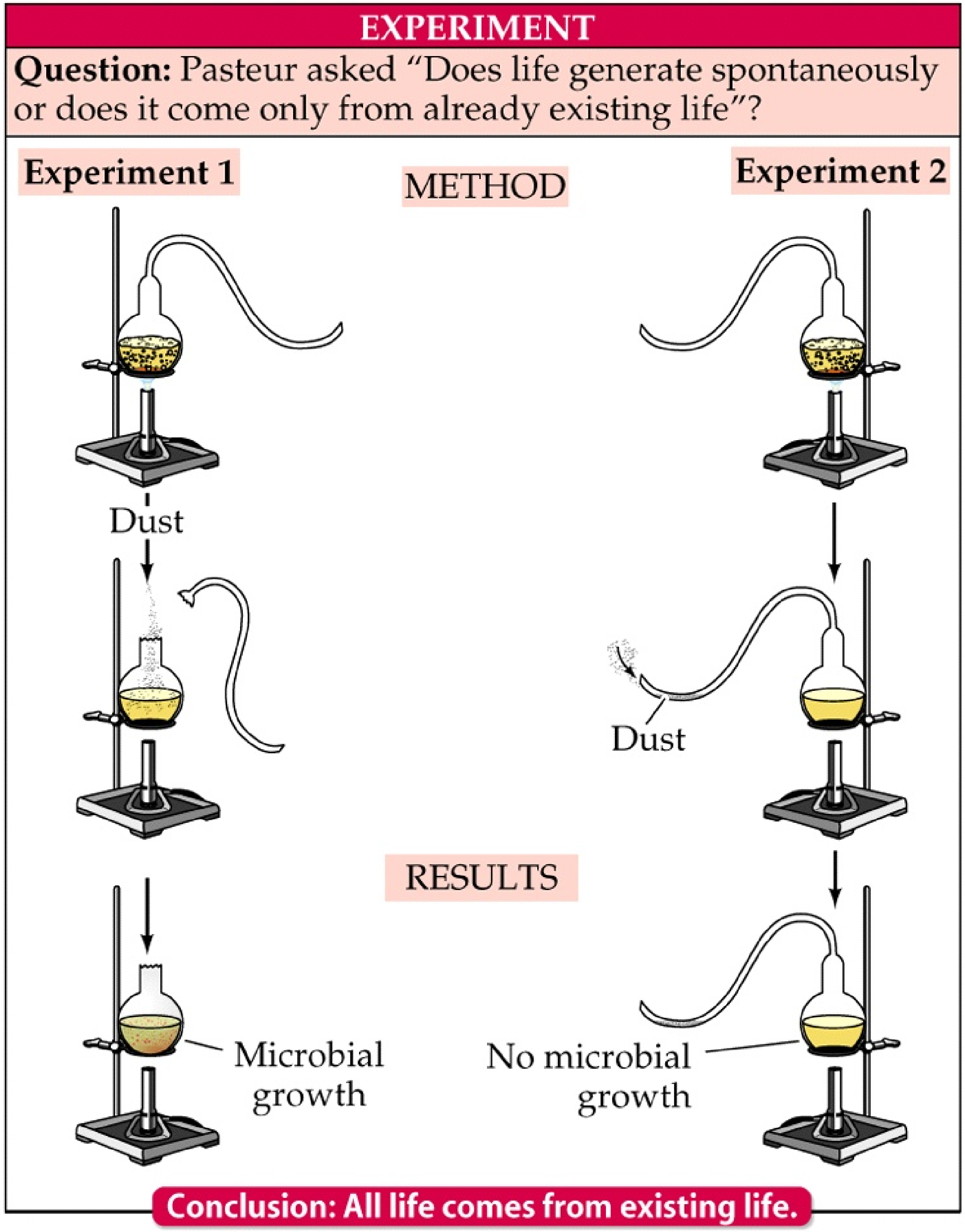
Model for the development of **Porphyrin Ring** diversity regarding metabolic pathways



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.

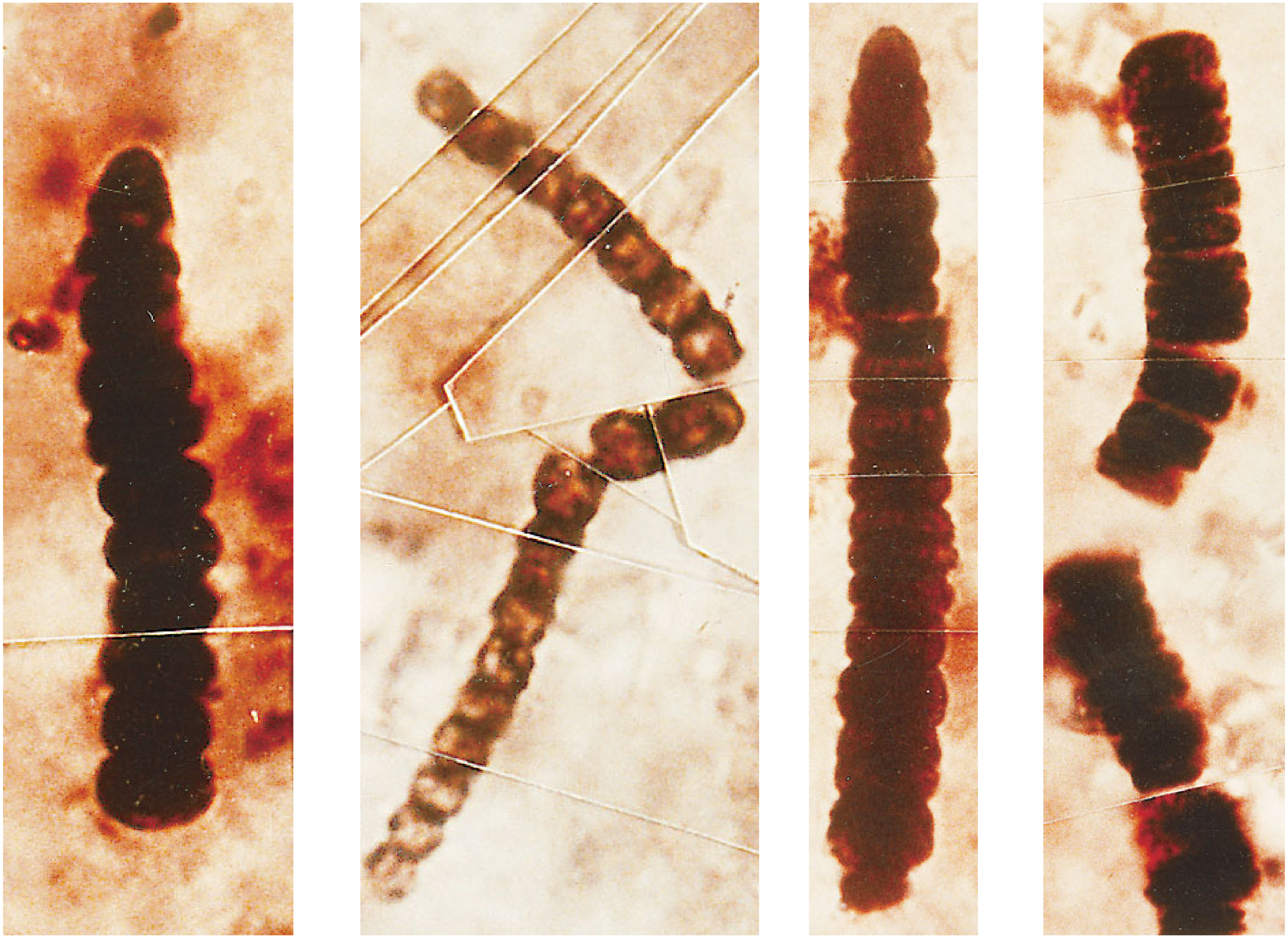


Pasteur (1860s) was also the father of "origins of life" research

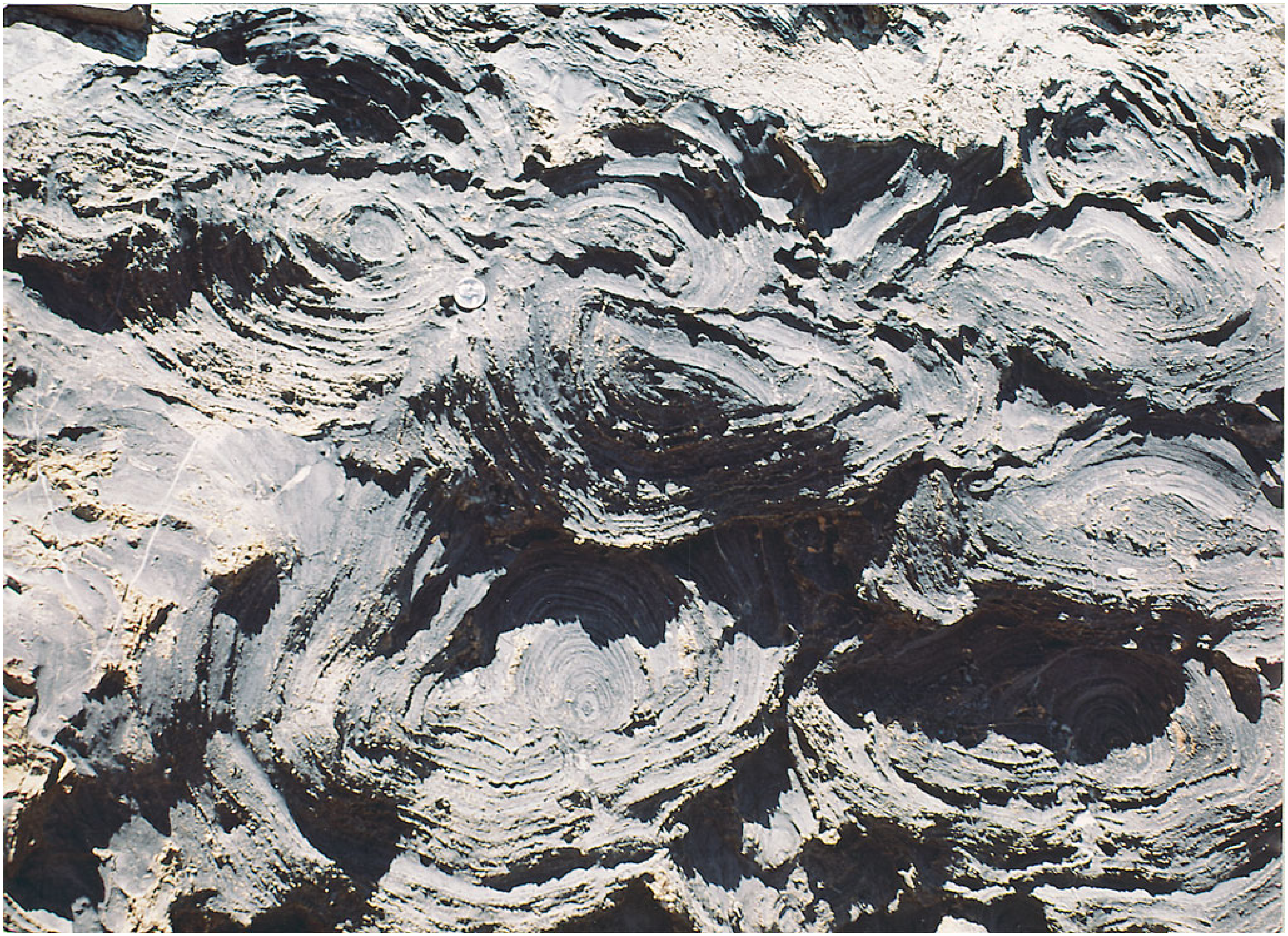
Is Life Evolving from Nonlife Today?

- 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!

Oldest Known Fossils of Living Organisms (~3500 Mya)



Fossil Stromatolites from Glacier Natl. Park



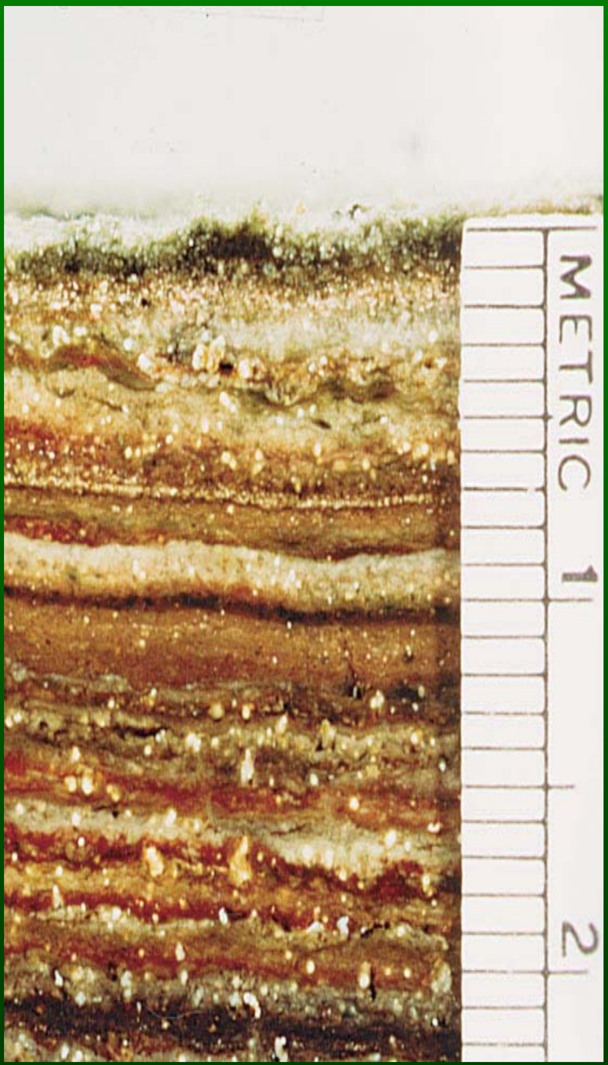
Living Columnar Stromatolites, Shark Bay, Western Australia

Modern Stromatolites from Yellowstone Natl. Park

Photosynthesis Is the Source of Atmospheric O_2

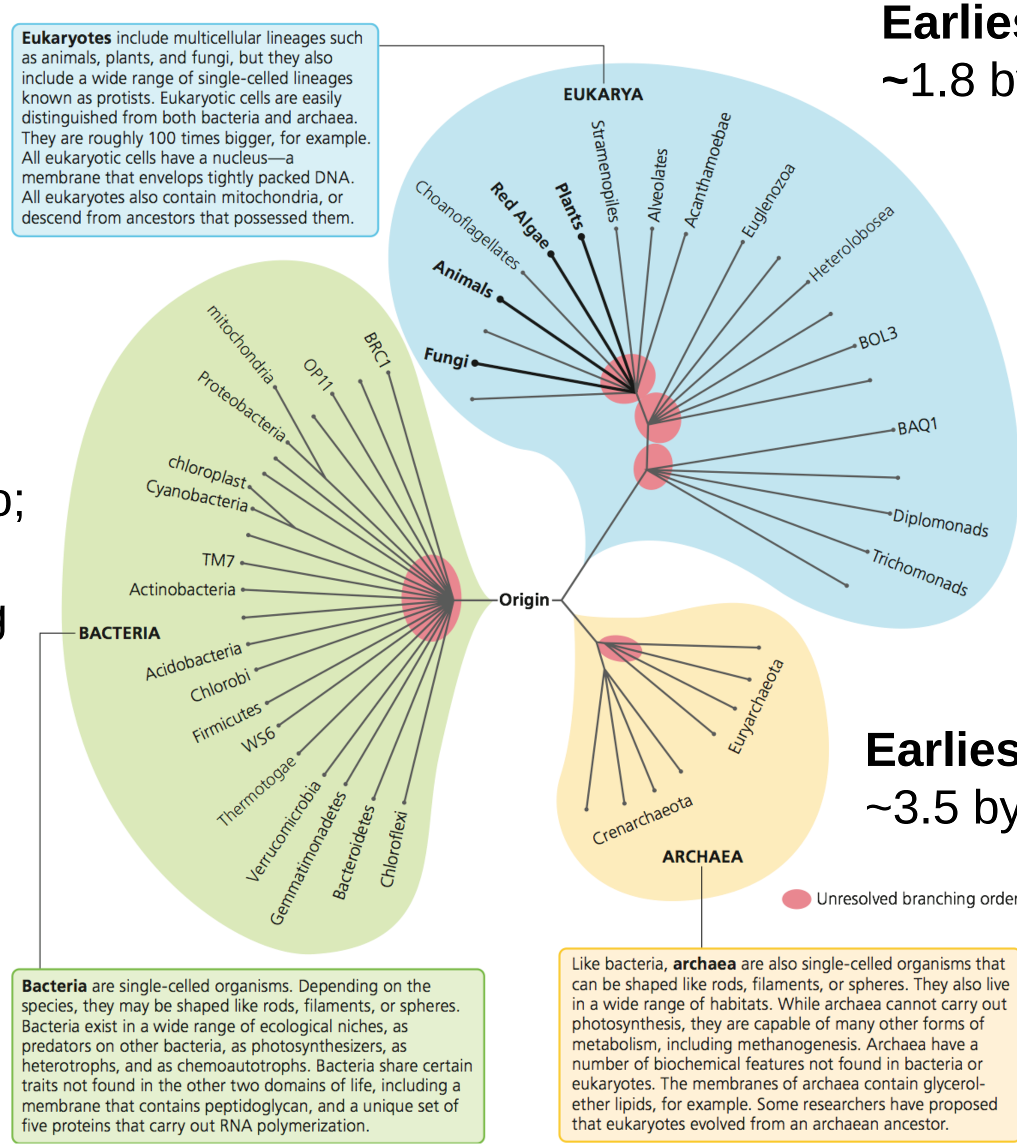
- Cyanobacteria, which evolved the ability to split water into hydrogen ions and O_2, created atmospheric O_2. Accumulation of free O_2 in the atmosphere made possible the evolution of aerobic metabolism.

Extant Microbial Mat Communities



How do early organisms fit in the tree of life?

Earliest fossils:
~1.8 bya



Earliest fossils:
potentially 3.45 byo; abundant by ~2.6 bya, corresponding to rise in oxygen

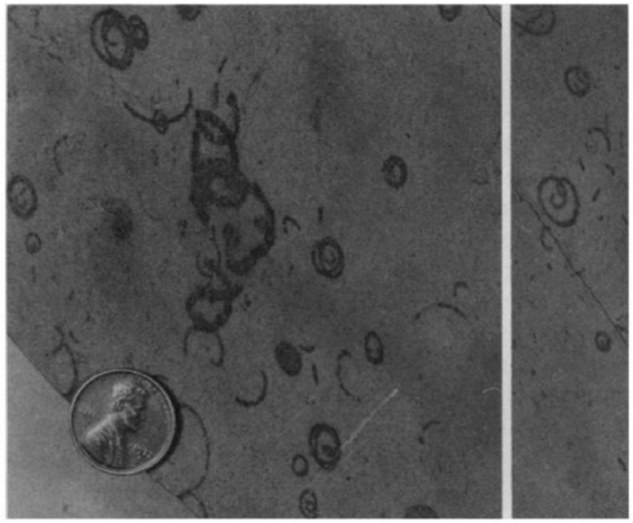
Earliest fossils:
~3.5 bya

Oldest fossils of multicellular life date back 2.1 billion years

- Unclear where they fit in the tree of life

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.



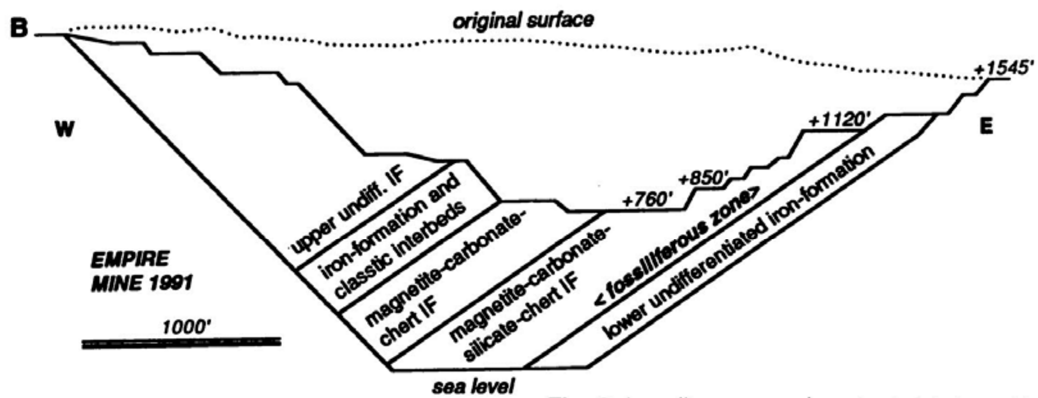


Fig. 2. Locality map and east-west cross section of the Empire Mine showing the 1991 and projected positions of the pit surface.

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

~2.1 Bya

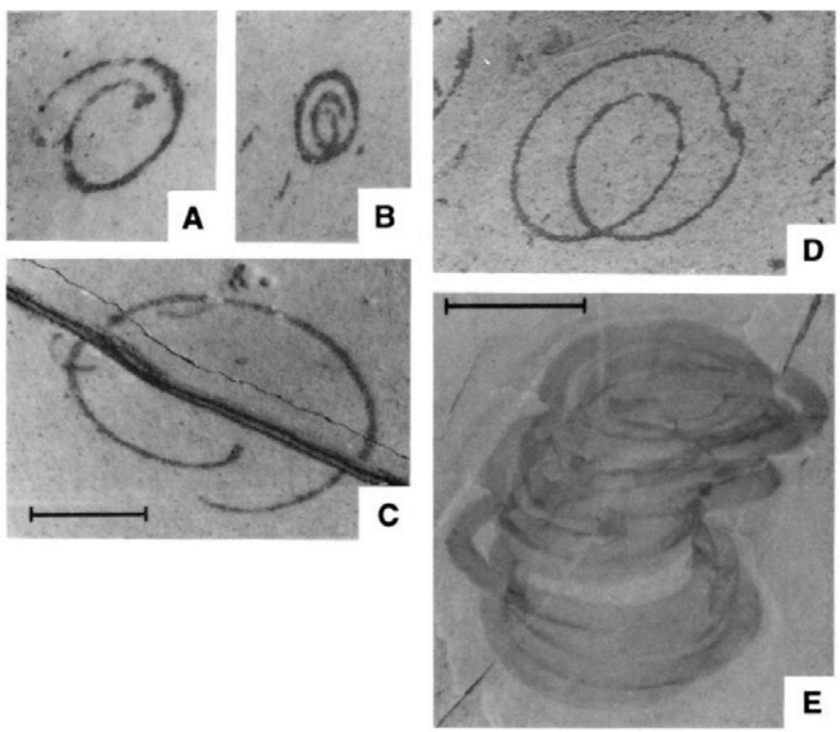


Fig. 3. (**A** to **D**) Specimens of *Grypania* from the Negaunee Iron-Formation, Empire Mine. (**E**) Large specimen of *Grypania spiralis*, about 1100 million years old, Rohtas Formation, Semri Group, Vindhyan Supergroup, central India. Scale bar in (C) (applies to A to D), 1 cm; scale bar in (E),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

~1.1 Bya

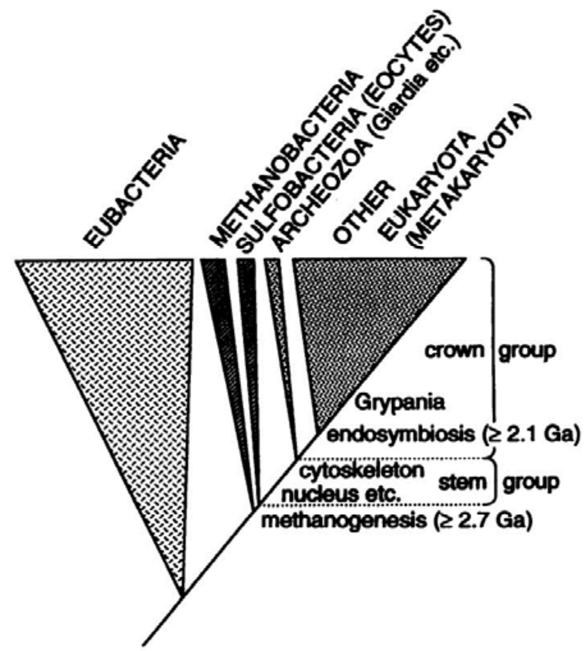


Fig. 5. Cartoon showing the major branches of the universal tree of life and the presumed position of *Grypania* in the tree.

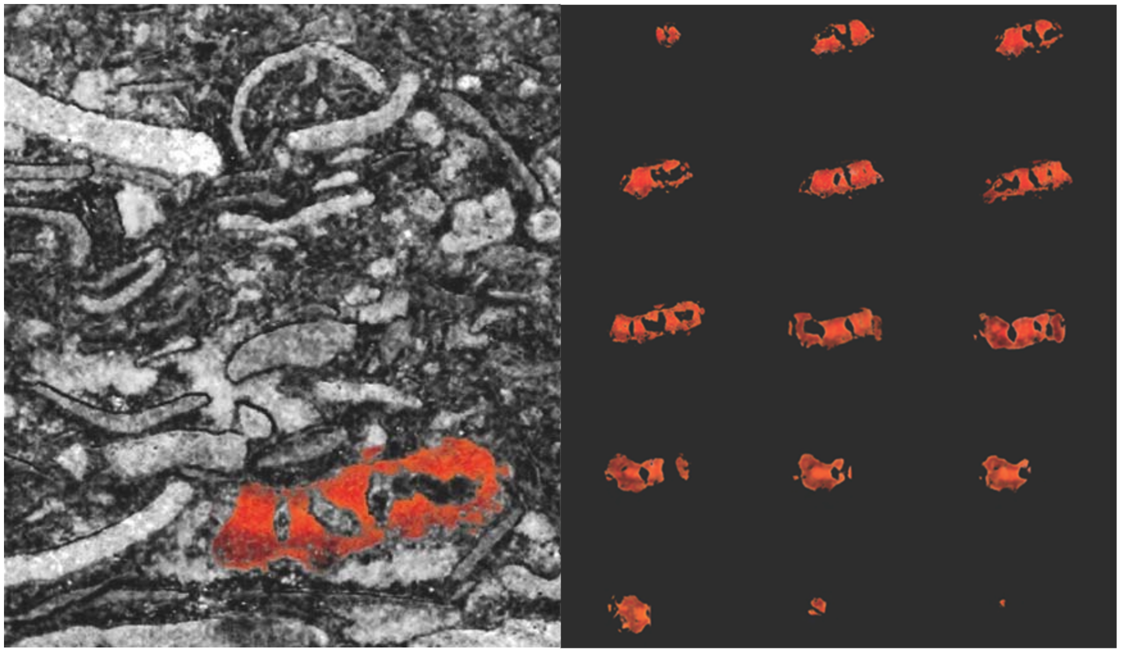
Eukaryotic multicelluar life

- Earliest fossils of algae date to 1.6 bya
  - Red algae: 1.2 bya
  - Green algae: 750 mya

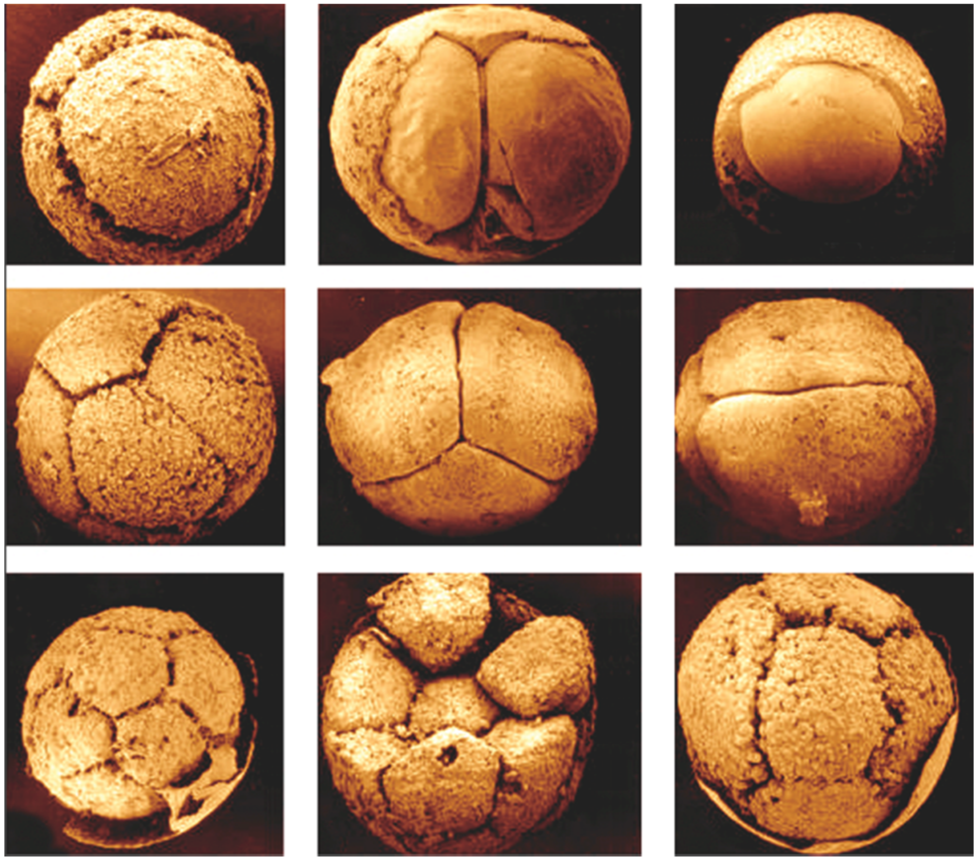
Red algae fossil; 1.2 bya

The dawn of animals

- Early animal life resemble sponges
  - Oldest fossils 650 myo
  - Biomarkers also demonstrate existence of sponges during this time



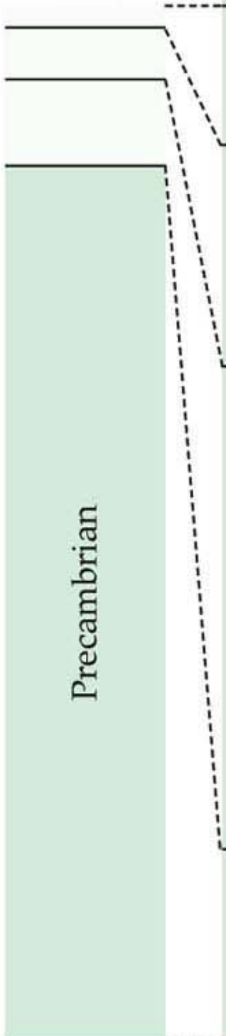
Search for early animals can be controversial



Animal embryos or single cell with cyst?

22.1 **Earth's Geological History** *(Part 1)*

RELATIVE TIME SPAN



ERA	PERIOD	ONSET	MAJOR PHYSICAL CHANGES ON EARTH
Cenozoic	Quaternary	1.8 mya[a]	Cold/dry climate; repeated glaciations
	Tertiary	65 mya	Continents near current positions; climate cools
Mesozoic	Cretaceous	144 mya	Northern continents attached; Gondwana drifts apart; meteorite strikes Yucatán Peninsula
	Jurassic	206 mya	Two large continents form: Laurasia and Gondwana; climate warm
	Triassic	248 mya	Pangaea begins to drift apart; hot/humid climate
Paleozoic	Permian	290 mya	Continents aggregate into Pangaea; large glaciers form; dry climates form in interior of Pangaea
	Carboniferous	354 mya	Climate cools; marked latitudinal climate gradients
	Devonian	417 mya	Continents collide at end of period; asteroid probably collides with Earth
	Silurian	443 mya	Sea levels rise; two large continents form; hot/humid climate
	Ordovician	490 mya	Gondwana moves over South Pole; massive glaciation, sea level drops 50 m
	Cambrian	543 mya	O_2 levels approach current levels
Precambrian		600 mya	O_2 level at >5% of current level
		1.5 bya[a]	O_2 level at >1% of current level
		3.8 bya	O_2 first appears in atmosphere
		4.5 bya	

[a]mya, million years ago; bya, billion years ago.

Rust the Crust

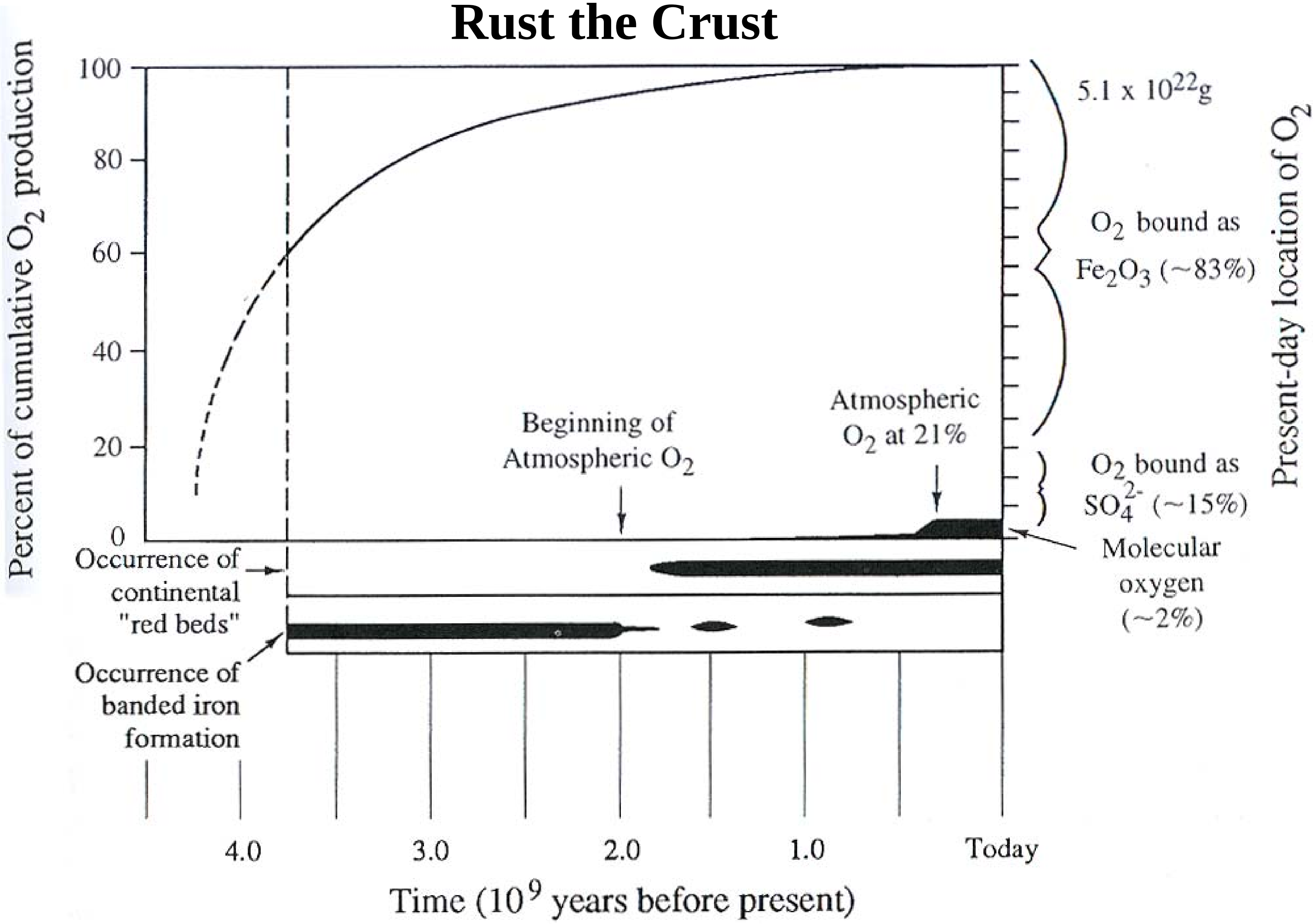
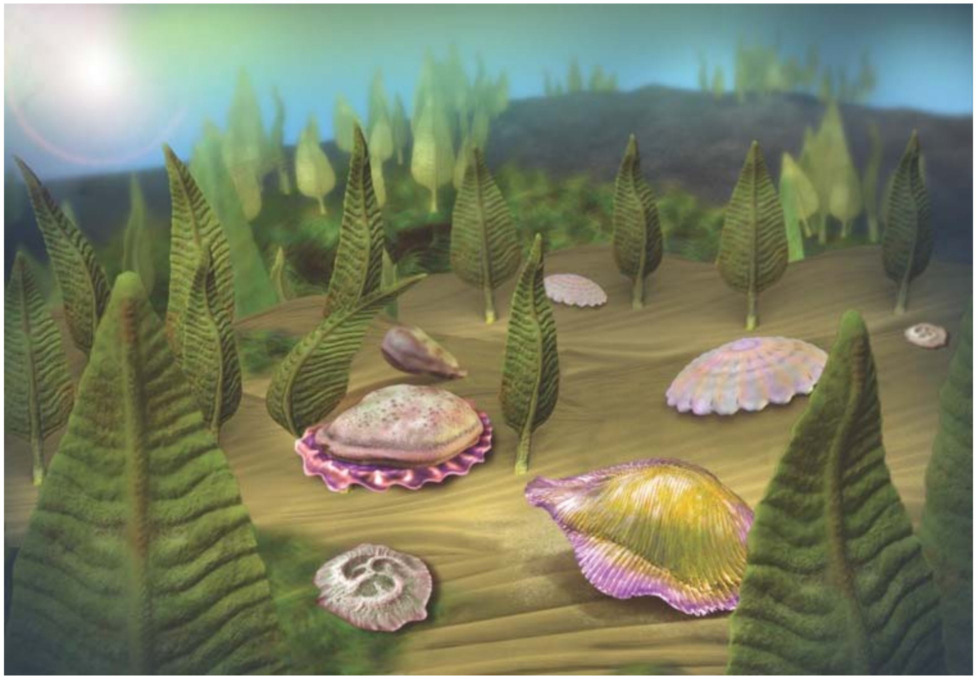


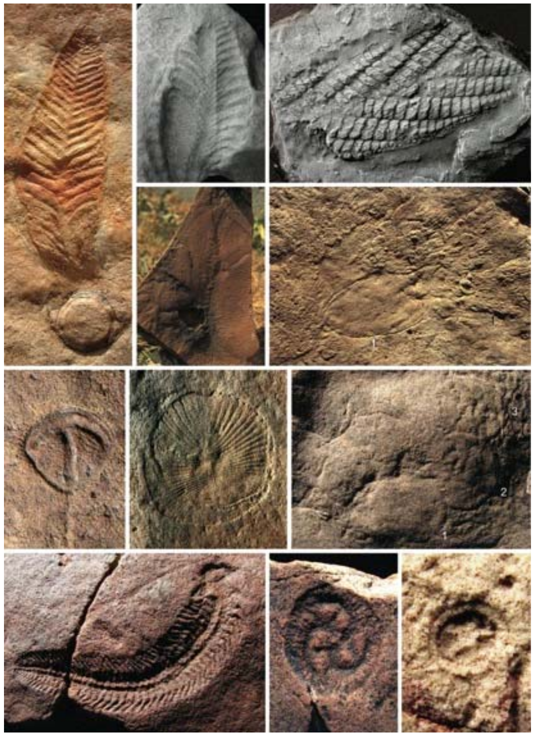
Figure 2.7 Cumulative history of O_2 released by photosynthesis through geologic time. Of more than 5.1×10^{22} g of O_2 released, about 98% is contained in seawater and sedimentary rocks, beginning with the occurrence of Banded Iron Formations at least 3.5 billion years ago (bya). Although O_2 was released 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

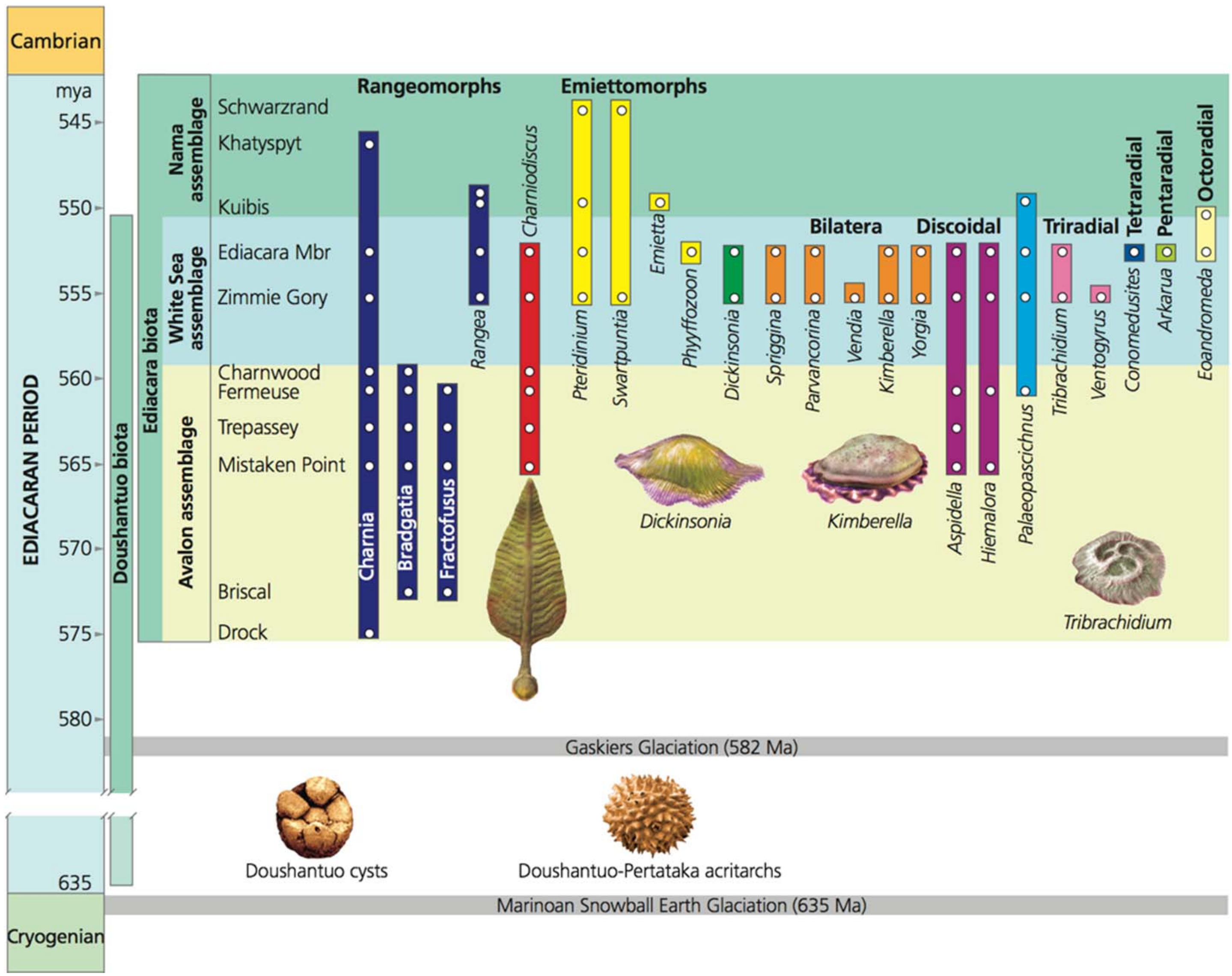
Ediacaran fauna

- Diverse and unique animals dominated the oceans from 575 – 535 mya
  - Many hard to place taxonomically

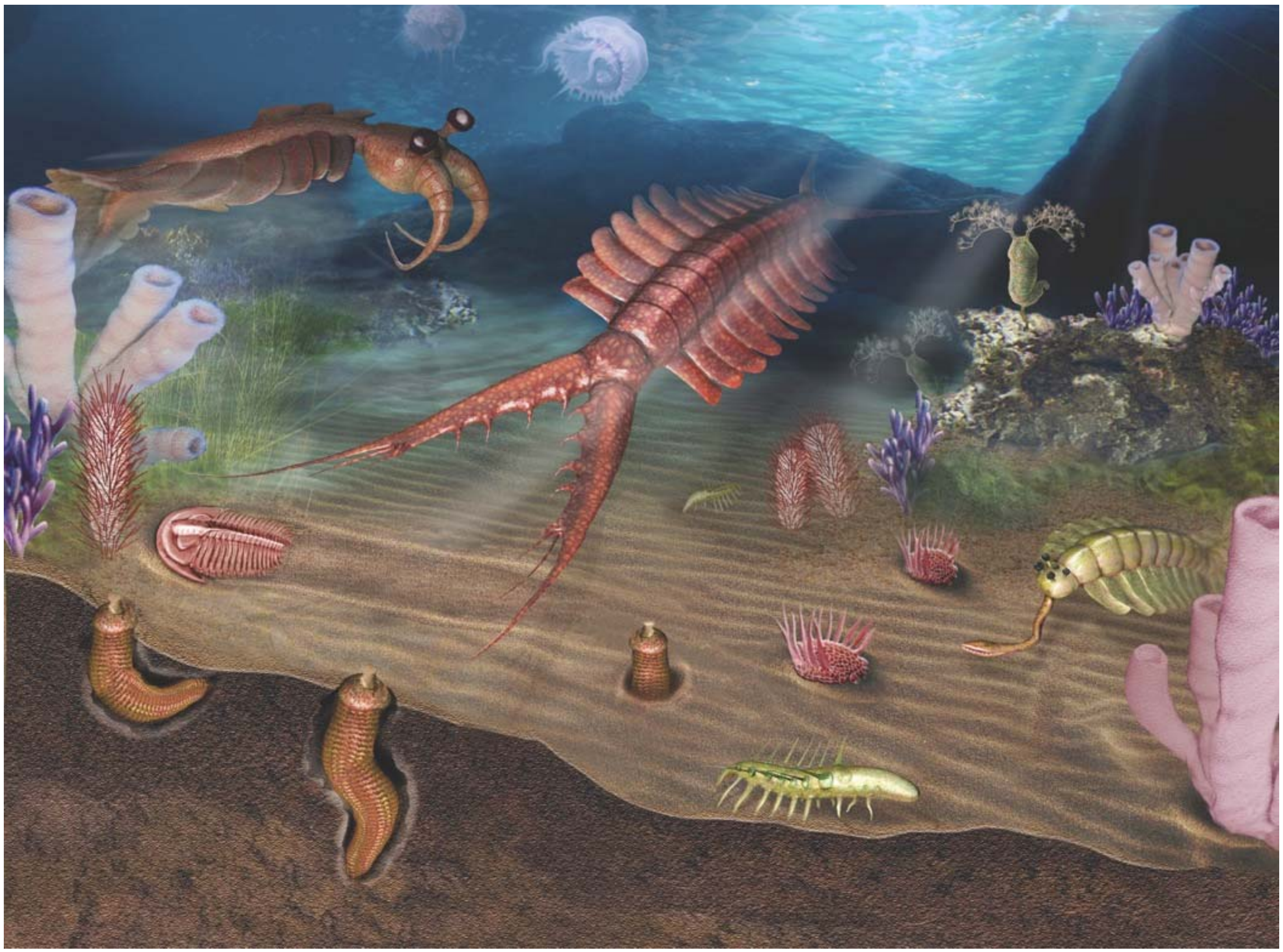




Evolution of Ediacaran fauna

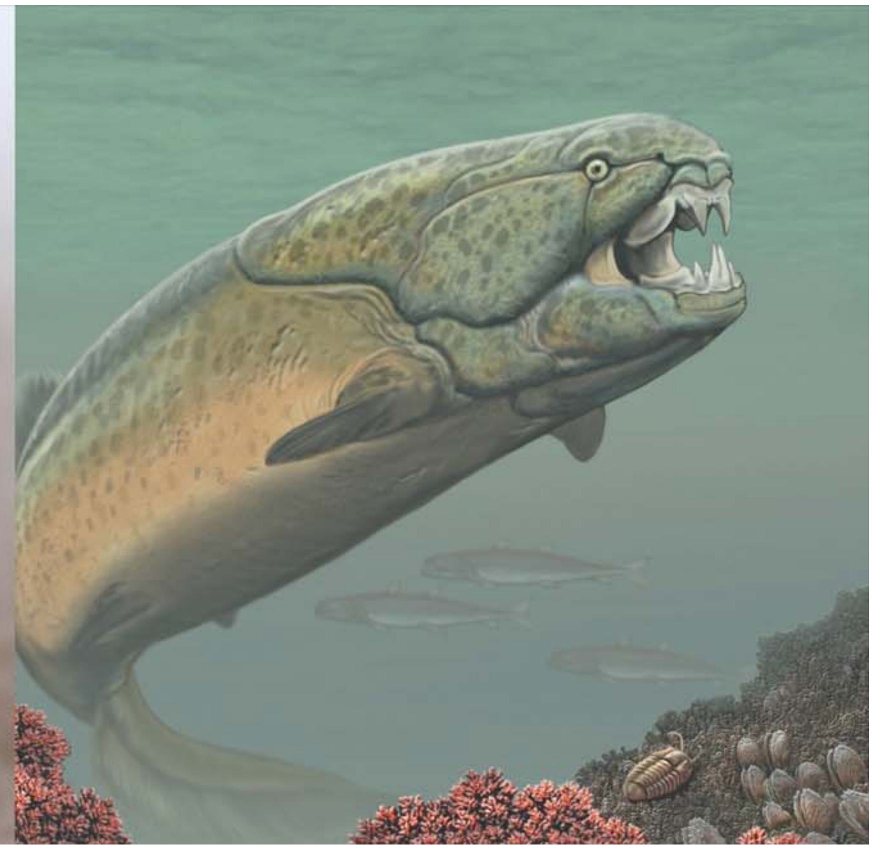


Currently existing lineages recognizable during the early Cambrian



Early Cambrian: 542 – 511 mya

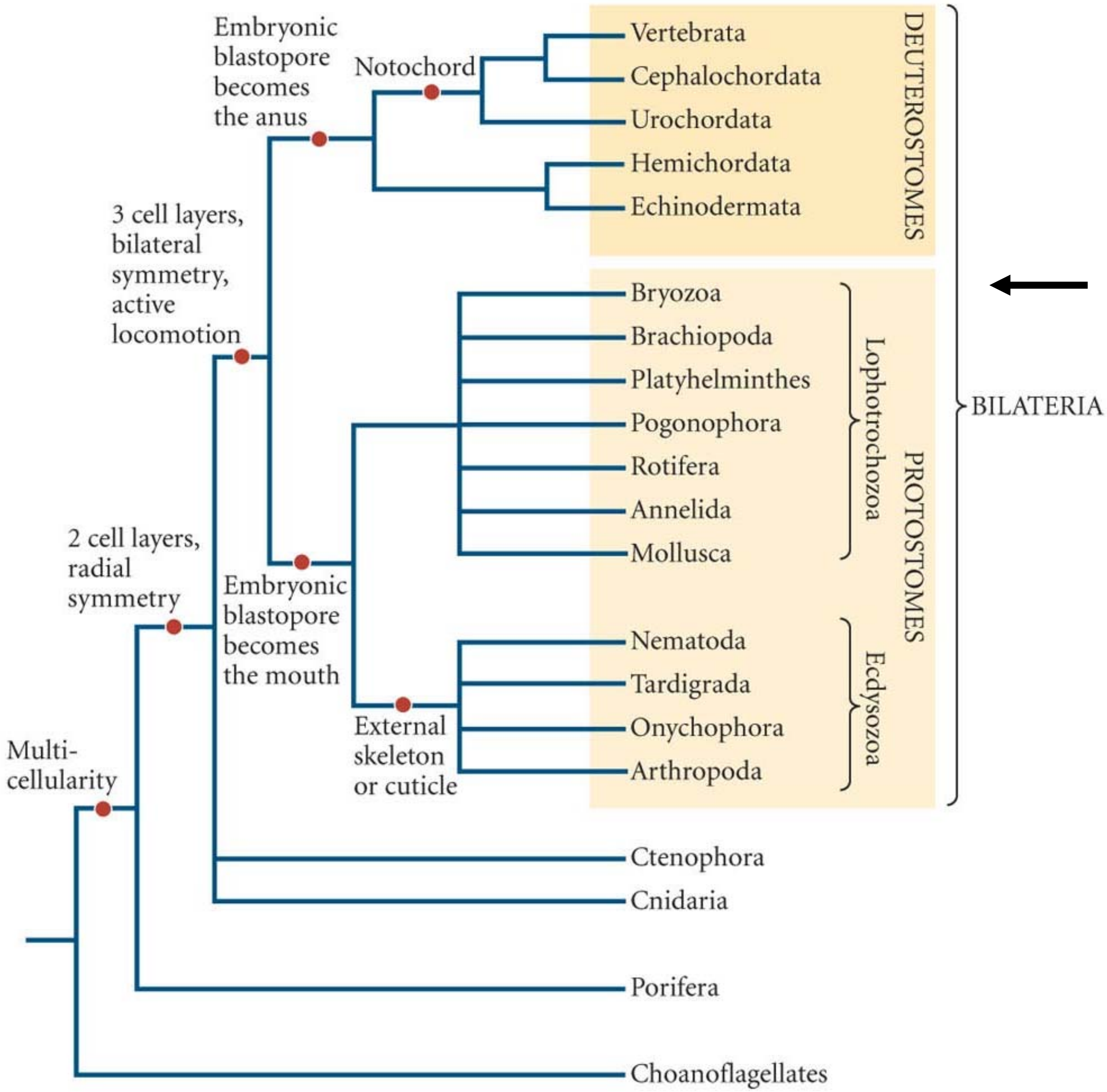
Chordates emerged during early Cambrian



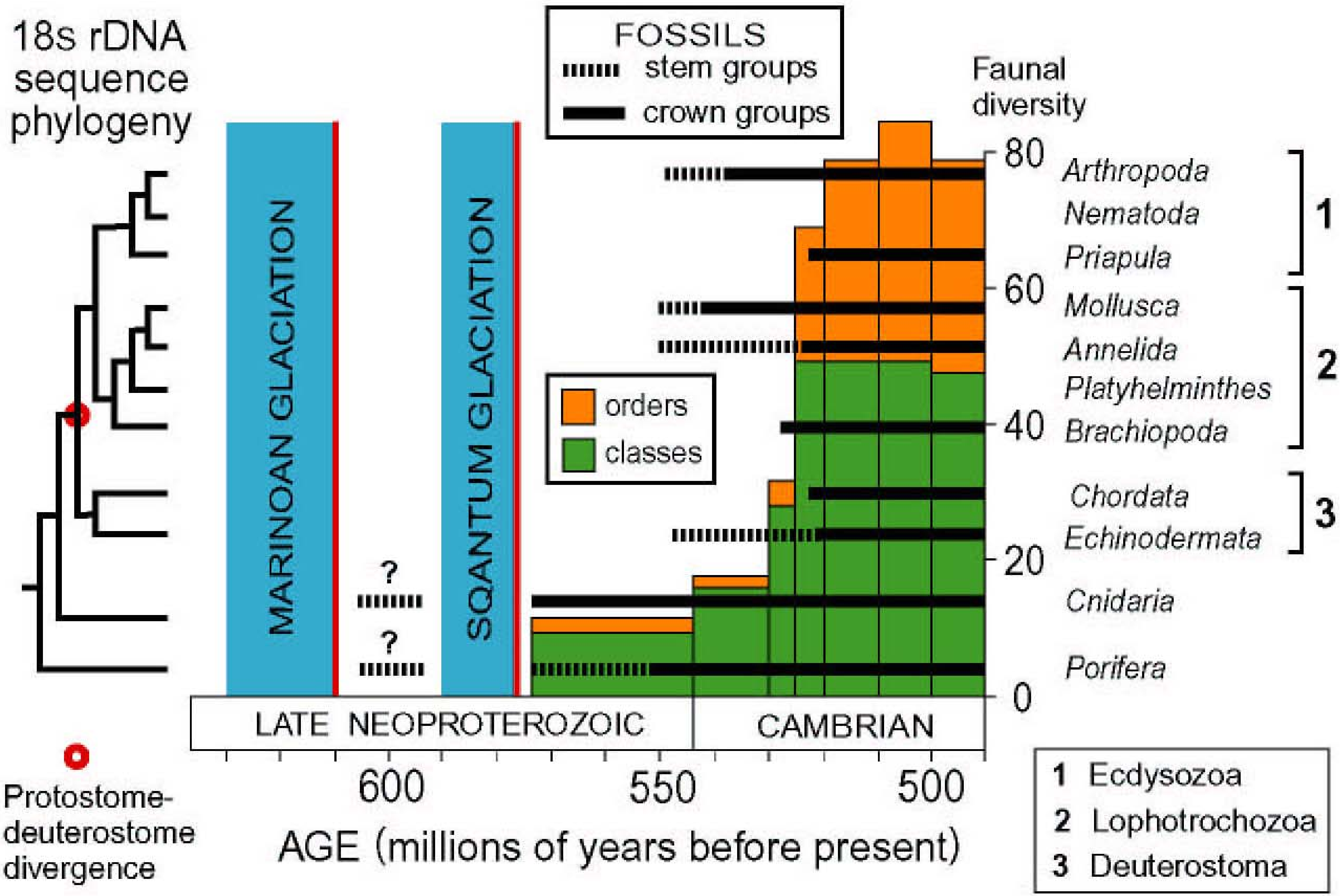
Key Concepts

- Only a fraction of Ediacaran fauna share traits with existing lineages
  - Almost all extinct within 40 million years
- Most existing lineages are found in the fossil record during the Cambrian period
  - Includes our own lineage, the chordates

A recent estimate of relationships among animal phyla



← Last One!



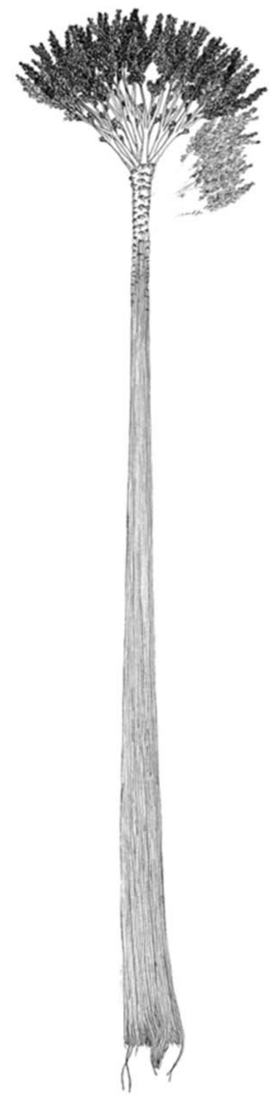
THE METAZOAN EXPLOSION

Transition from ocean to land a major event in evolution

- Prokaryotes colonized terrestrial environments first
  - Fossils date to 2.6 bya
- Terrestrial animals, plants, and fungi, appeared much later

First terrestrial plant and fungal life

- Oldest terrestrial plant fossils are 475 myo
  - Early plants resembled mosses and liverworts
- Large forest ecosystems within 100 million years
- Fungi appear ~ 400 myo
  - Associated with plants

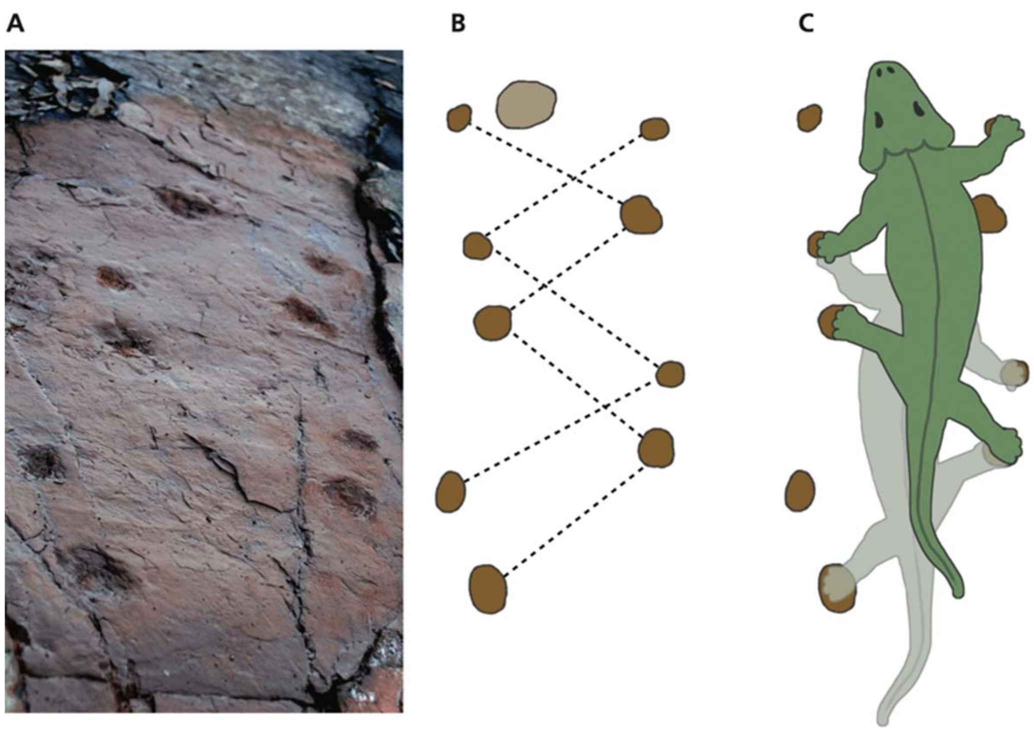


First terrestrial animal life

- Invertebrate trackways date to 480 mya
  - Probably relatives of insects and spiders
  - Not clear whether they lived on land permanently
- Oldest fossil of fully terrestrial animal dates to 428 mya

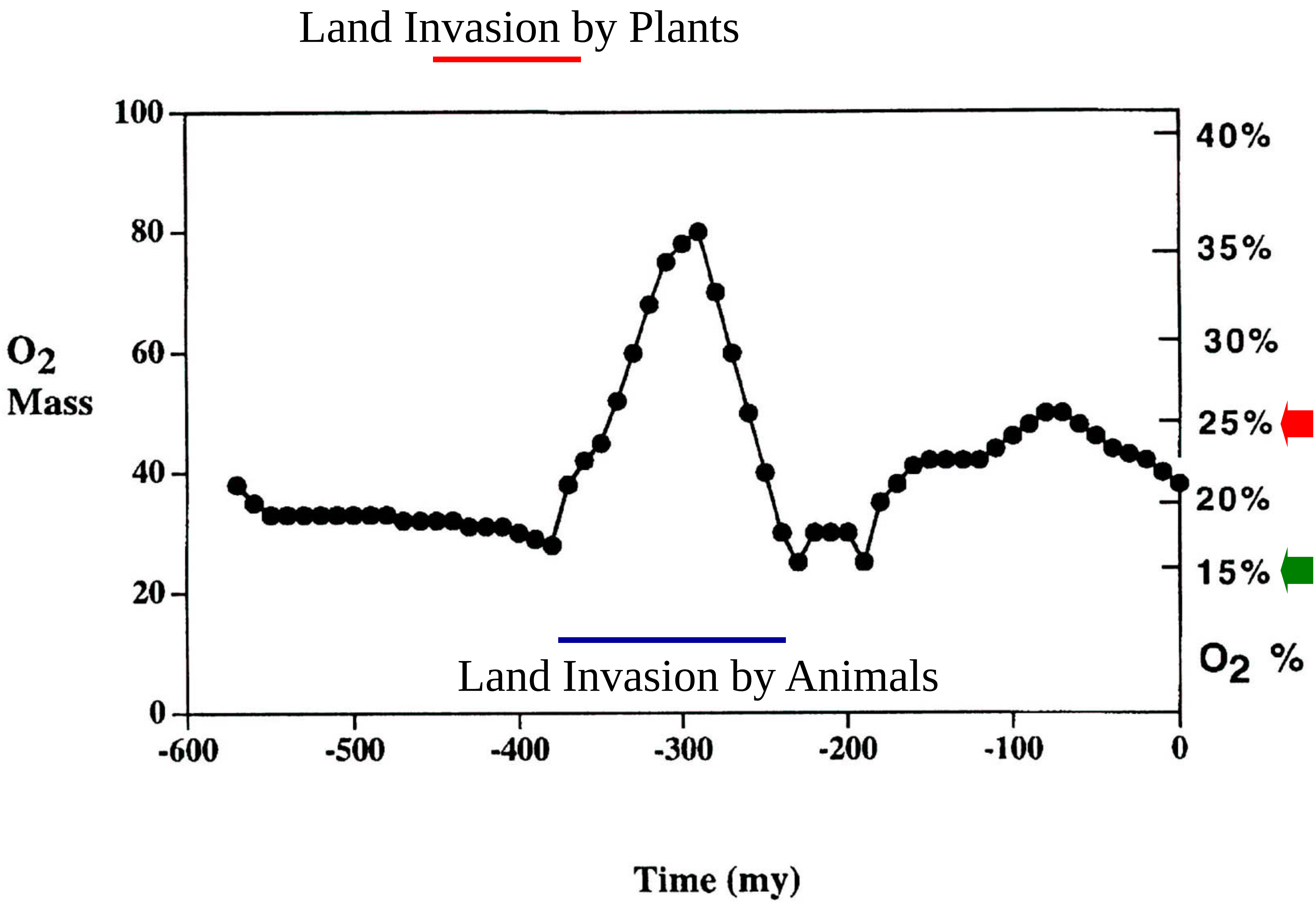
First terrestrial vertebrates

- Oldest trackways date to 390 mya
- Oldest fossils of **tetrapods** date to 370 mya



Familiar forms of life did not emerge until recently

- 350 million years ago many currently existing lineages had yet to evolve
  - Teleost fish
  - Mammals
  - Birds
  - Flowering plants



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!
  - 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**

Evolution of mammals

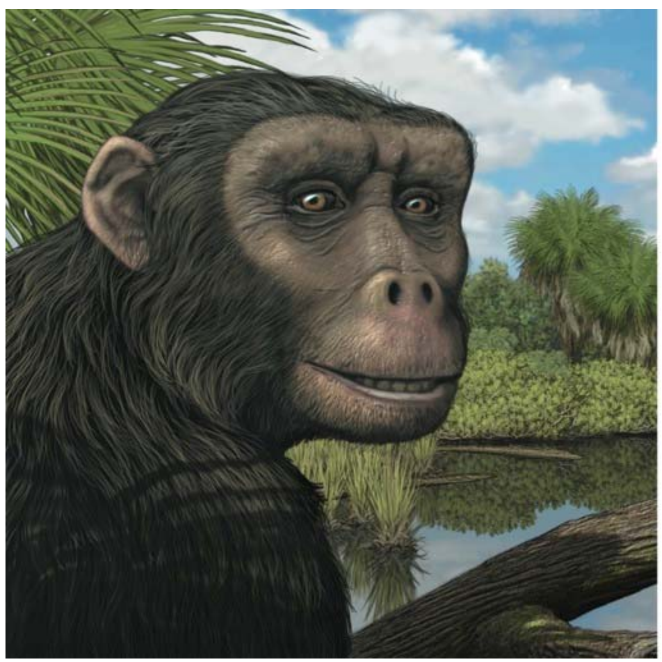
- Mammals evolved from **synapsids**
  - Dominant vertebrates around 280 myo
  - First mammals emerged 150 mya

Evolution of other major lineages

- Birds: ~150 mya
  - Descendants of dinosaurs
- Flowering plants: ~132 mya
  - Grasses did not diversify until ~20 mya
- Insects: emerged ~400 mya but most current lineages appear much later

Diversification of mammals

- Mammals diversified after dinosaurs went extinct (~65 mya)
- Whales, bats, and primates all emerged around 50 mya

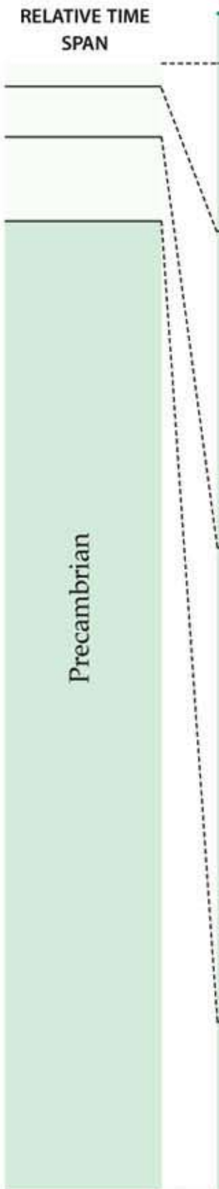


Oldest human fossils are ~200,000 years old

Key Concepts

- Many of the most diverse existing plant and animal lineages evolved relatively recently
- Fortuitous Contingency concept once again regarding oxygen and extinctions, etc.

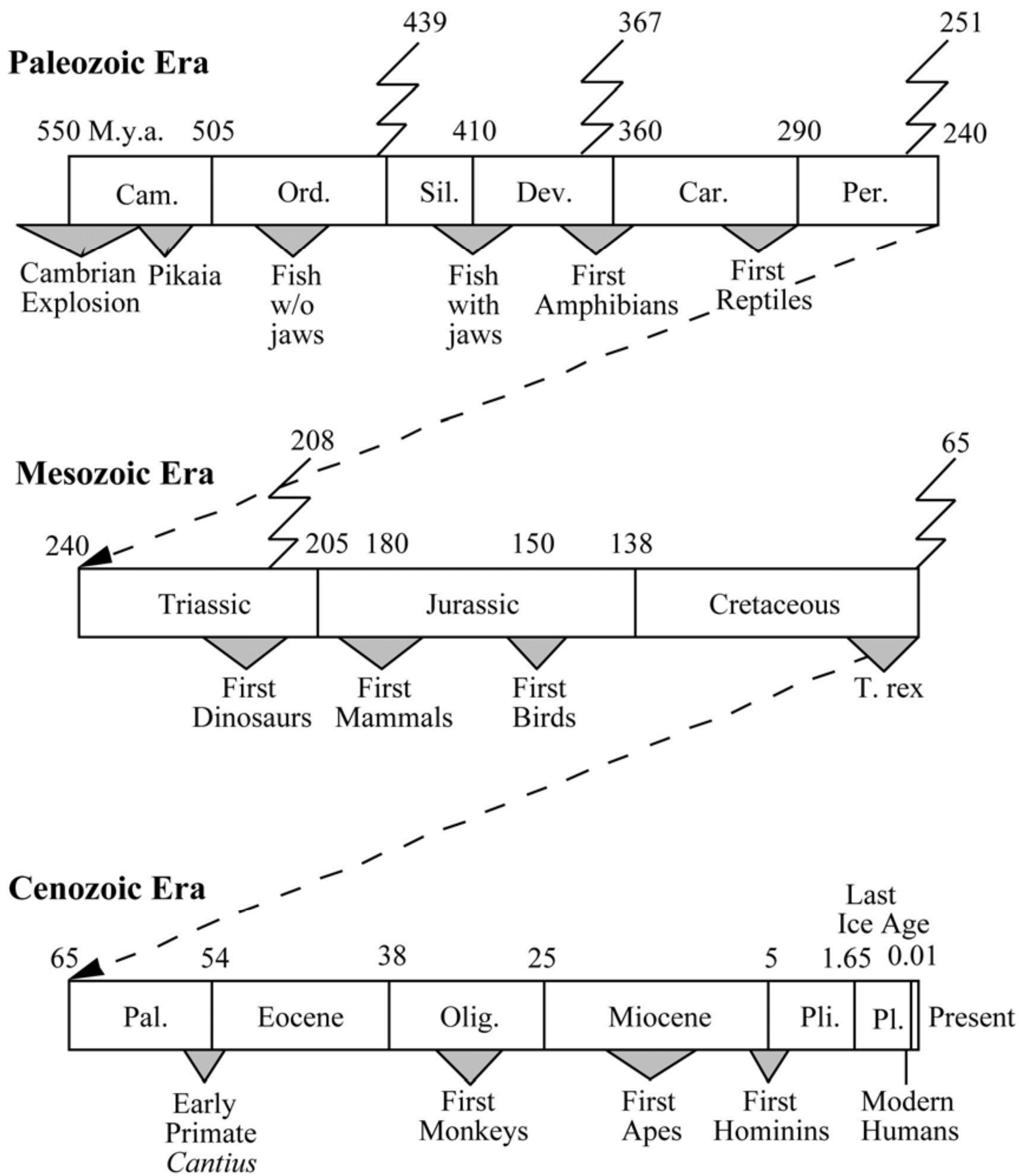
22.1 **Earth's Geological History** *(Part 2)*



ERA	PERIOD	ONSET	MAJOR EVENTS IN THE HISTORY OF LIFE
Cenozoic	Quaternary	1.8 mya[a]	Humans evolve; many large mammals become extinct
	Tertiary	65 mya	Diversification of birds, mammals, flowering plants, and insects
Mesozoic	Cretaceous	144 mya	Dinosaurs continue to diversify; flowering plants and mammals diversify. **Mass Extinction** at end of period (≈76% of species disappear)
	Jurassic	206 mya	Diverse dinosaurs; radiation of ray-finned fishes
	Triassic	248 mya	Early dinosaurs; first mammals; marine invertebrates diversify; first flowering plants; **Mass Extinction** at end of period (≈65% of species disappear)
Paleozoic	Permian	290 mya	Reptiles diversify; amphibians decline; **Mass Extinction** at end of period (≈96% of species disappear)
	Carboniferous	354 mya	Extensive "fern" forests; first reptiles; insects diversify
	Devonian	417 mya	Fishes diversify; first insects and amphibians. **Mass Extinction** at end of period (≈75% of species disappear)
	Silurian	443 mya	Jawless fishes diversify; first ray-finned fishes; plants and animals colonize land
	Ordovician	490 mya	**Mass Extinction** at end of period (≈75% of species disappear)
	Cambrian	543 mya	Most animal phyla present; diverse algae
Precambrian		600 mya	Ediacaran fauna
		1.5 bya[a]	Eukaryotes evolve; several animal phyla appear
		3.8 bya	Origin of life; prokaryotes flourish
		4.5 bya	

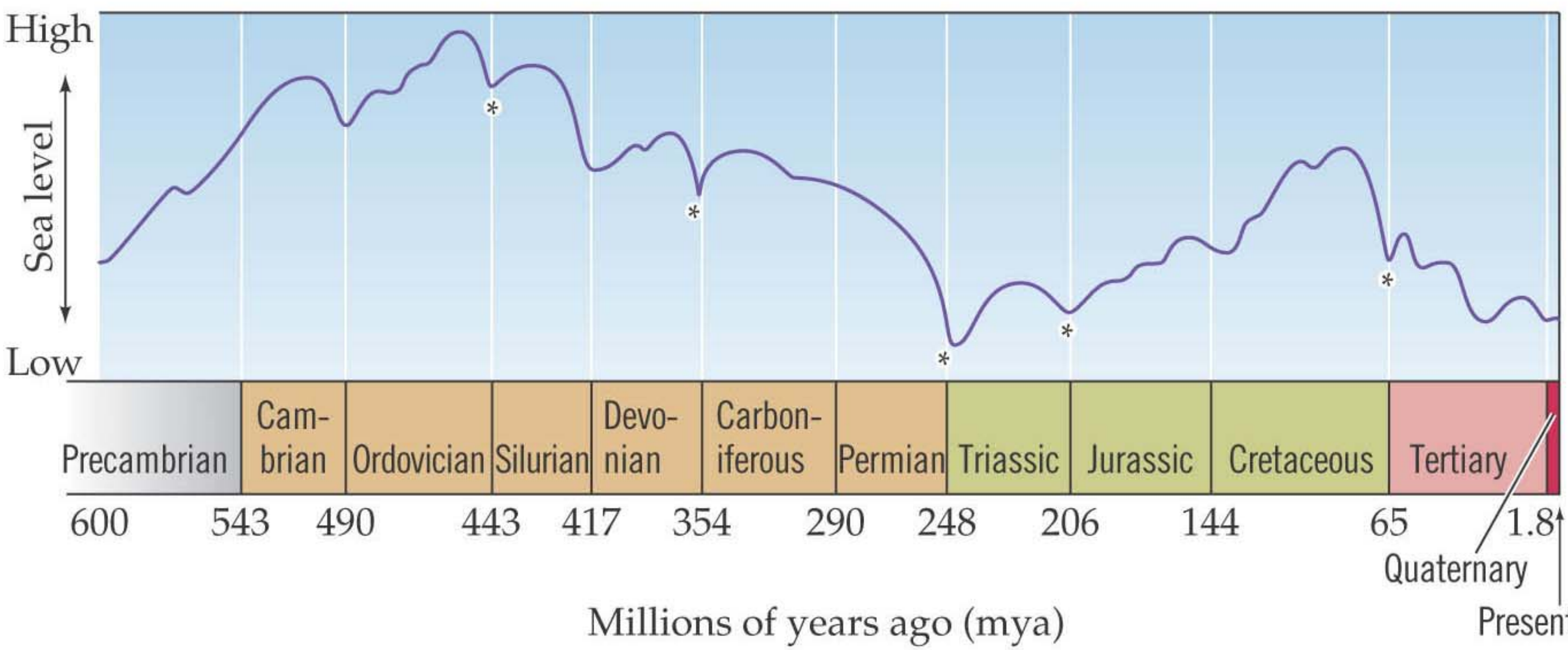
[a]mya, million years ago; bya, billion years ago.

The Phanerozoic Eon

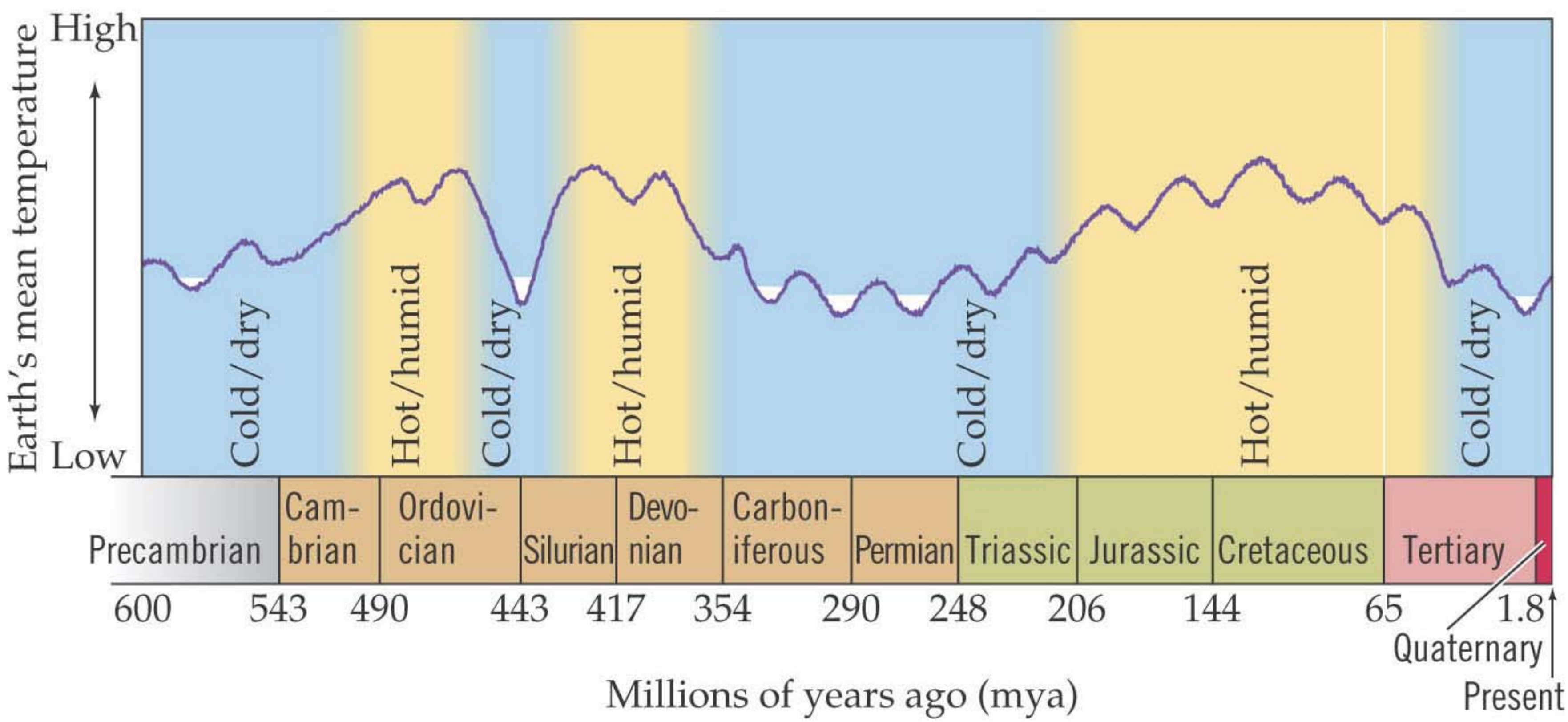


All dates are in millions of years ago, M.y.a.

Sea Levels Have Changed Repeatedly



Hot/Humid and Cold/Dry Conditions Have Alternated Over Earth's History

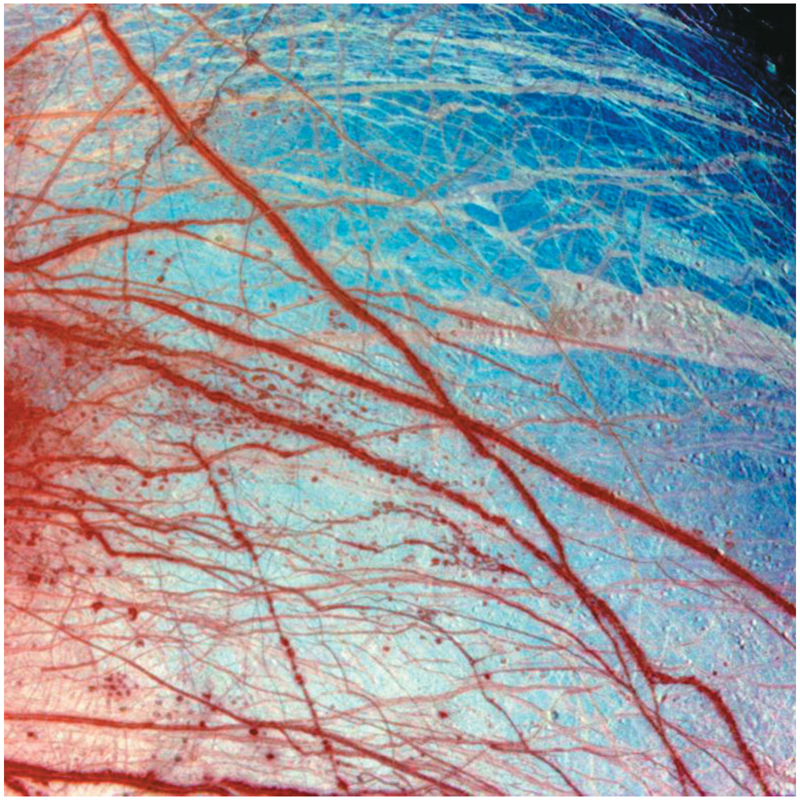


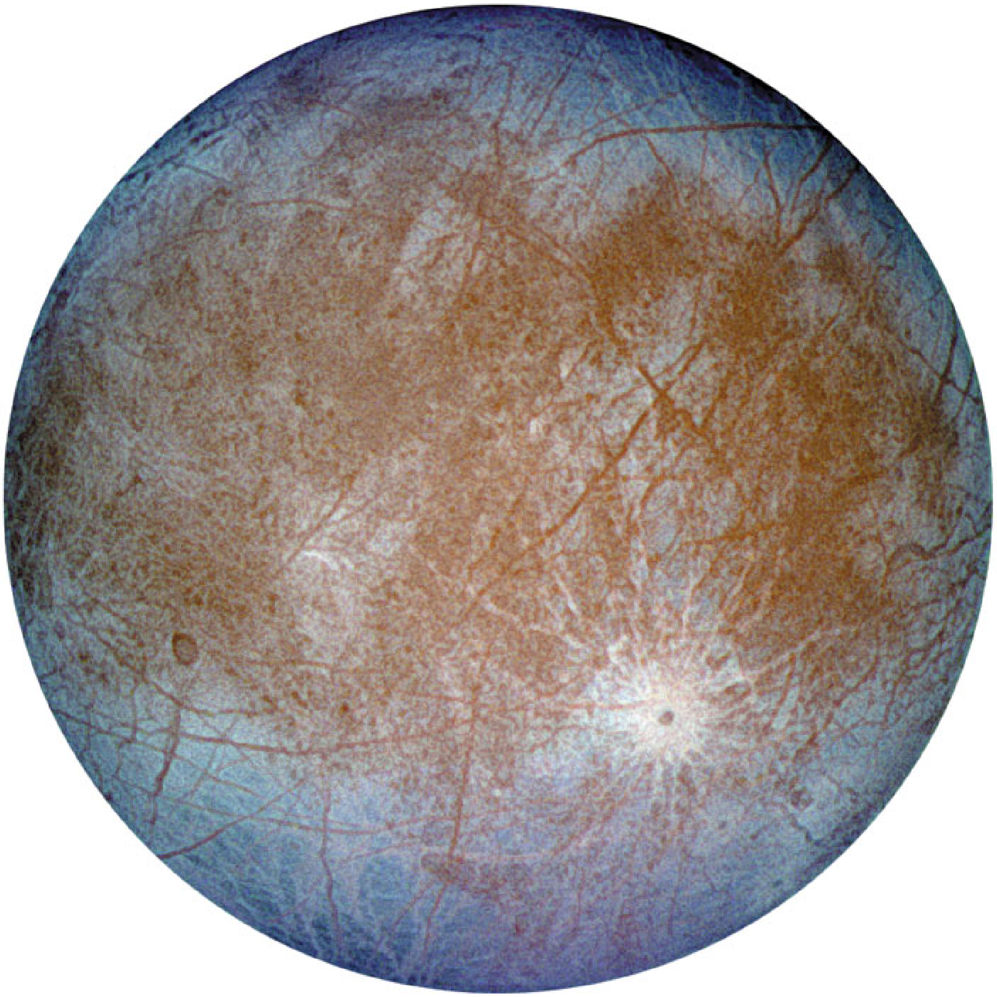
Does Life Exist Elsewhere in the Universe?

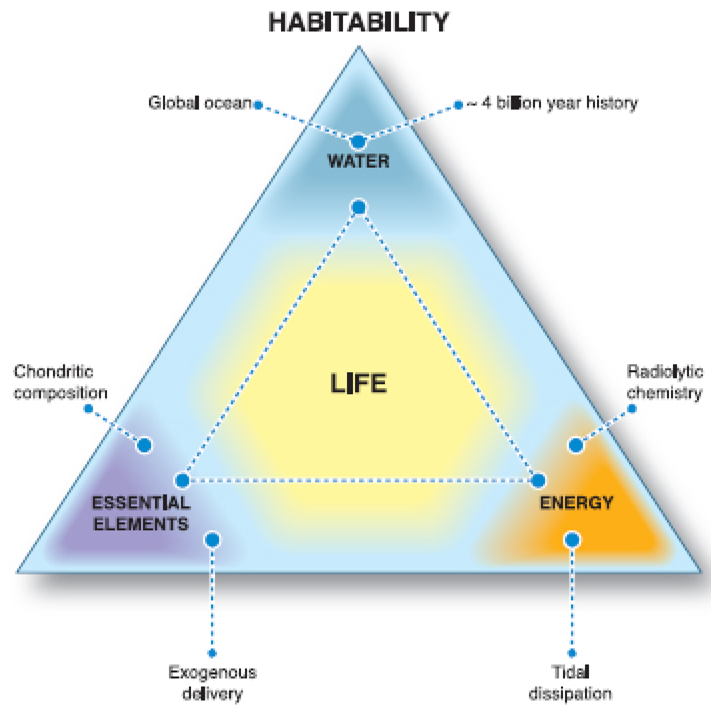
- Conditions that permit the evolution and maintenance of simple prokaryotic life may be widespread in the universe, but multicellular life has more stringent requirements.
  - a planet with a relatively circular orbit
  - a rapid rate of spin
  - nearby planets that intercept impacts
  - a large moon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

Such conditions may be very rare.

Europa, Jupiter's moon: Astrobiology???







The habitability of Europa. At present, our understanding of the conditions necessary for life can be distilled down to three broad requirements: (1) a sustained liquid water environment, (2) a suite of elements critical for building life (e.g., C, H, N, O, P, S), and (3) a source of energy that can be utilized by life. Here we show how these "pillars of habitability" intersect with our current understanding of the conditions on, and within, Europa.