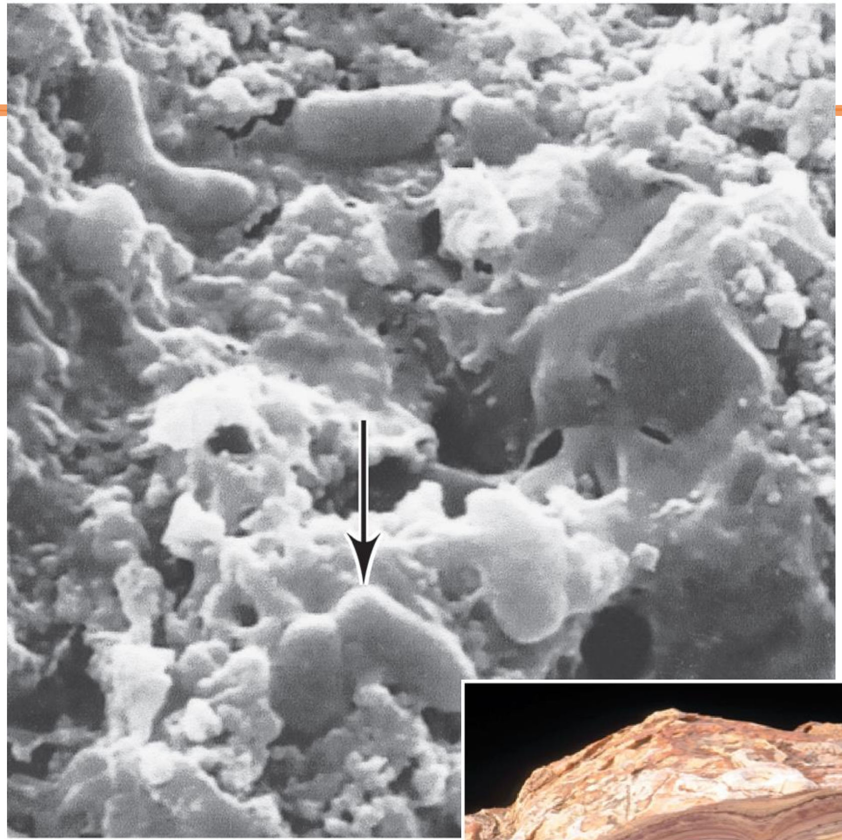
History of life on Earth

Formation and Early History of Earth

- Earth is ~4.5 billion years old
- Bombardment of Earth by rocks and ice vaporized water and prevented seas from forming before about 4 billion years ago
- Earth's early atmosphere had little oxygen and likely contained water vapor and chemicals released by volcanic eruptions
  - Liquid water required for life; first appeared ~4.3 billion years ago
  - Fossilized remains of cells can be found in rocks ~3.5 billion years old
    - **stromatolites** formed by prokaryotes



Microfossil bacteria from 3.45-billion-year-old rocks. Section stromatolites.

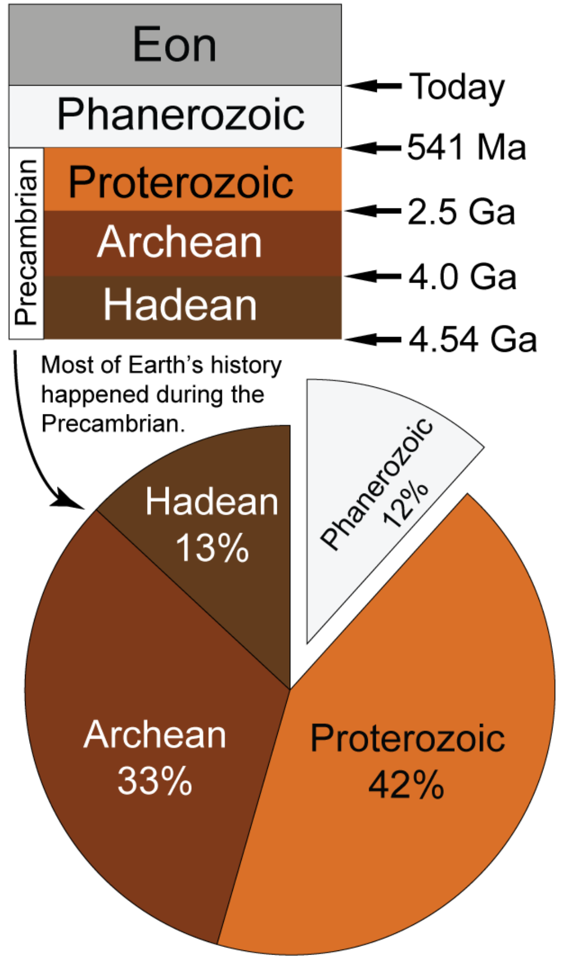
Geologic time scale

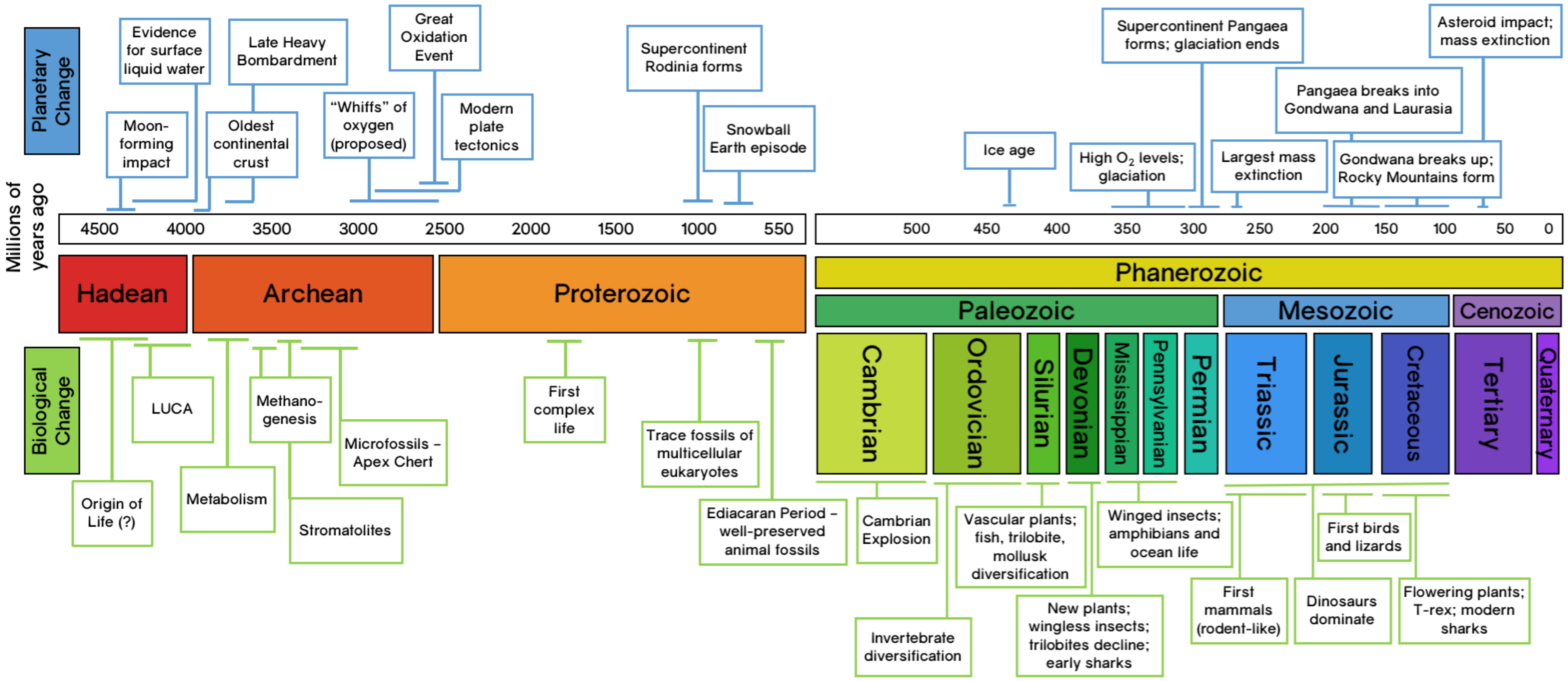
- Eons are typically divided into smaller units called eras, which are further subdivided into periods, epochs, and ages.

Younger ↔ Older

Eon	Era	Period		Epoch
Phanerozoic	Cenozoic	Quaternary		Holocene
				Pleistocene
		Neogene		Pliocene
				Miocene
		Paleogene		Oligocene
				Eocene
				Paleocene
	Mesozoic	Cretaceous		~
		Jurassic		~
		Triassic		~
	Paleozoic	Permian		~
		Carboni-ferous	Pennsylvanian	~
			Mississippian	~
		Devonian		~
		Silurian		~
		Ordovician		~
		Cambrian		~
Proterozoic	~	~		~
Archean	~	~		~
Hadean	~	~		~

Today
11.8 Ka
66 Ma
252 Ma
541 Ma
2.5 Ga
4.0 Ga
4.54 Ga





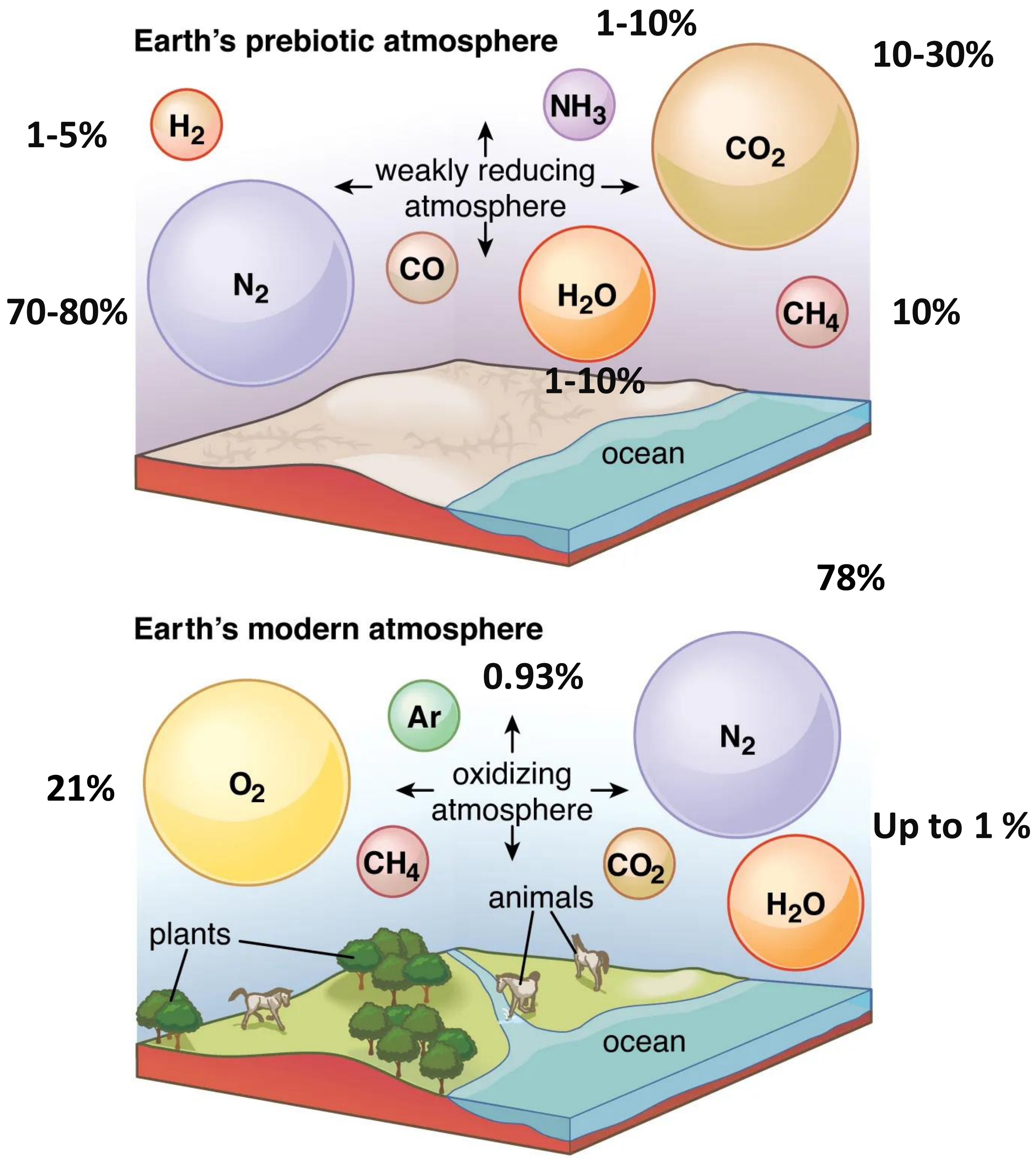
Planetary Change
Evidence for surface liquid water
Late Heavy Bombardment
Great Oxidation Event
Supercontinent Rodinia forms
Supercontinent Pangaea forms; glaciation ends
Asteroid impact; mass extinction
Moon-forming impact
Oldest continental crust
"Whiffs" of oxygen (proposed)
Modern plate tectonics
Snowball Earth episode
Pangaea breaks into Gondwana and Laurasia
Ice age
High O_2 levels; glaciation
Largest mass extinction
Gondwana breaks up; Rocky Mountains form
Millions of years ago
4500
4000
3500
3000
2500
2000
1500
1000
550
500
450
400
350
300
250
200
150
100
50
0
Hadean
Archean
Proterozoic
Phanerozoic
Paleozoic
Mesozoic
Cenozoic
Cambrian
Ordovician
Silurian
Devonian
Mississippian
Pennsylvanian
Permian
Triassic
Jurassic
Cretaceous
Tertiary
Quaternary
Biological Change
LUCA
Methano-genesis
Microfossils – Apex Chert
First complex life
Trace fossils of multicellular eukaryotes
Origin of Life (?)
Metabolism
Stromatolites
Ediacaran Period – well-preserved animal fossils
Cambrian Explosion
Vascular plants; fish, trilobite, mollusk diversification
Winged insects; amphibians and ocean life
First birds and lizards
Invertebrate diversification
New plants; wingless insects; trilobites decline; early sharks
First mammals (rodent-like)
Dinosaurs dominate
Flowering plants; T-rex; modern sharks

Eons and major events in the history of life: summary

On Earth, geologists recognize four major eons in the planet's history:

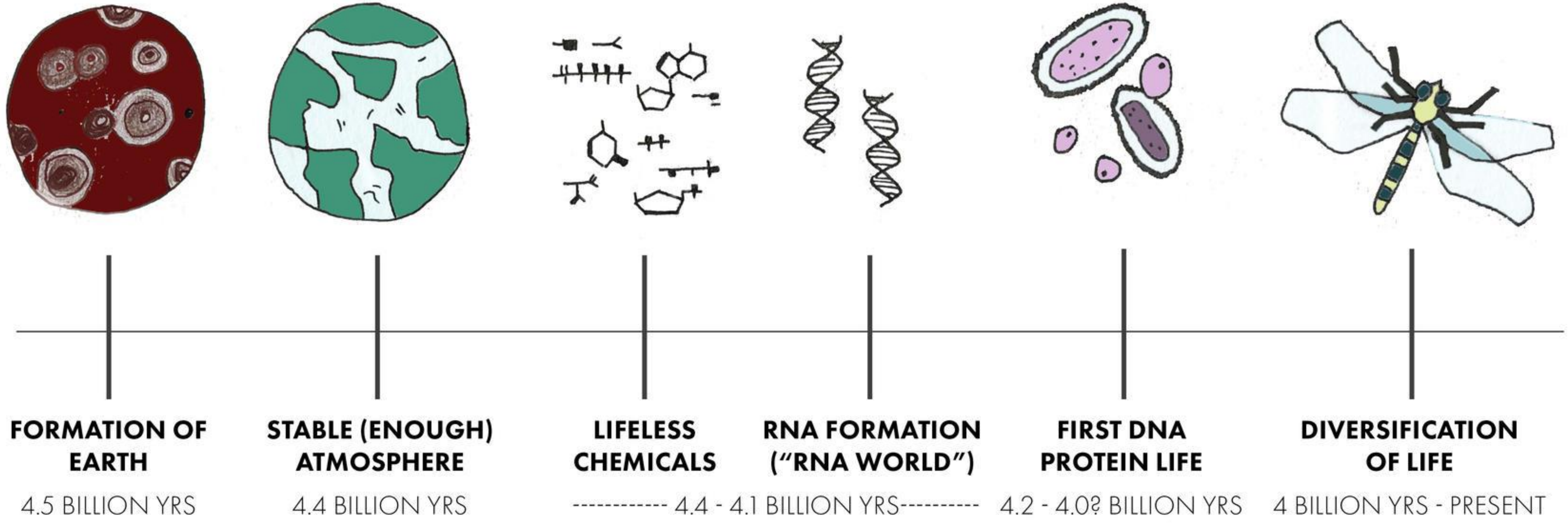
1. **Hadean Eon**: This is the earliest eon in Earth's history, spanning from the formation of the planet about 4.6 billion years ago to around 4 billion years ago. The Hadean Eon is characterized by intense heat, frequent impacts from asteroids and comets, and the formation of the Earth's core, mantle, and crust.
2. **Archean Eon**: The Archean Eon extends from about 4 billion years ago to around 2.5 billion years ago. It is characterized by the emergence of life on Earth, the formation of the first continents and oceans, and the development of an early atmosphere and hydrosphere.
3. **Proterozoic Eon**: The Proterozoic Eon spans from around 2.5 billion years ago to about 541 million years ago. It is marked by significant geological and biological events, including the evolution of photosynthetic organisms, the rise of atmospheric oxygen, the formation of multicellular life, and the development of complex ecosystems.
4. **Phanerozoic Eon**: The Phanerozoic Eon began around 541 million years ago and continues to the present day. It is characterized by the proliferation of complex life forms, including vertebrates, plants, and invertebrates, as well as the diversification of ecosystems and the formation of the continents as we know them today. The Phanerozoic Eon is further divided into three eras: the Paleozoic, Mesozoic, and Cenozoic.

The early prebiotic atmosphere



Abiogenesis

Abiogenesis is the scientific hypothesis stating that life arose from non-living matter through natural processes. It proposes that the complex molecules necessary for life, such as proteins, nucleic acids, and other organic compounds, gradually formed from simpler chemicals in the early Earth's environment. Over time, these molecules organized themselves into the first self-replicating entities, eventually leading to the emergence of life as we know it.



Abiotic Synthesis of Organic Molecules Is Possible

- In the 1920s, the Russian chemist A. I. Oparin and the British scientist J. B. S. Haldane independently proposed that conditions on early Earth could have generated organic molecules.
- In 1953, Stanley Miller and Harold Urey conducted lab experiments demonstrating that the abiotic synthesis of organic molecules in a reducing atmosphere was possible
- As a strong oxidizing agent, O_2 tends to disrupt chemical bonds. However, before the early photosynthetic prokaryotes added O_2 to the air, Earth may have had a reducing atmosphere.

Origins of abiogenesis theories: Oparin and Haldane, 1920

- **Reducing atmosphere**: Oparin and Haldane suggested that the Earth's early atmosphere was reducing, meaning it lacked oxygen, and contained gases like methane, ammonia, hydrogen, and water vapor. They proposed that energy from sources such as lightning, volcanic activity, and UV radiation could have triggered chemical reactions among these simple gases, leading to the formation of more complex organic molecules.

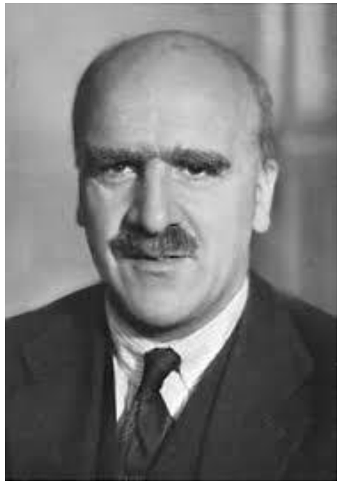
- **Formation of Organic Molecules**: Within this primordial soup, Oparin and Haldane hypothesized that simple organic molecules, such as amino acids, nucleotides, and sugars, could have formed through chemical reactions. These molecules would have been the building blocks of life.

- **Polymerization**: Once these organic molecules formed, they could have undergone polymerization, a process in which smaller molecules link together to form larger, more complex molecules. This process could have given rise to macromolecules like proteins, nucleic acids, and carbohydrates, which are essential for life.

- **Formation of Protocells**: Oparin and Haldane proposed that these complex organic molecules could have assembled into protocells—predecessors to modern cells—that were enclosed by lipid membranes. While not yet true cells, protocells may have exhibited some rudimentary properties of life, such as metabolism and replication.

- **Origin of Life**: Over time, these protocells could have evolved further through natural selection and other mechanisms, eventually leading to the emergence of cellular life forms.

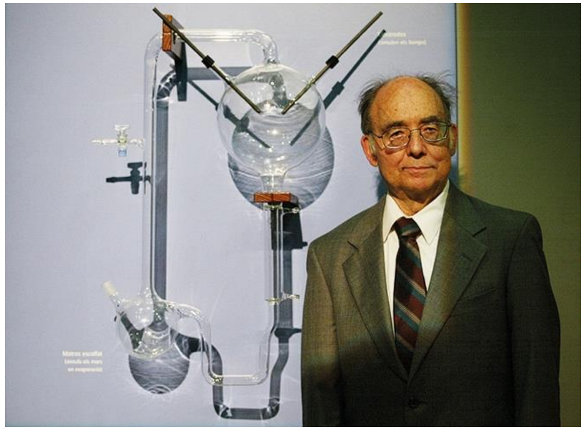
Aleksander Oparin



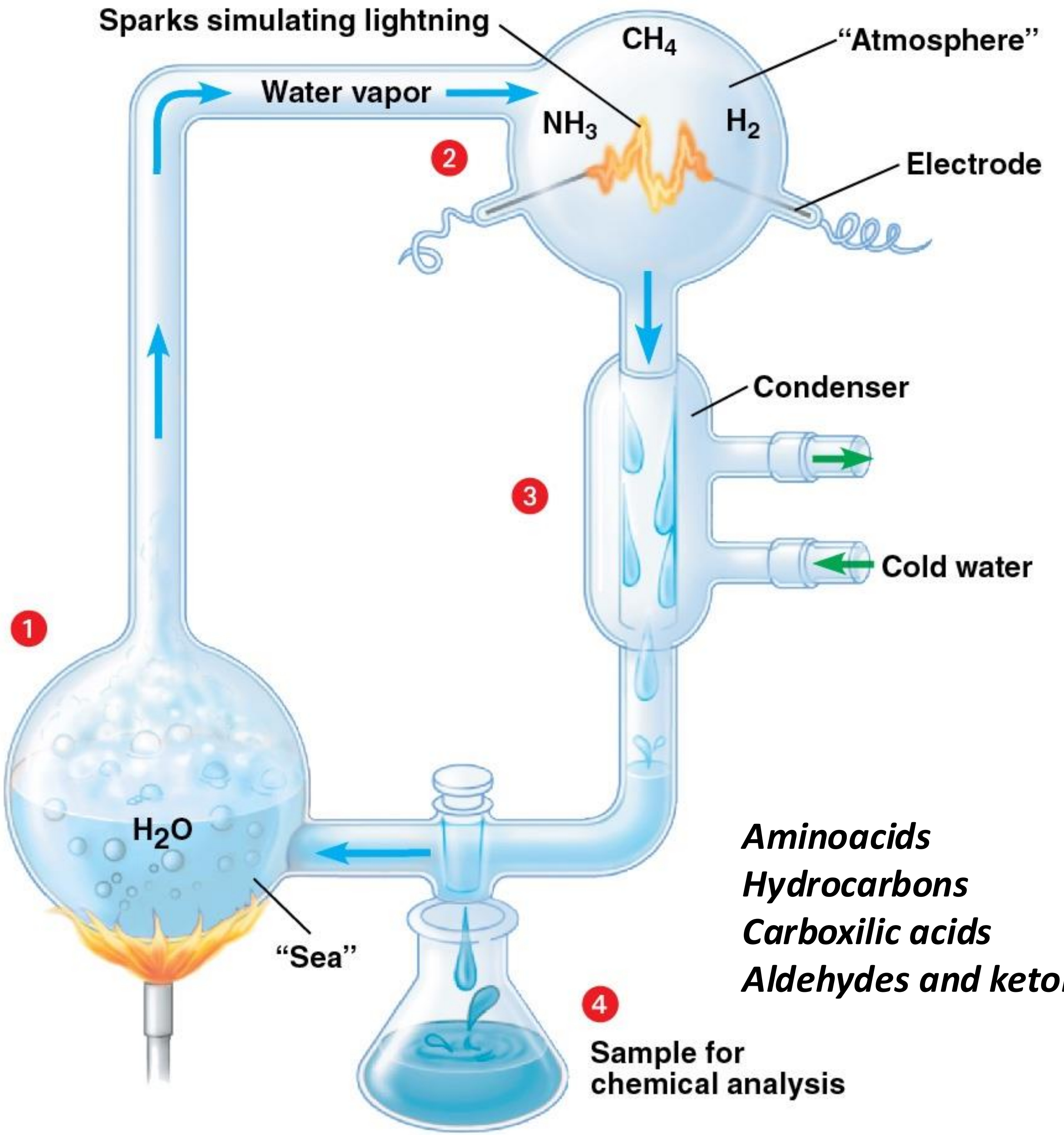
J.B.S. Haldane

Experiment Miller and Urey, 1953

Harold Urey (1893-1981)



Stanley Milley (1930-2007)



Aminoacids
Hydrocarbons
Carboxilic acids
Aldehydes and ketones

Abiogenesis, summary

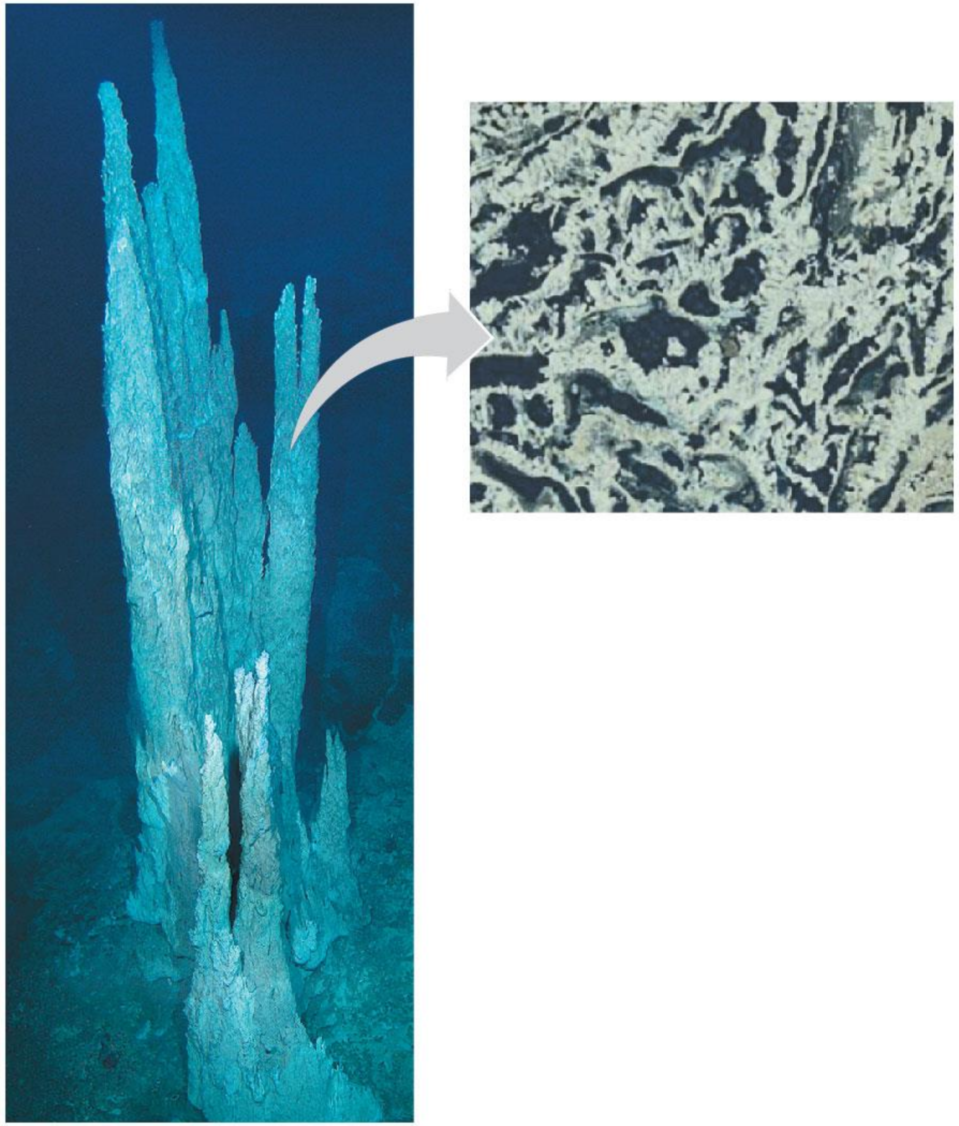
- Chemical and physical processes on early Earth may have produced very simple cells through a sequence of stages
  1. Abiotic synthesis of small organic molecules, such as amino acids and nitrogenous bases
  2. Joining of these small molecules into macromolecules (polymers such as nucleic acids and proteins)
  3. Packaging of molecules into **protocells**
  4. Origin of self-replicating molecules - making inheritance possible

Abiogenesis: role volcanoes

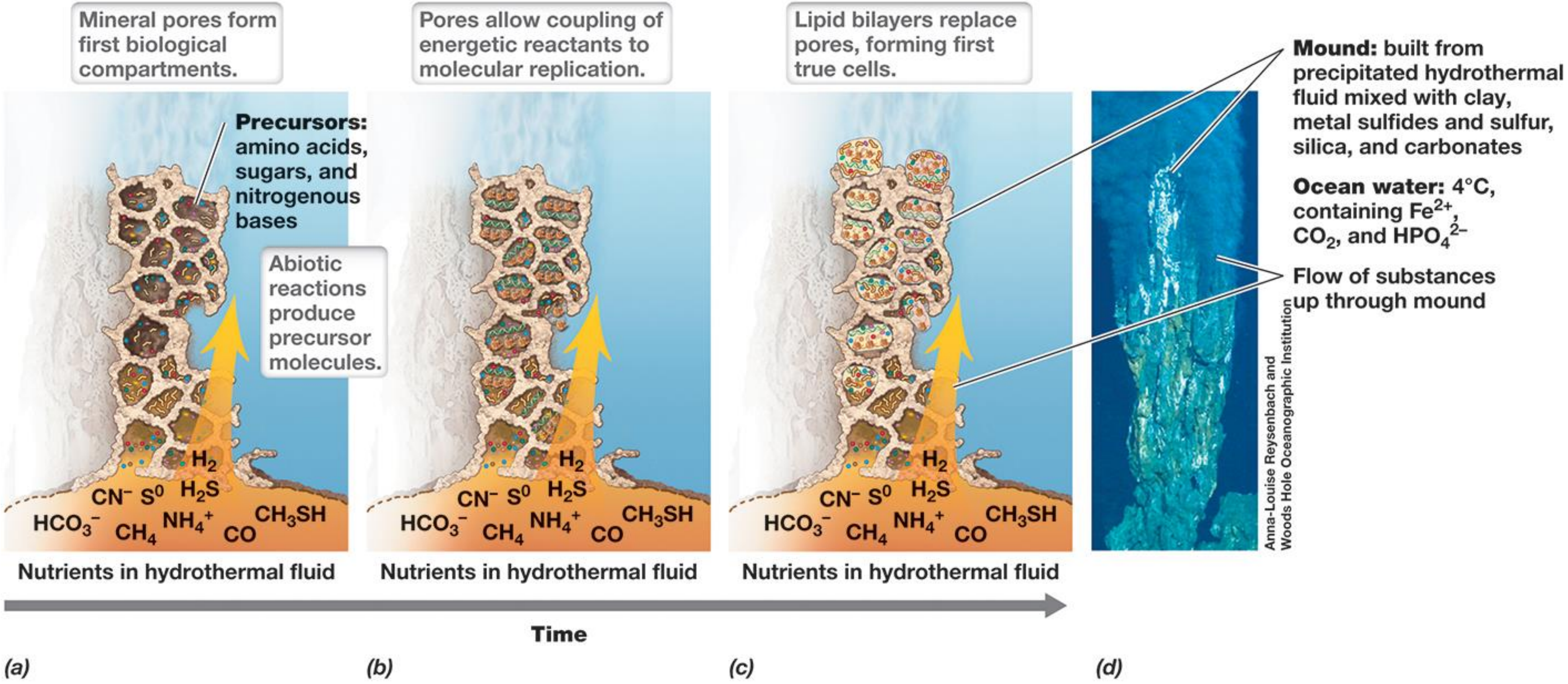
- However, some evidence suggests that the early atmosphere was neither reducing nor oxidizing
- The first organic compounds may have formed in reducing conditions near the openings of volcanoes
- Reanalysis of molecules formed in Miller’s experiments found that numerous amino acids formed under conditions simulating volcanic eruption
- Volcanoes and hydrothermal vents can produce reducing environments due to the release of gases and fluids rich in reducing compounds such as hydrogen (H2), methane (CH4), and hydrogen sulfide (H2S).

Abiogenesis: role hydrothermal vents

- Organic compounds may have been produced in deep-sea **hydrothermal vents**, areas on the seafloor where hot water and minerals gush from Earth's interior into the ocean
- Environmental conditions produced near deep-sea vents vary
- "Black smokers" release water at 300–400 °C
- **Alkaline vents** release water with high pH (9–11) and warm water (40–90 °C)
- Conditions near alkaline vents were likely very suitable for the formation of stable organic compounds



Submarine Mounds and Their Possible Link to the Origin of Life



Meteorites may have been an additional source of organic molecules

- For example, fragments of the Murchison meteorite (Australia) contain more than 80 amino acids and other key organic molecules, including lipids, simple sugars, and nitrogenous bases

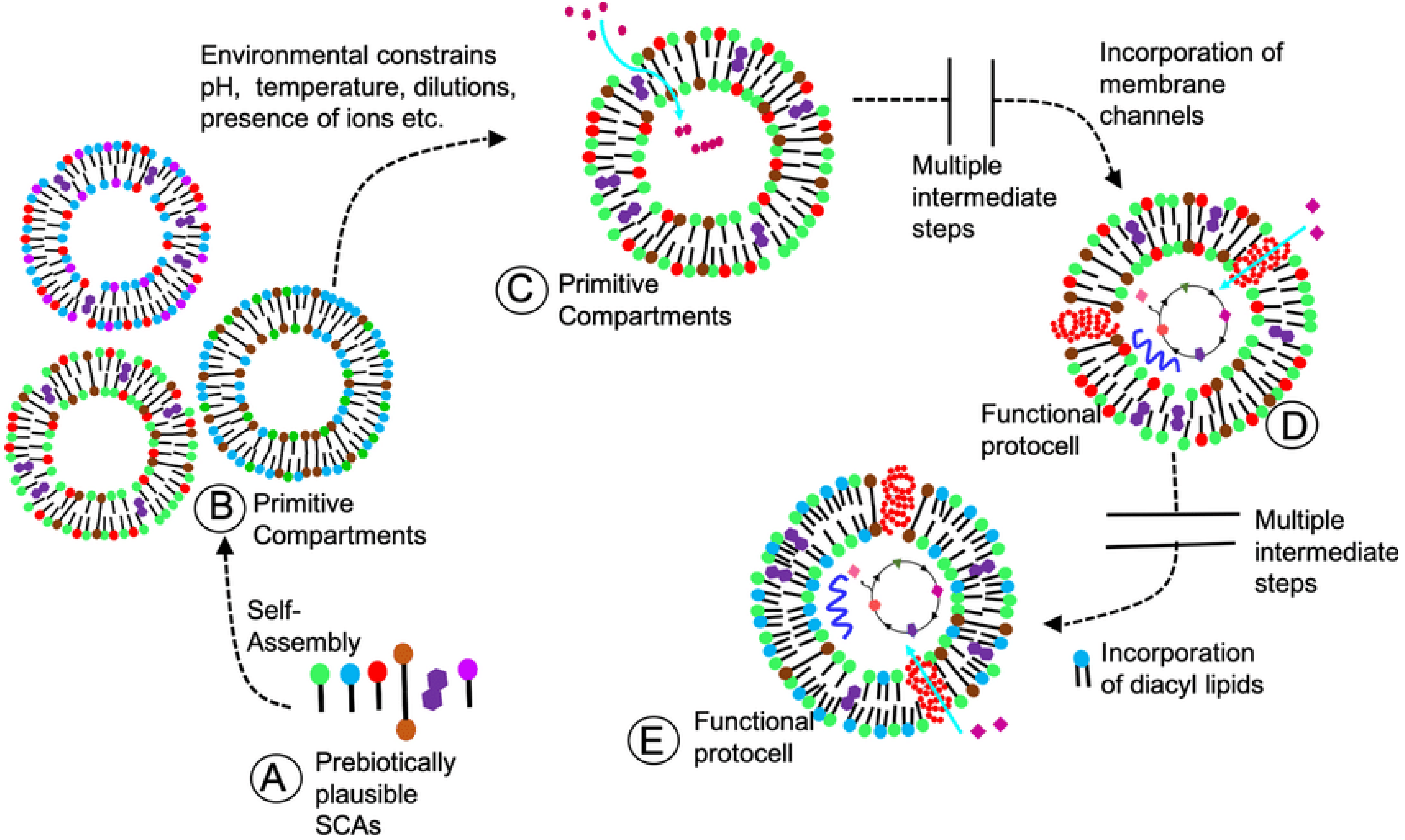
Origin of the First Cells

- The next three stages could have occurred on early Earth.
  1. Abiotic synthesis of polymers
  2. Formation of protocells
  3. Self-replicating RNA:
     RNA monomers have been produced spontaneously from simple molecules

Natural selection could have acted on protocells that contained self-replicating molecules.

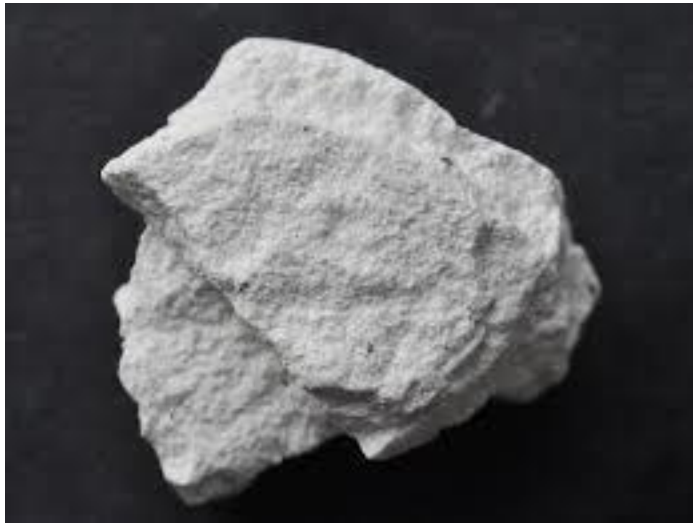
Protocells

- Replication and metabolism are key properties of life and may have appeared together in protocells
- Protocells may have formed from fluid-filled vesicles with a membrane-like structure
- In water, lipids and other organic molecules can spontaneously form vesicles with a lipid bilayer

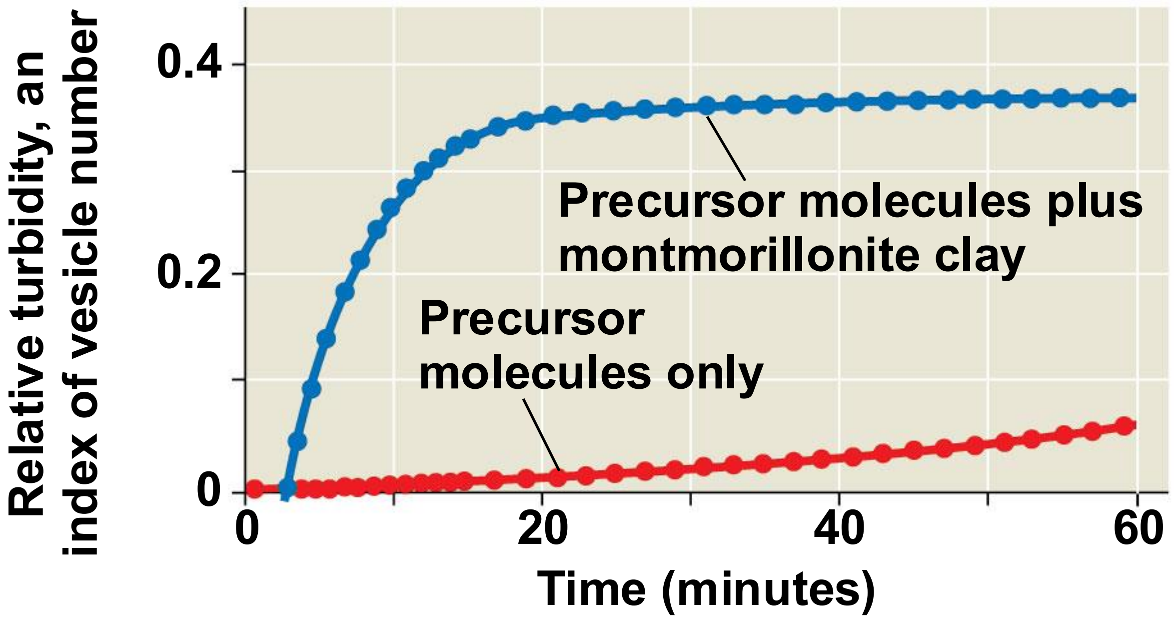


Environmental constrains
pH, temperature, dilutions,
presence of ions etc.
C Primitive Compartments
Multiple intermediate steps
Incorporation of membrane channels
Functional protocell
D
B Primitive Compartments
Self-Assembly
A Prebiotically plausible SCAs
Multiple intermediate steps
Incorporation of diacyl lipids
E Functional protocell

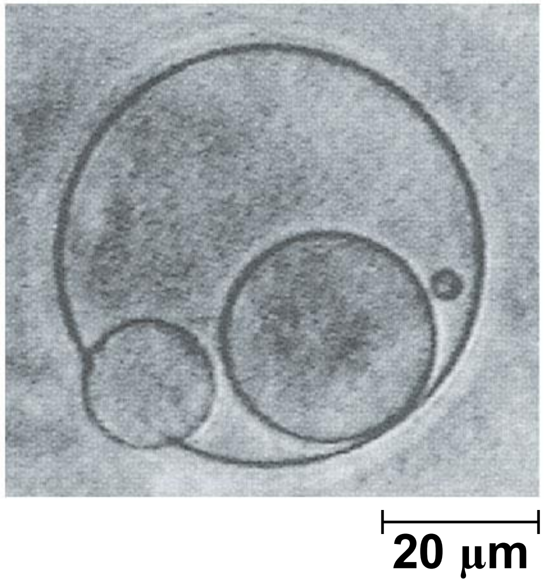
- Adding montmorillonite, a soft mineral clay common on early Earth, greatly increases the rate of vesicle formation
- Vesicles exhibit simple growth, reproduction, and metabolism
- They can absorb organic molecules attached to montmorillonite particles through a selectively permeable bilayer



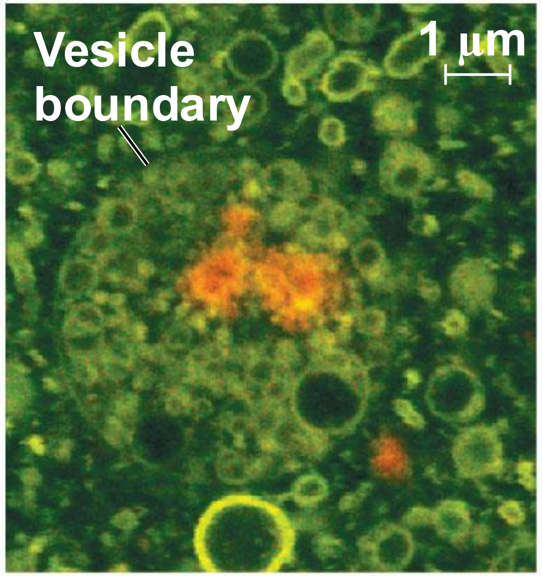
Montmorillonite



Self-assembly



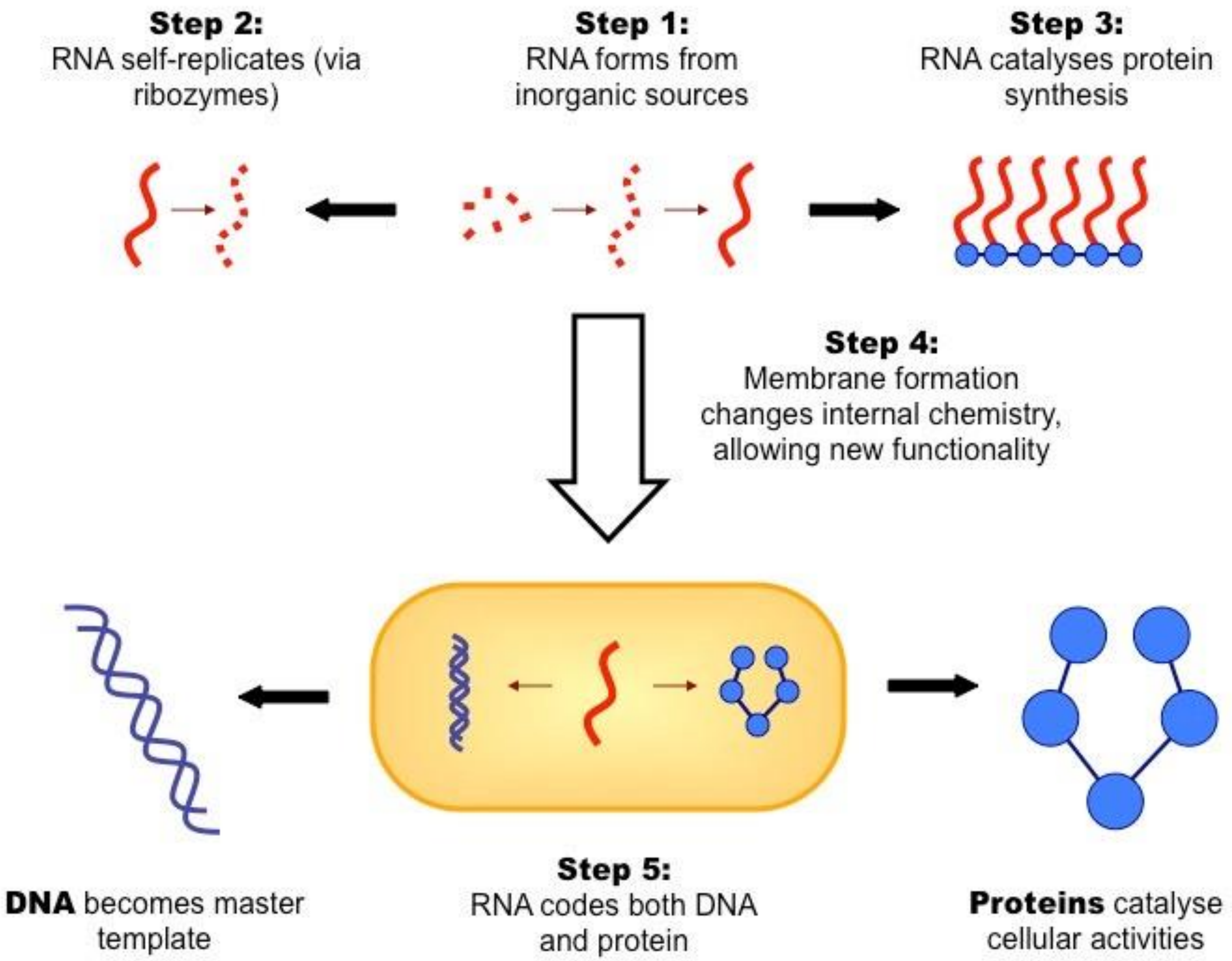
Reproduction



Absorption of RNA

Origins of cellular life: RNA world hypothesis

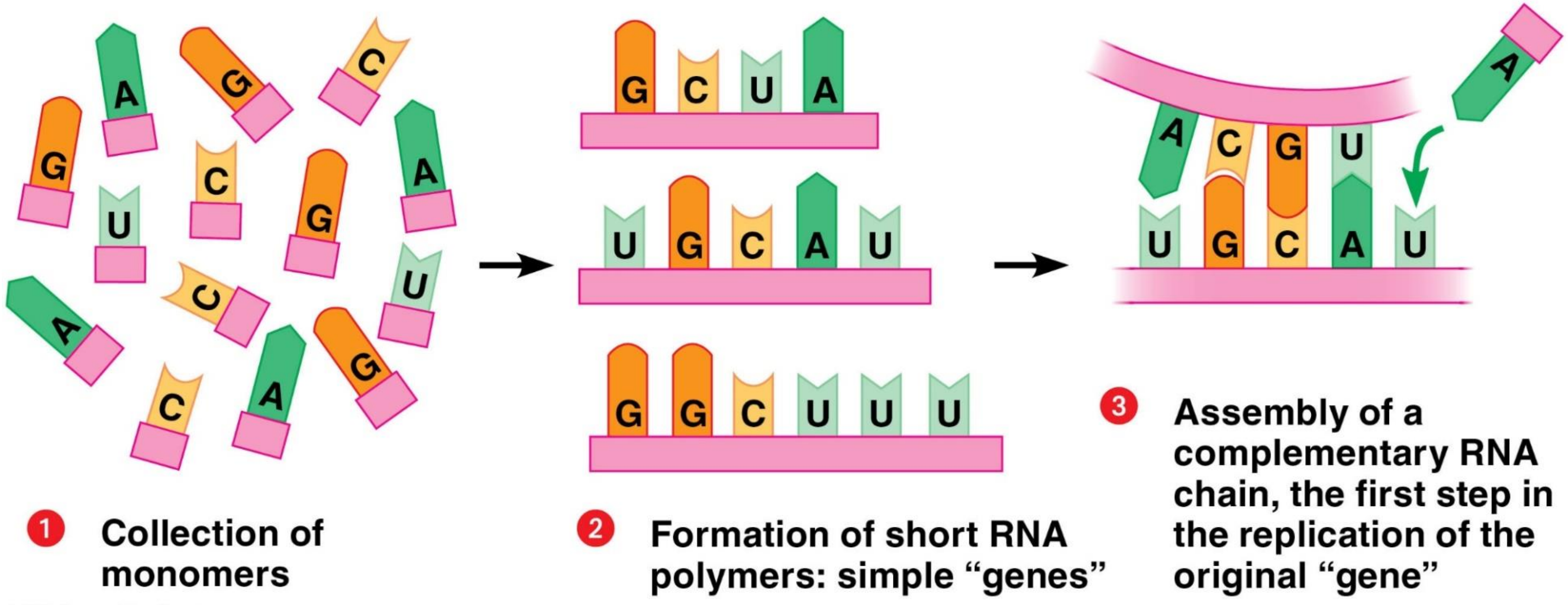
- The first genetic material was probably RNA, not DNA
- RNA can fold into complex three-dimensional structures and catalyse biochemical reactions, serving as both a genetic material and an enzyme (ribozyme).
- **Ribozymes** have been found to catalyze many different reactions
    - For example, ribozymes can make complementary copies of short stretches of RNA
    - Backbone of essential molecules (**e.g.,** ATP, NADH, coenzyme A)
    - Can bind small molecules (**e.g.,** nucleotides, amino acids)
    - Can catalyze some biochemical reactions
    - Can be template for own synthesis
    - Can catalyze protein synthesis
- RNA is thought to be relatively simple to synthesize under prebiotic conditions, which were likely characterized by the availability of simple organic molecules and energy sources such as ultraviolet (UV) radiation, lightning, and volcanic activity.
- Laboratory experiments and theoretical studies have demonstrated that the building blocks of RNA, namely ribonucleotides, can be formed through plausible chemical pathways from simple precursor molecules.


Step 2:
RNA self-replicates (via ribozymes)
Step 1:
RNA forms from inorganic sources
Step 3:
RNA catalyses protein synthesis
Step 4:
Membrane formation changes internal chemistry, allowing new functionality
DNA becomes master template
Step 5:
RNA codes both DNA and protein
Proteins catalyse cellular activities

- Natural selection has produced self-replicating RNA molecules
- Copying errors would have occasionally resulted in RNA molecules more adept at self-replication
- RNA molecules that were more stable or replicated more quickly would have left the most descendant RNA molecules

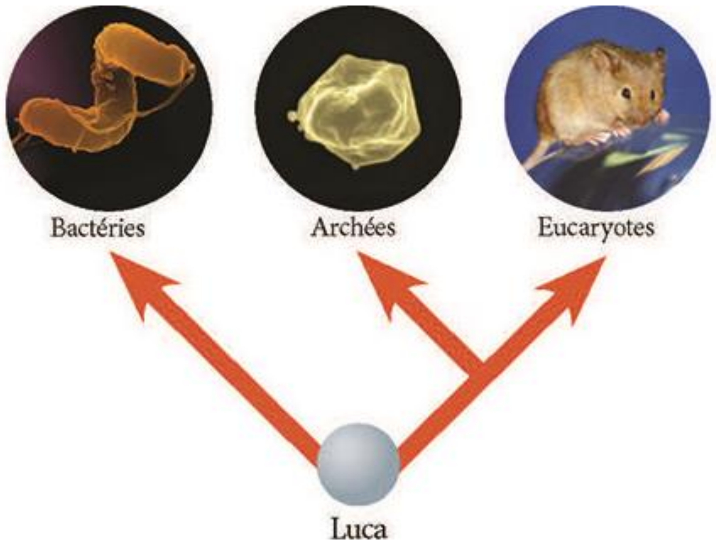
- In 2013, researchers constructed a vesicle whose RNA could self-replicate within the vesicle
- If a vesicle on early Earth could grow, split, and pass on its RNA to its "daughters," the daughters would be protocells
- The most successful of the early protocells could have increased through natural selection

A hypothesis for the origin of the first genes

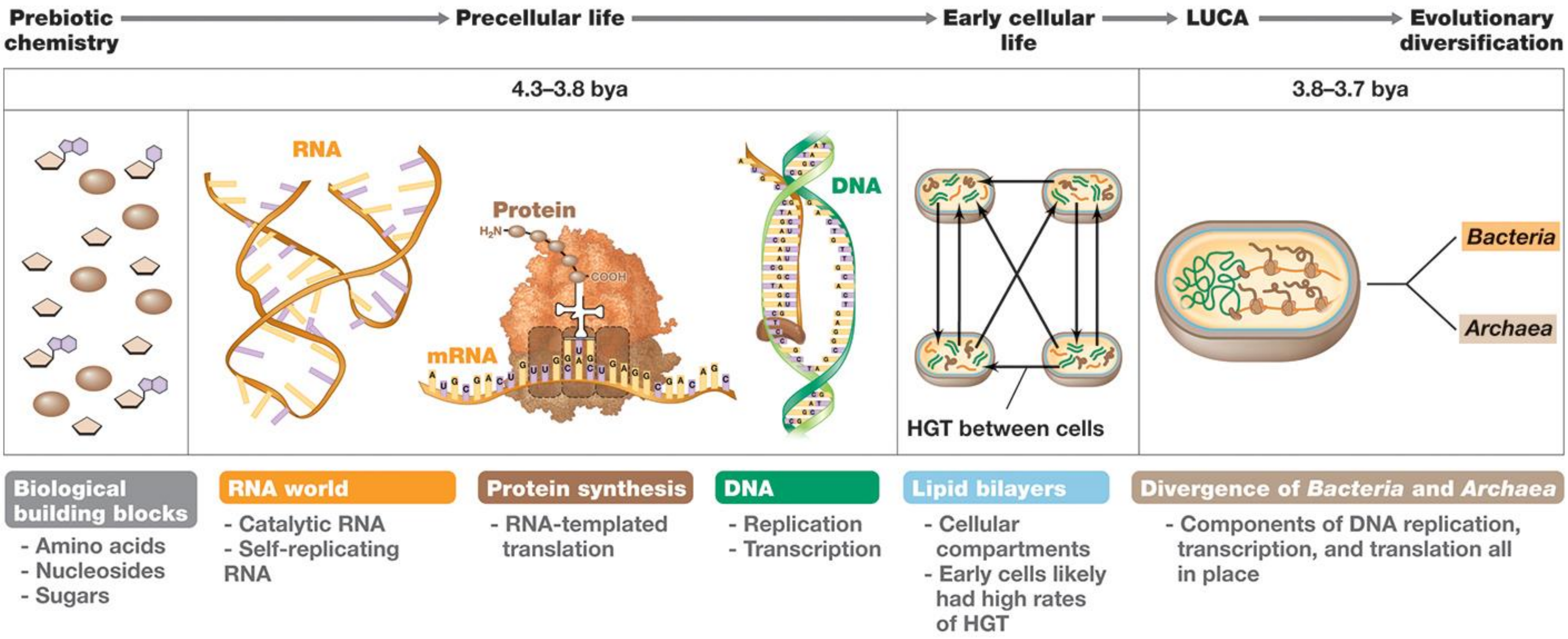


Origin of Cellular Life (continues)

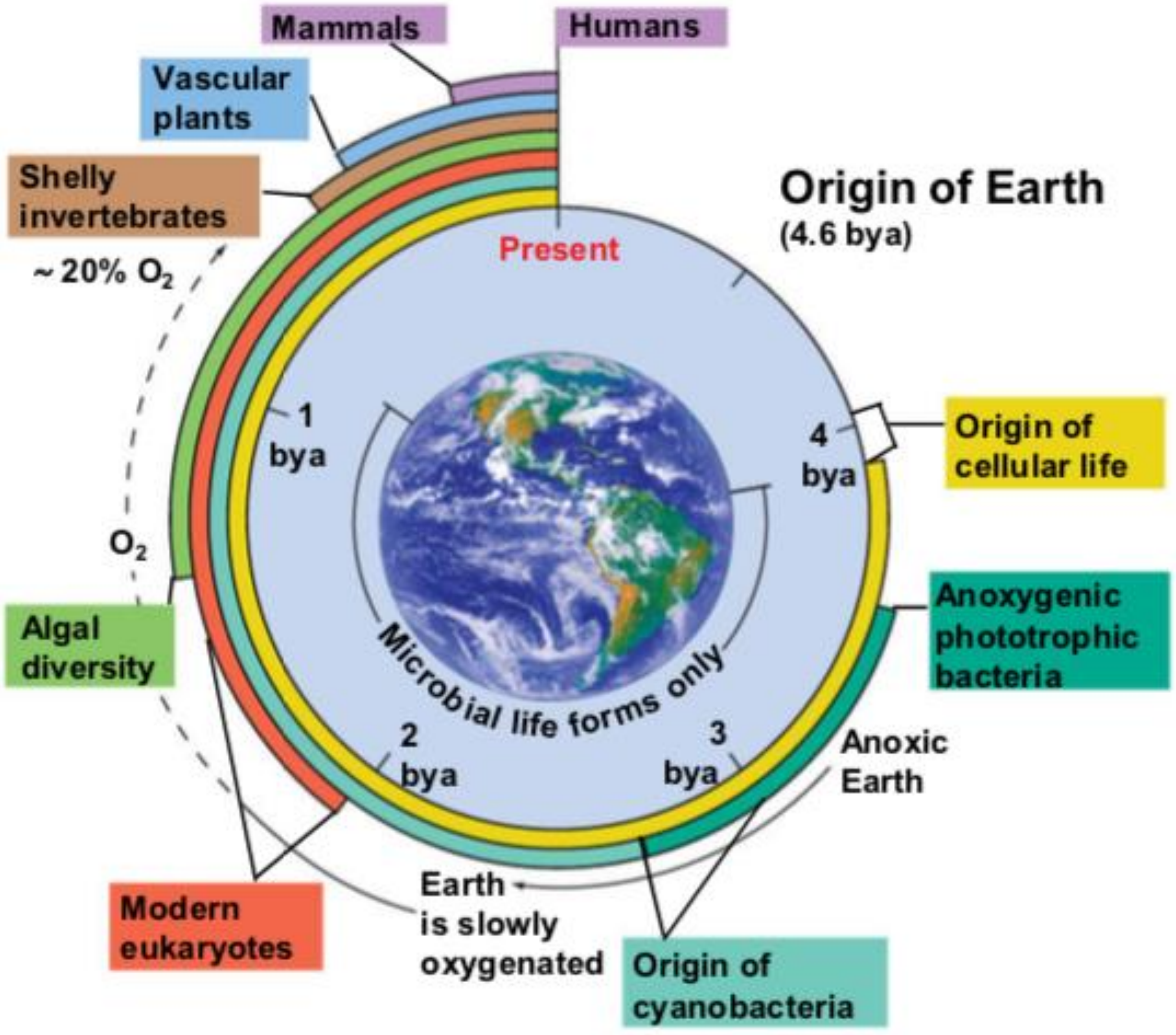
- Proteins eventually replaced RNAs as catalysts
- DNA (more stable) became genome and template for RNA
- Earliest cells probably had DNA, RNA, protein, and membrane system for energy conservation
- **Last universal common ancestor** (**LUCA**) existed 3.8–3.7 billion years ago, then ***Bacteria*** and ***Archaea*** diverged



Events Hypothesized to Precede the Origin of Cellular Life



- The analogy of a clock can be used to place the major events in the history of life on Earth in the context of the geologic record

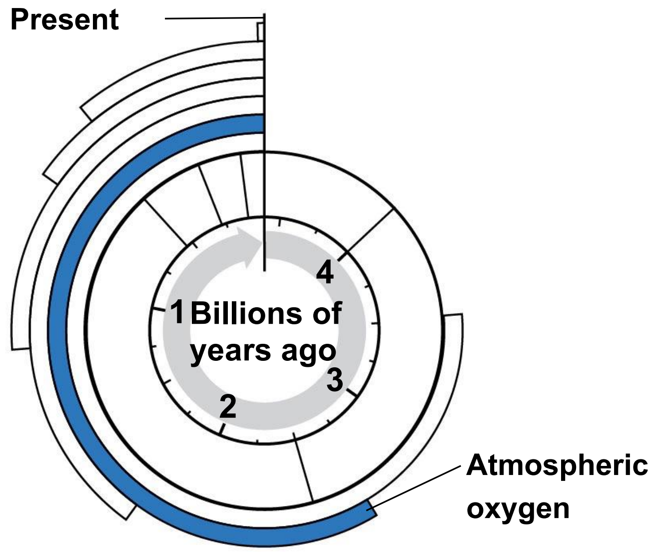


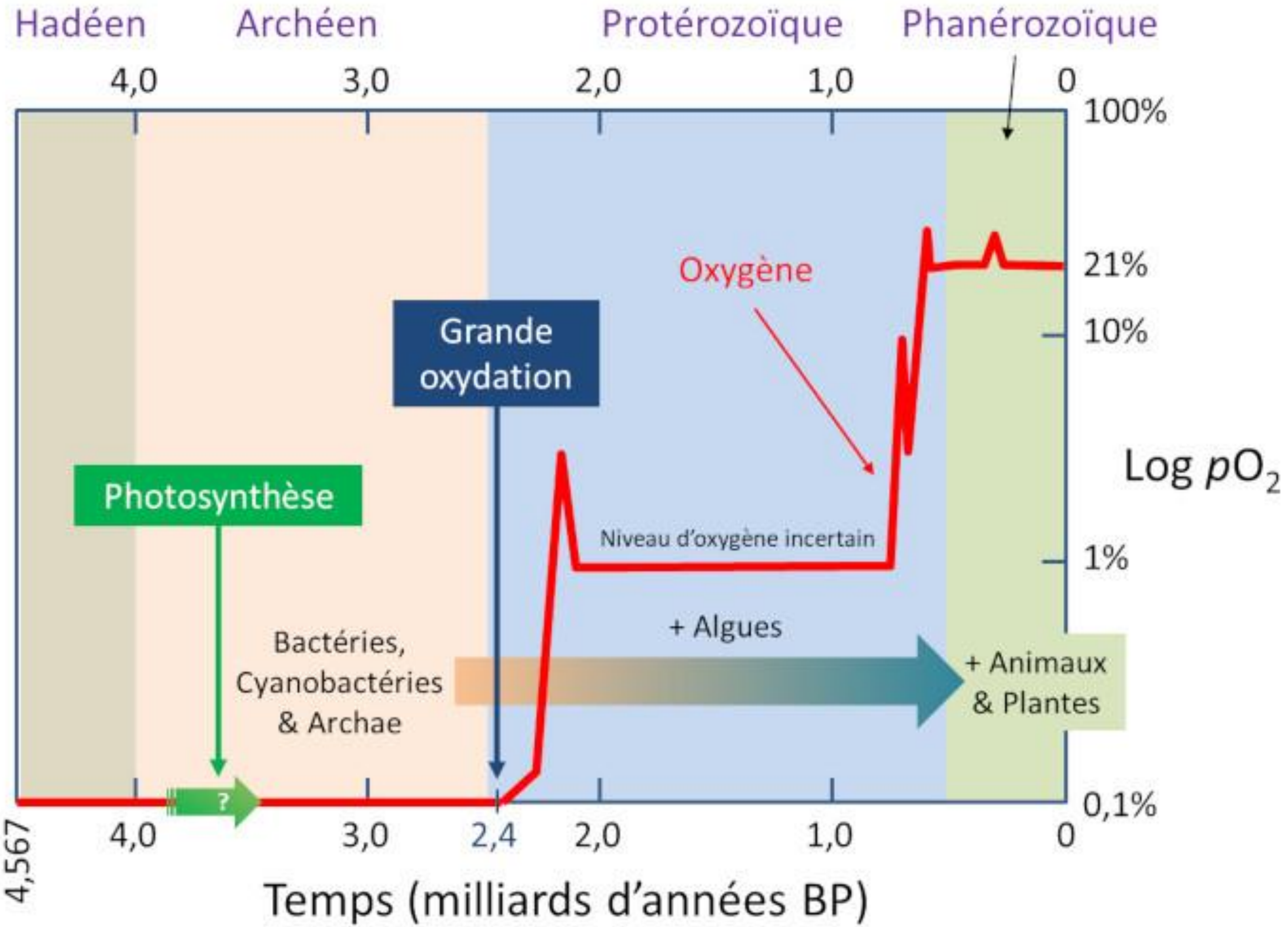
First single cell organisms: stromatolites

Stromatolites are structures built by microbial communities, primarily cyanobacteria, in shallow water. These mats trap and bind sediment creating layered structures over time. Stromatolites represent one of the earliest forms of life on Earth and have been around for over 3.5 billion years. They played a vital role in the oxygenation of Earth's atmosphere. Though once abundant, stromatolites are now relatively rare due to changes in environmental conditions and competition from other organisms.

Photosynthesis and the oxygen revolution

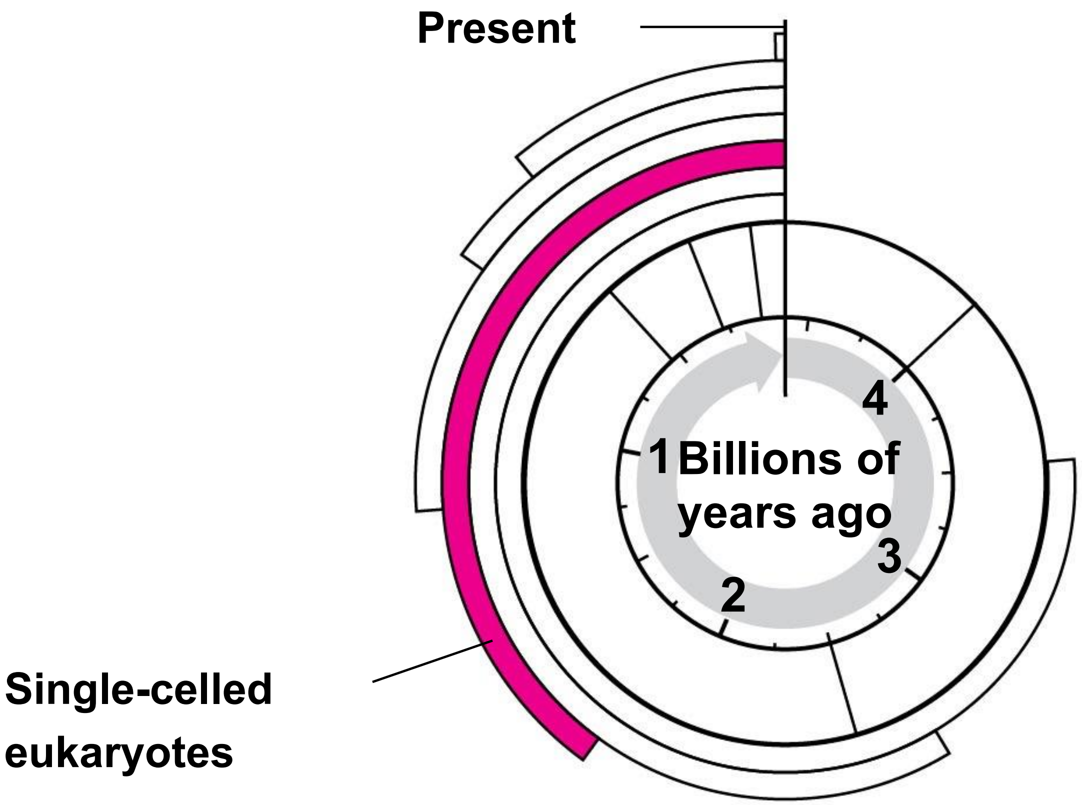
- Most atmospheric oxygen (O_2) is of biological origin
- O_2 accumulated gradually in the atmosphere from about 2.7 to 2.4 billion years ago, and then shot up rapidly to between 1% and 10% of its present level
- This "oxygen revolution" caused the extinction of many prokaryotic groups
- Some groups survived in anaerobic environments; others adapted using cellular respiration to harvest energy

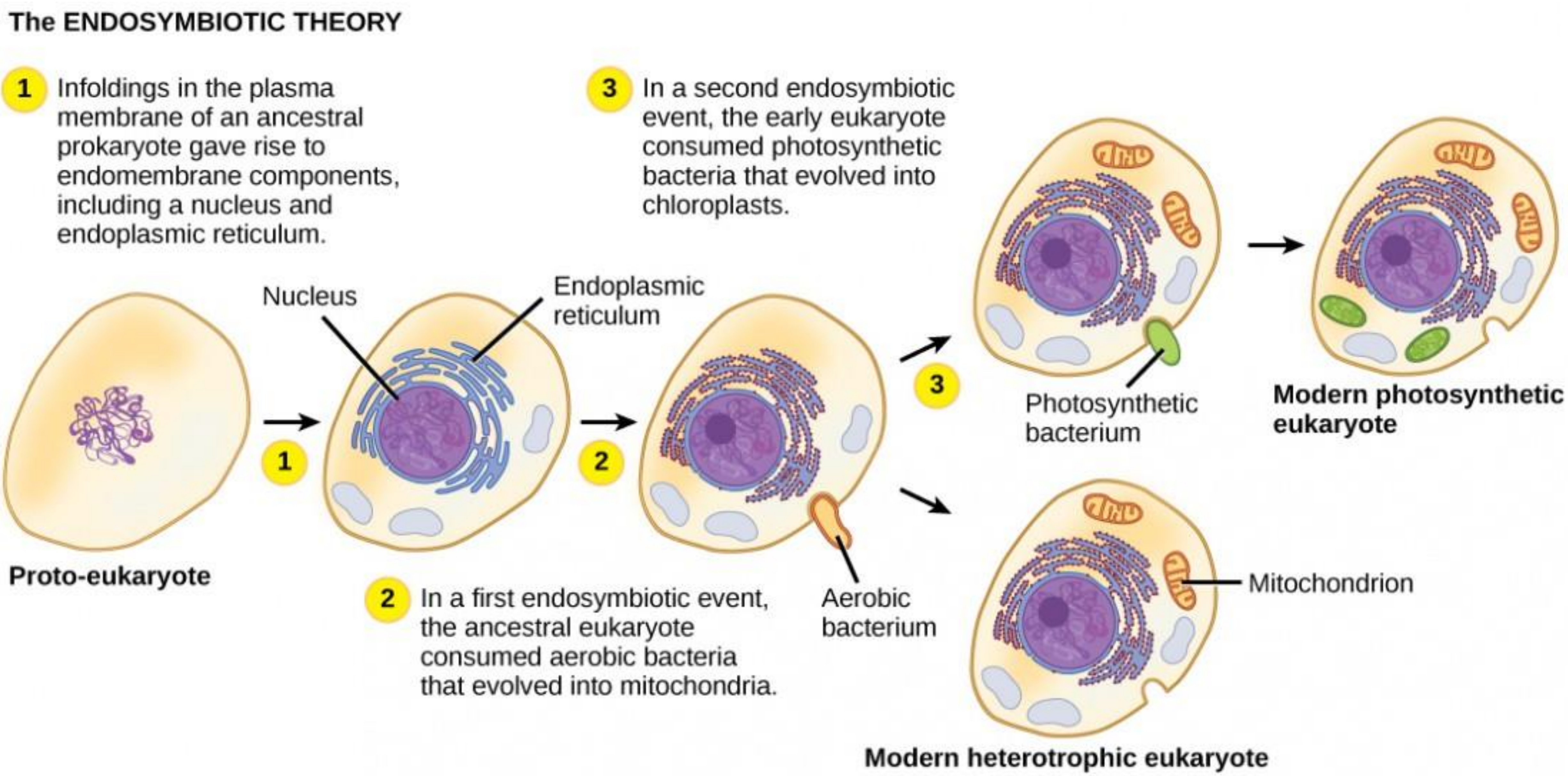



Hadéen
Archéen
Protérozoïque
Phanérozoïque
4,0
3,0
2,0
1,0
0
100%
21%
10%
1%
0,1%
Oxygène
Grande oxydation
Log pO_2
Photosynthèse
Niveau d'oxygène incertain
+ Algues
Bactéries, Cyanobactéries & Archae
+ Animaux & Plantes
?
4,567
2,4
Temps (milliards d'années BP)

The First Eukaryotes

- The oldest fossils of eukaryotic cells date back
  1.8 billion years
- Eukaryotic cells have a nuclear envelope, mitochondria, endoplasmic reticulum, and a cytoskeleton
- Eukaryotes originated by **endosymbiosis** when a prokaryotic cell engulfed a small cell that would evolve into a mitochondrion
- An endosymbiont is a cell that lives within a host cell



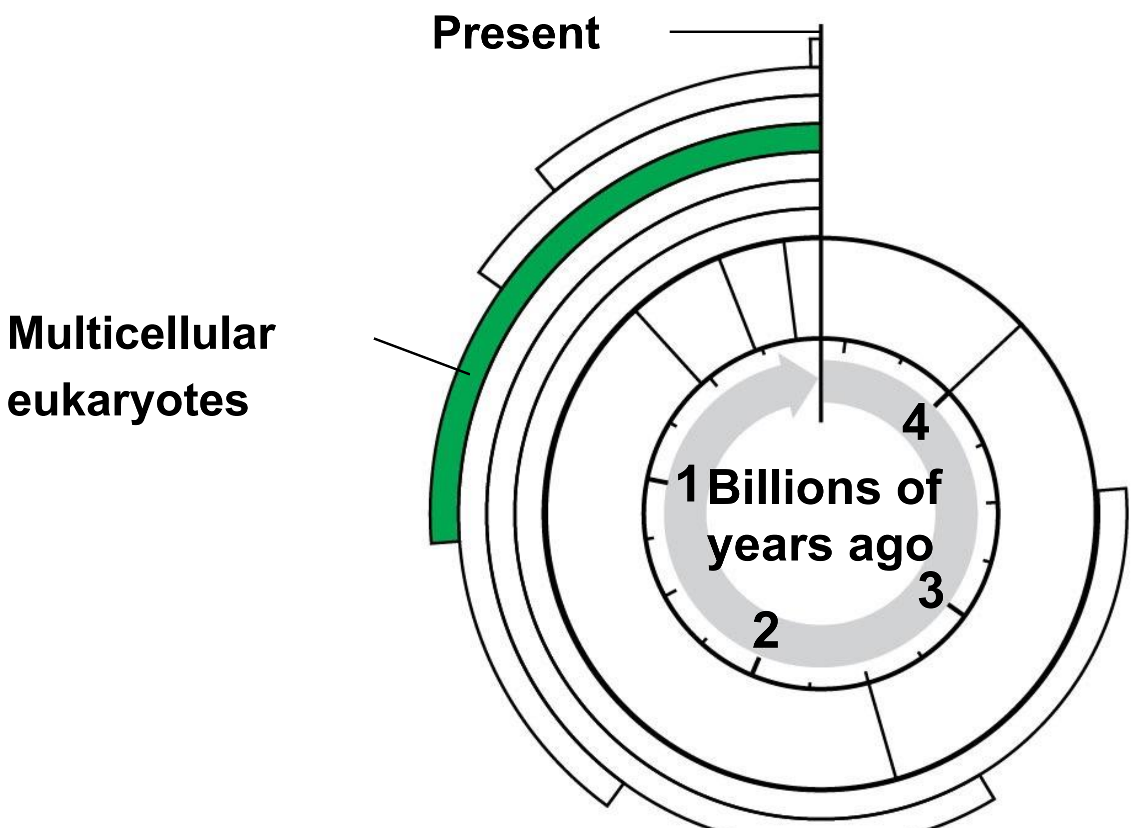

The ENDOSYMBIOTIC THEORY
1 Infoldings in the plasma membrane of an ancestral prokaryote gave rise to endomembrane components, including a nucleus and endoplasmic reticulum.
3 In a second endosymbiotic event, the early eukaryote consumed photosynthetic bacteria that evolved into chloroplasts.
Nucleus
Endoplasmic reticulum
Proto-eukaryote
1
2
3
Photosynthetic bacterium
Modern photosynthetic eukaryote
2 In a first endosymbiotic event, the ancestral eukaryote consumed aerobic bacteria that evolved into mitochondria.
Aerobic bacterium
Mitochondrion
Modern heterotrophic eukaryote

Benefits of endosymbiosis

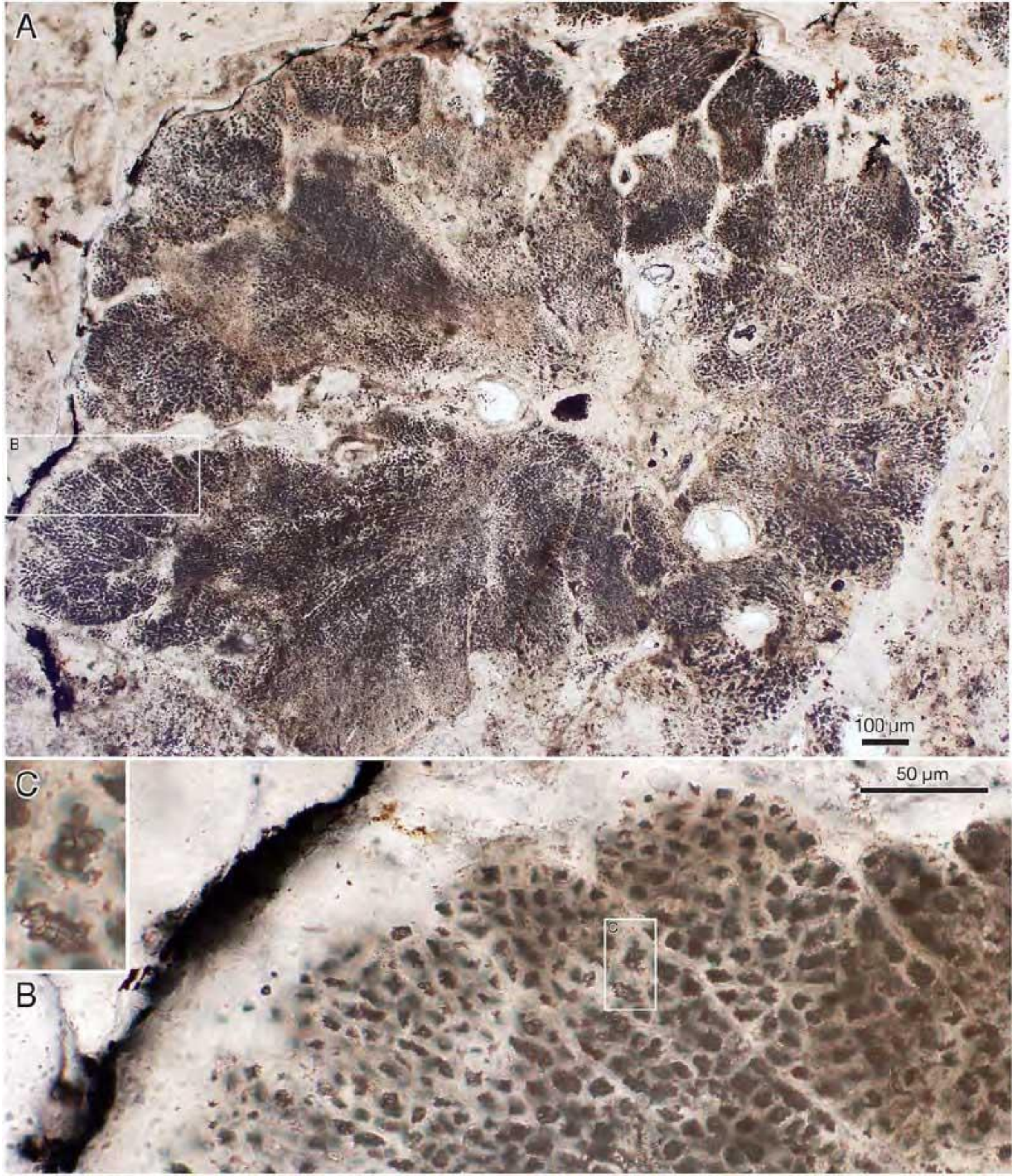
- Anaerobic host cells would have benefited from endosymbionts that could use oxygen as it built up in the atmosphere
- Over time, the host and endosymbionts would have become interdependent, forming a single organism
- All eukaryotes have mitochondria or remnants of mitochondria, but not all have plastids (chloroplasts and related organelles)
- **Serial endosymbiosis** supposes that mitochondria evolved before plastids through a sequence of endosymbiotic events
- Mitochondria and plastids likely descended from bacterial cells; the original host is thought to be an archaean or close relative

Early Multicellular Eukaryotes

- The evolution of eukaryotic cells allowed for a greater range of unicellular forms
- The oldest fossils of multicellular eukaryotes are small red algae from about 1.2 billion years ago
- Older fossils from about 1.8 billion years ago may also be multicellular eukaryotes, but they can't be resolved taxonomically

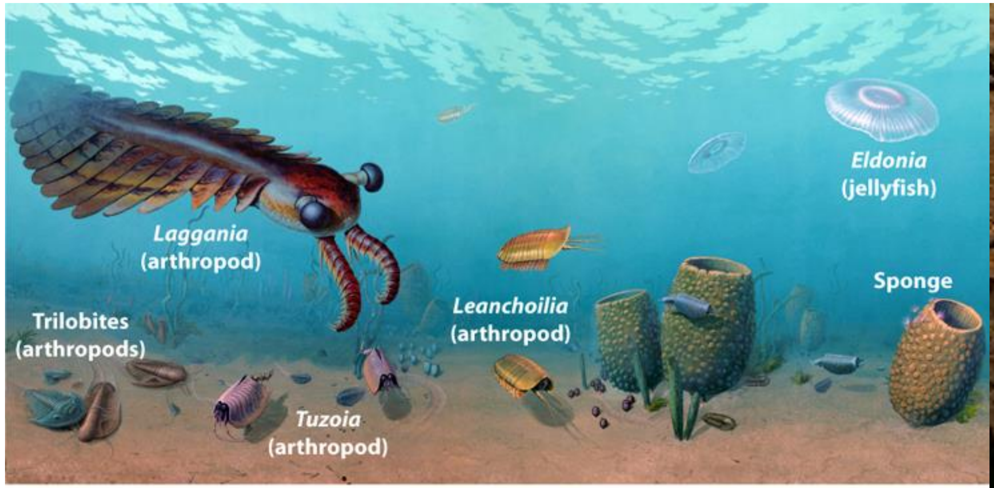


Oldest multicellular eukaryotes fossiles

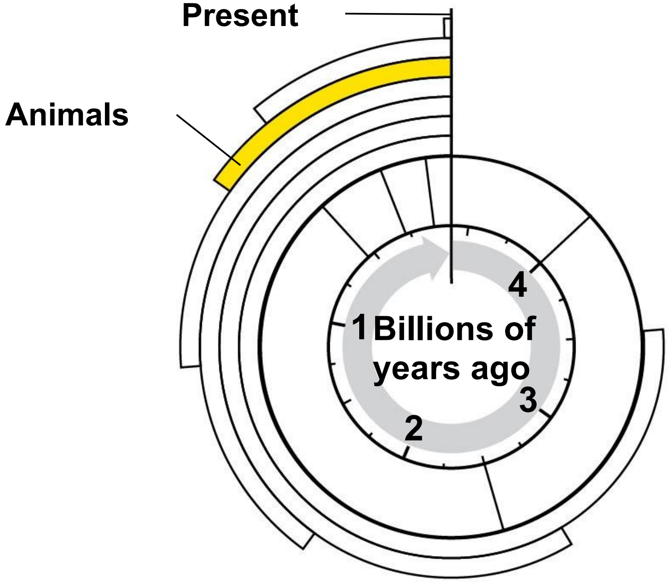


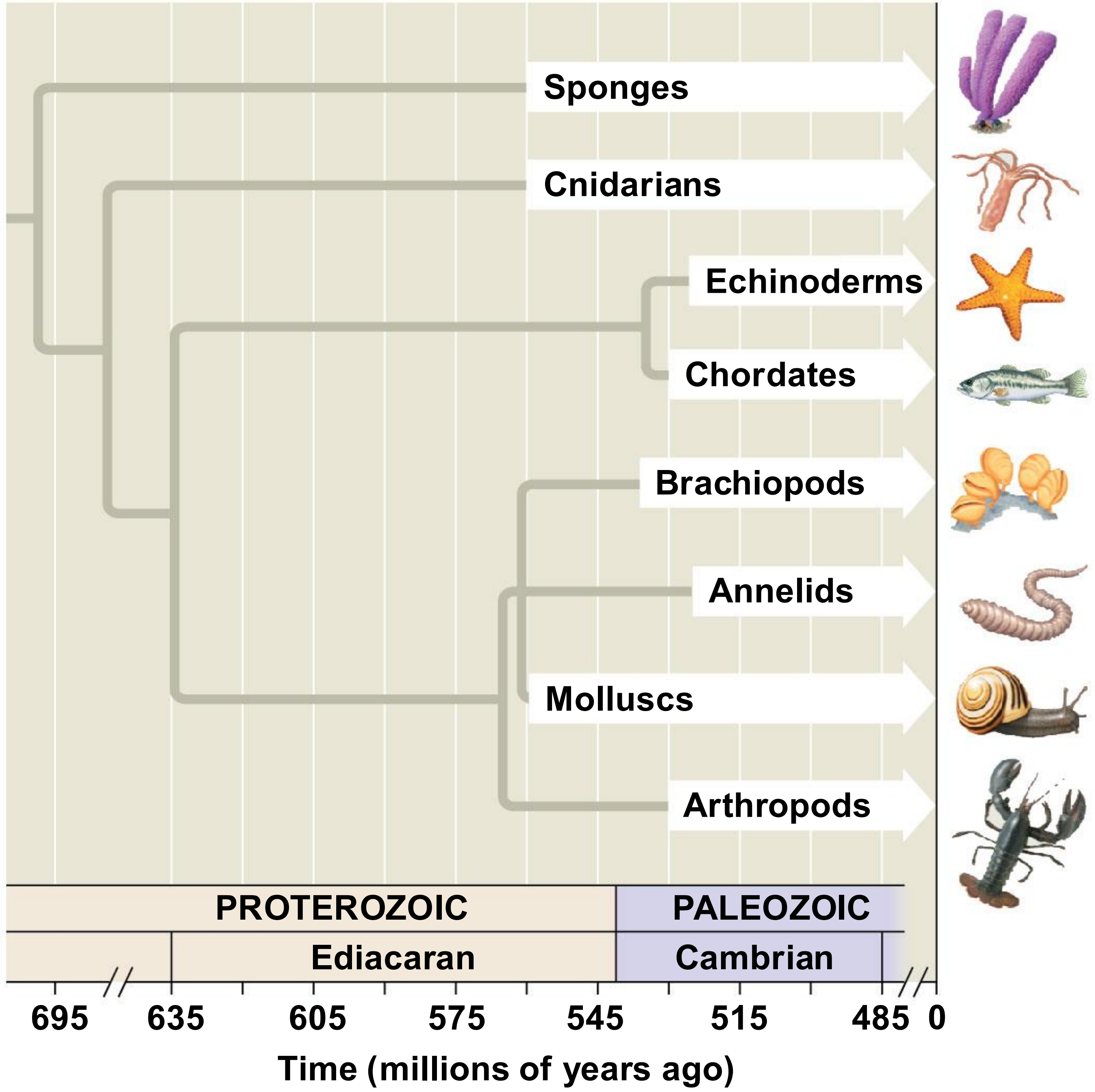
The Cambrian Explosion

- The **Cambrian explosion** refers to the sudden appearance of fossils resembling modern animal phyla in the Cambrian period (535 to 525 million years ago)
- A few animal phyla appear even earlier: sponges, cnidarians, and molluscs



Chase Studios

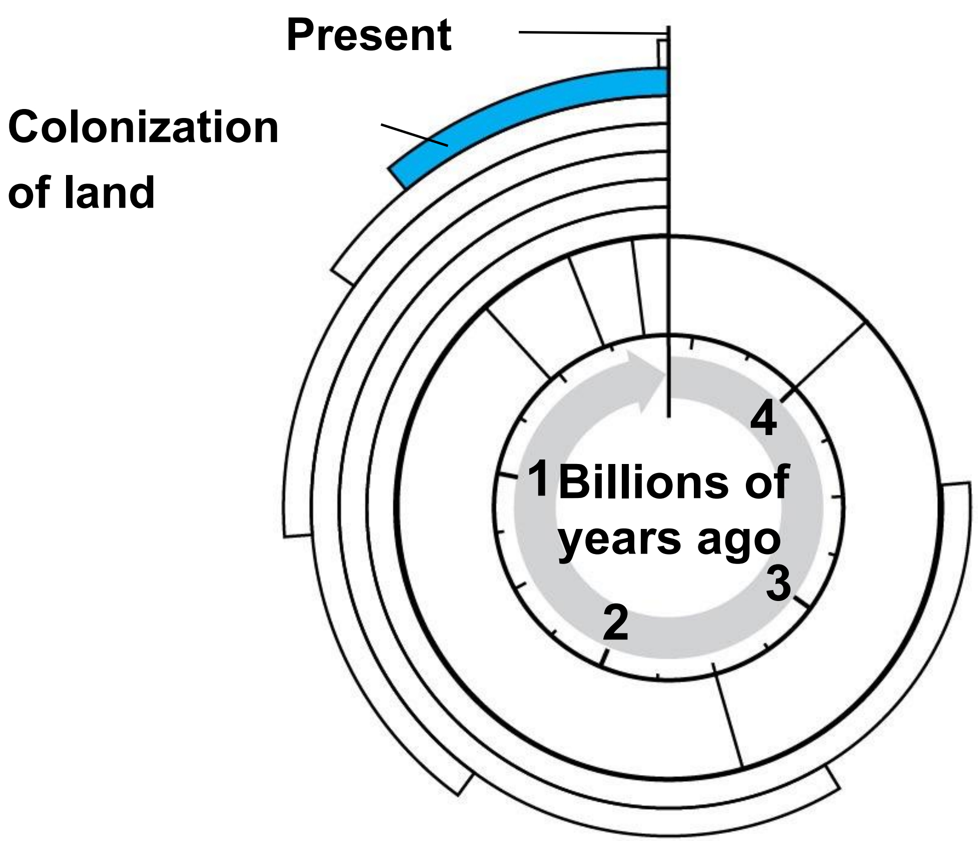


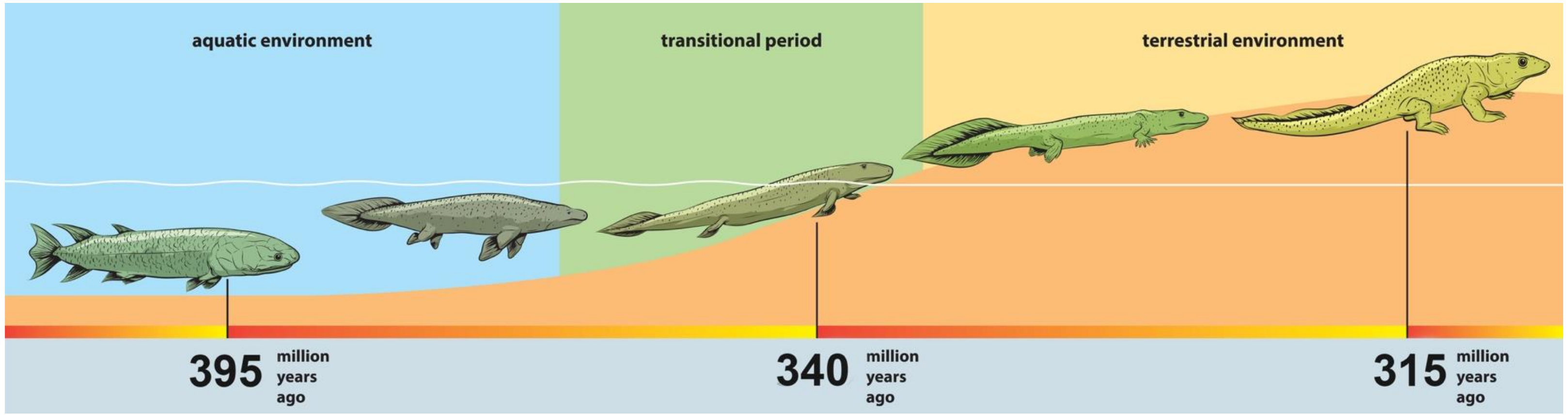


Sponges
Cnidarians
Echinoderms
Chordates
Brachiopods
Annelids
Molluscs
Arthropods
PROTEROZOIC
PALEOZOIC
Ediacaran
Cambrian
695
635
605
575
545
515
485
0
Time (millions of years ago)

The Colonization of Land

- Fungi, plants, and animals began to colonize land about 500 million years ago
- Many plants evolved adaptations to reproduce on land and avoid dehydration
  - For example, a vascular system for transporting materials appeared by about 420 million years ago





An ancient symbiosis

- Plants and fungi likely colonized land together
- Fossilized plants show evidence of mutually beneficial associations with fungi (mycorrhizae) that are still seen today

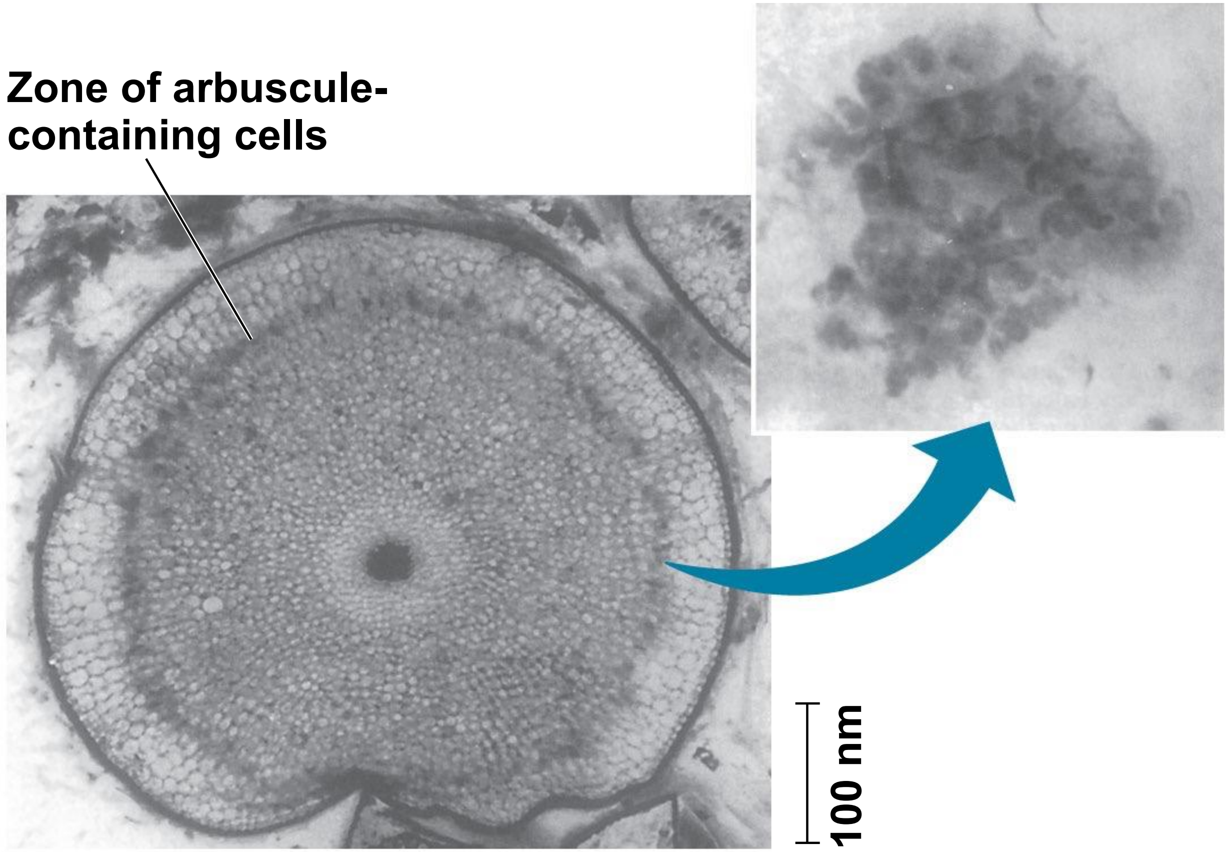
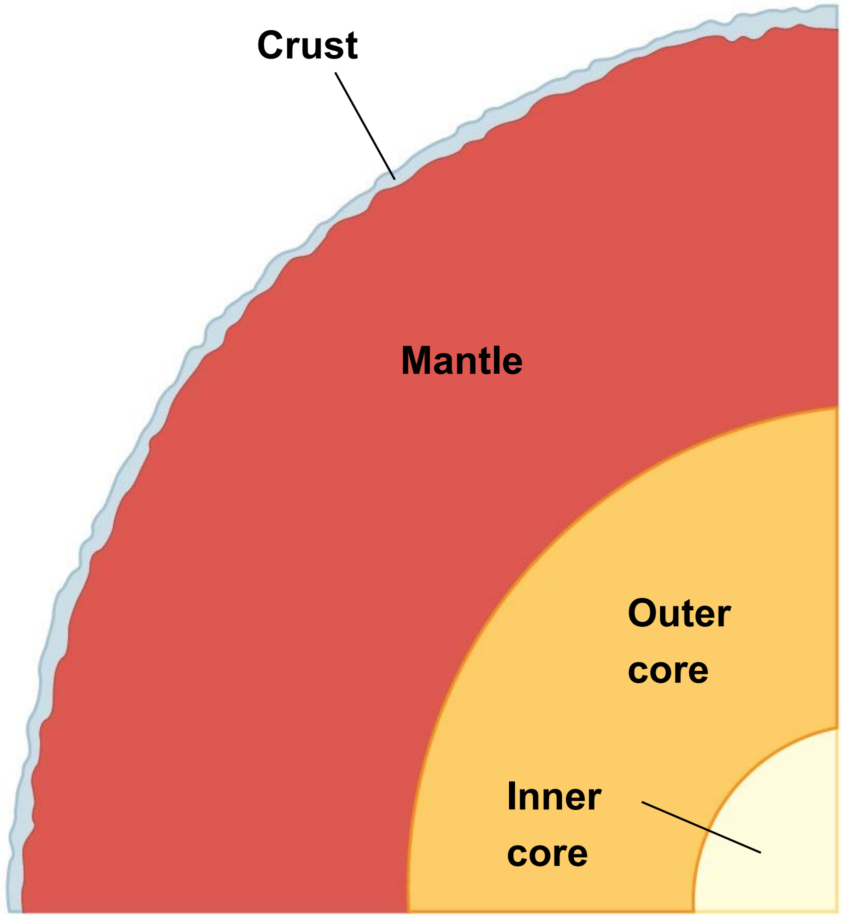
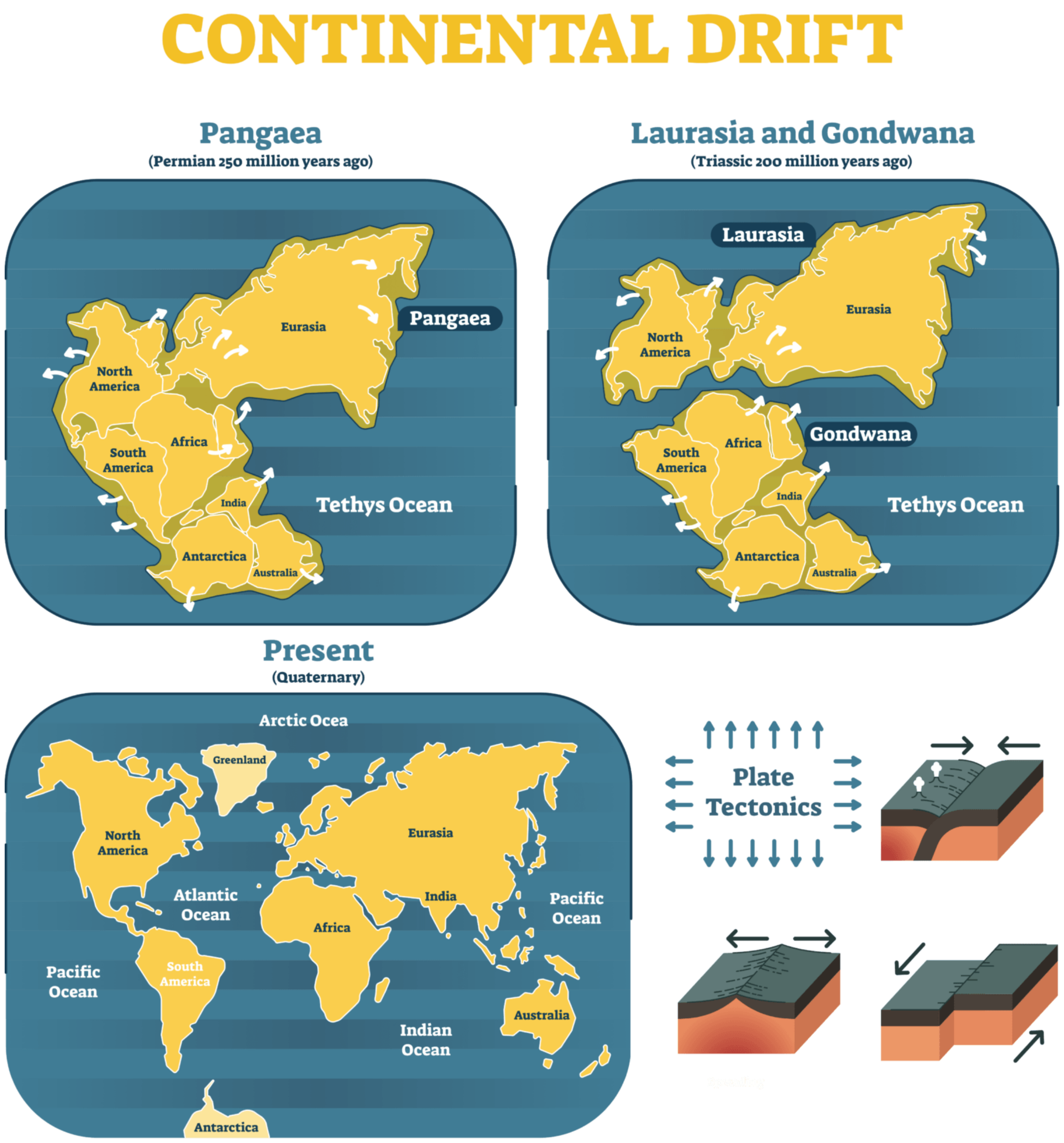


Plate Tectonics

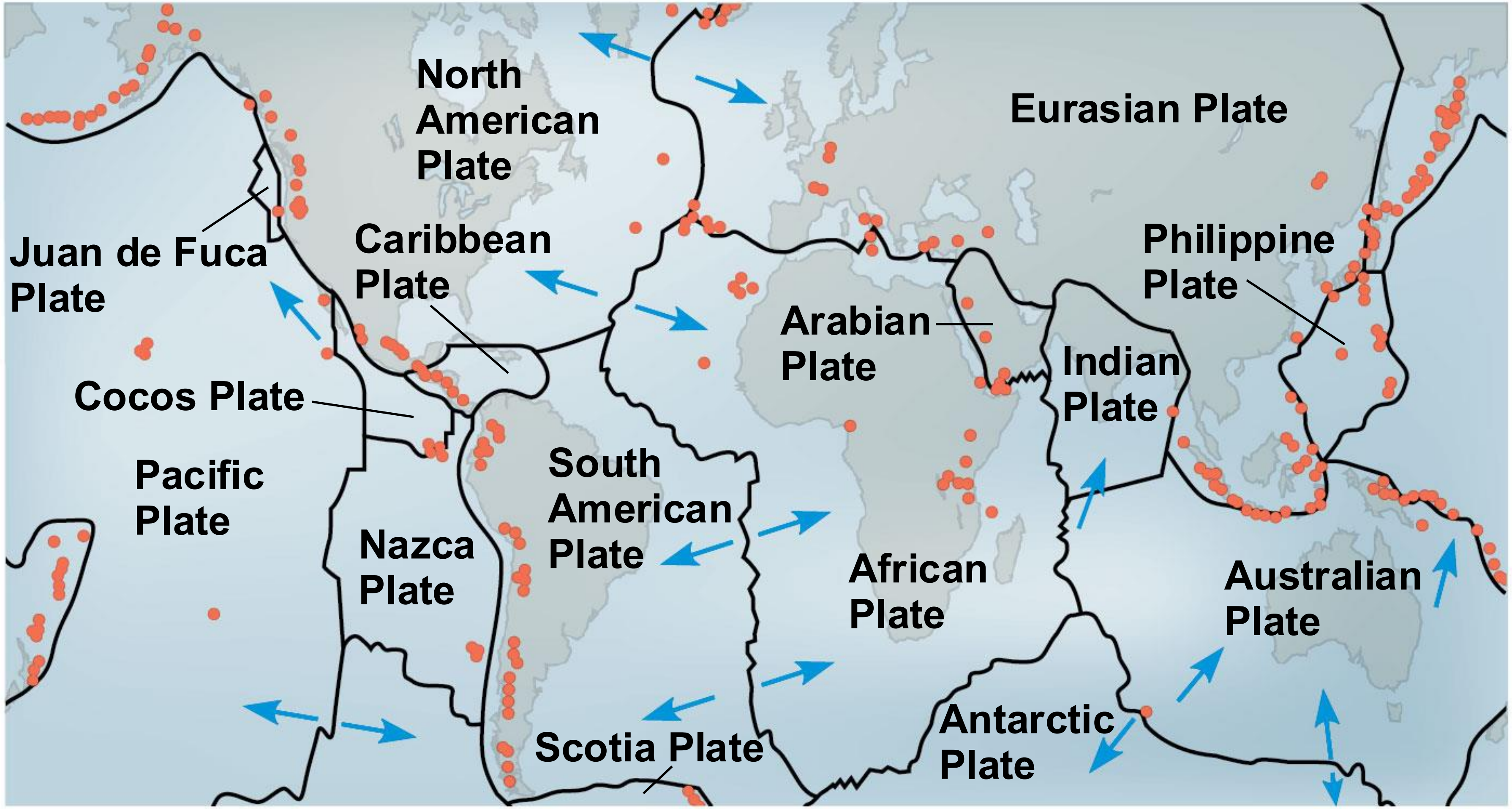
- The landmasses of Earth have formed a supercontinent three times over the past billion years (1 billion, 600 million, and 250 million years ago)
- According to the theory of **plate tectonics**, Earth's crust is composed of plates floating on Earth's mantle



- Movements in the mantle cause the plates to move over time in a process called continental drift
- Oceanic and continental plates can drift apart, collide to form mountains, or slide past each other, causing earthquakes

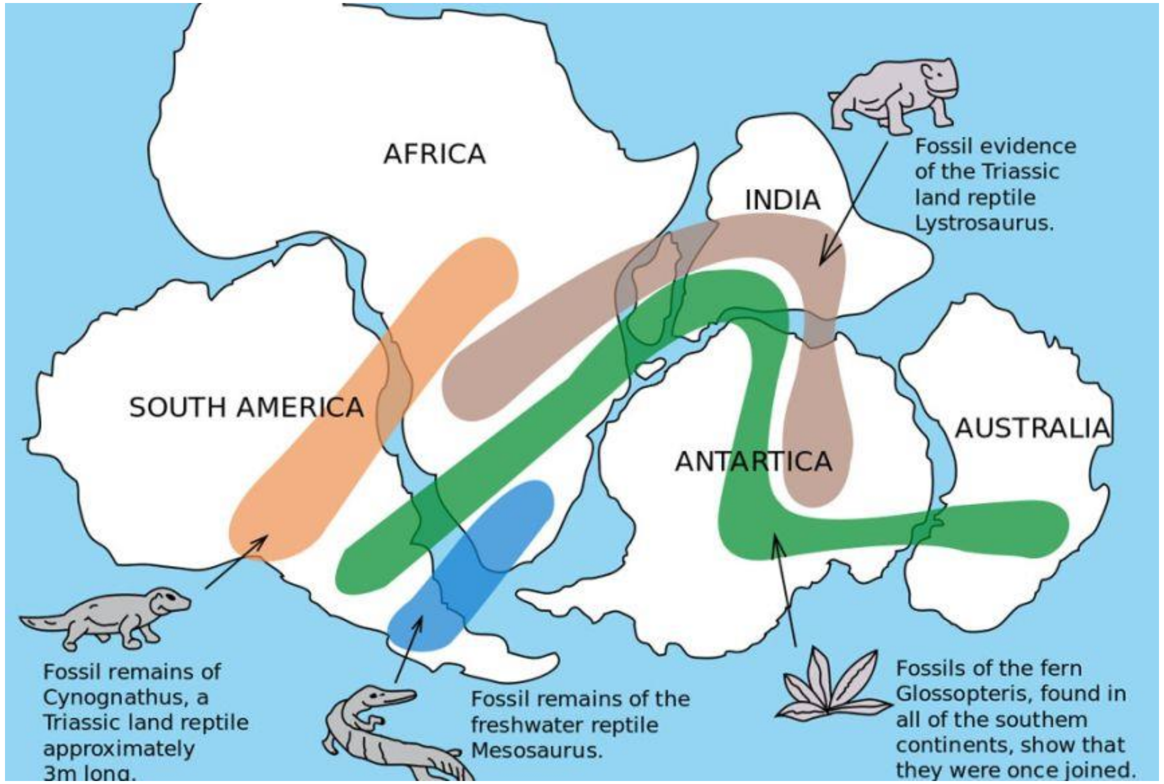


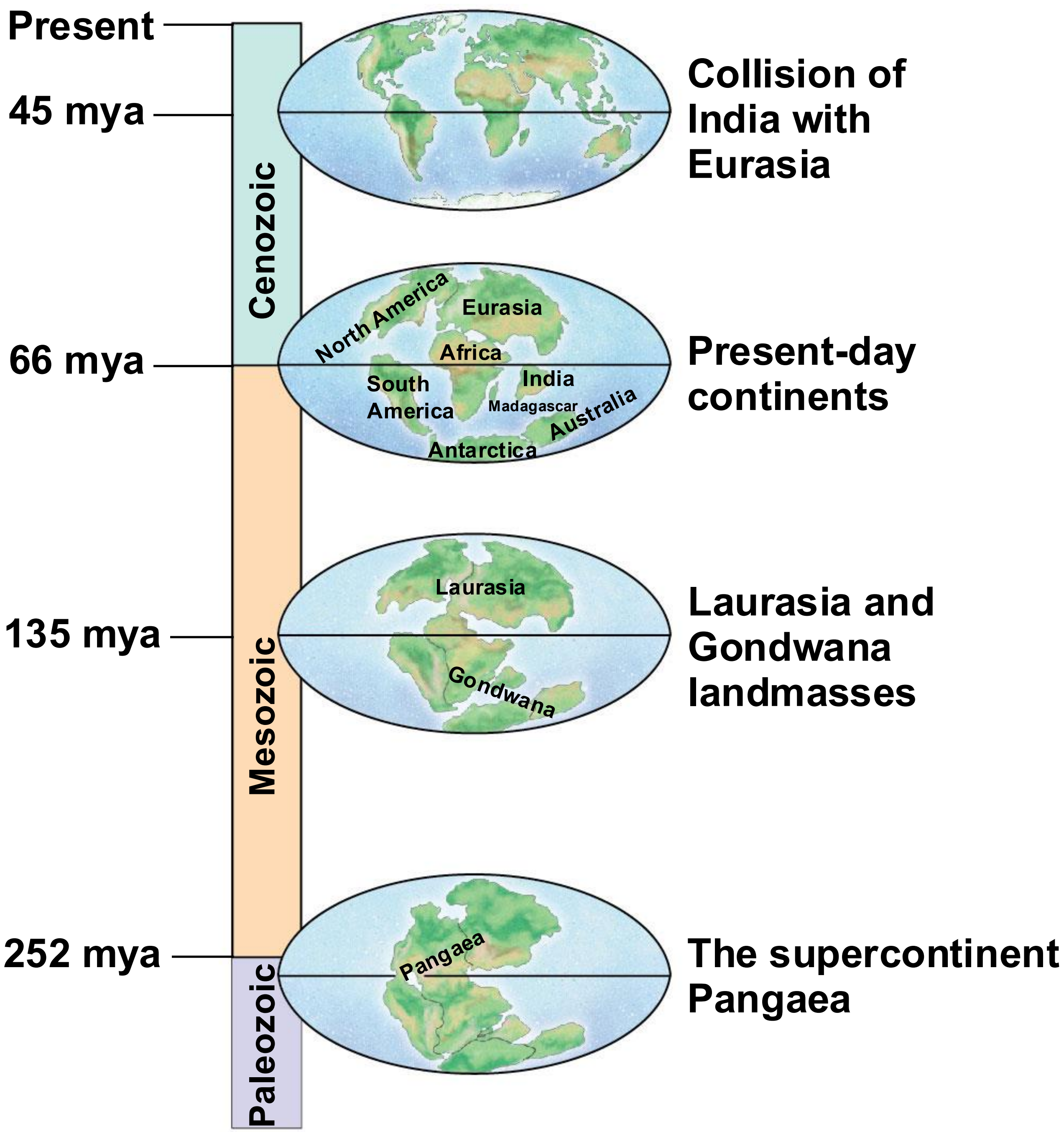
Earth's major tectonic plates



Consequences of Continental Drift for Earth

- Formation of the supercontinent **Pangaea** about 250 million years ago had many effects:
  - a deepening of ocean basins
  - a reduction in shallow-water habitat
  - a colder and drier climate inland




Present
45 mya
66 mya
135 mya
252 mya
Cenozoic
Mesozoic
Paleozoic
North America
Eurasia
Africa
South America
India
Madagascar
Australia
Antarctica
Laurasia
Gondwana
Pangaea
Collision of India with Eurasia
Present-day continents
Laurasia and Gondwana landmasses
The supercontinent Pangaea

Consequences of Continental Drift on life

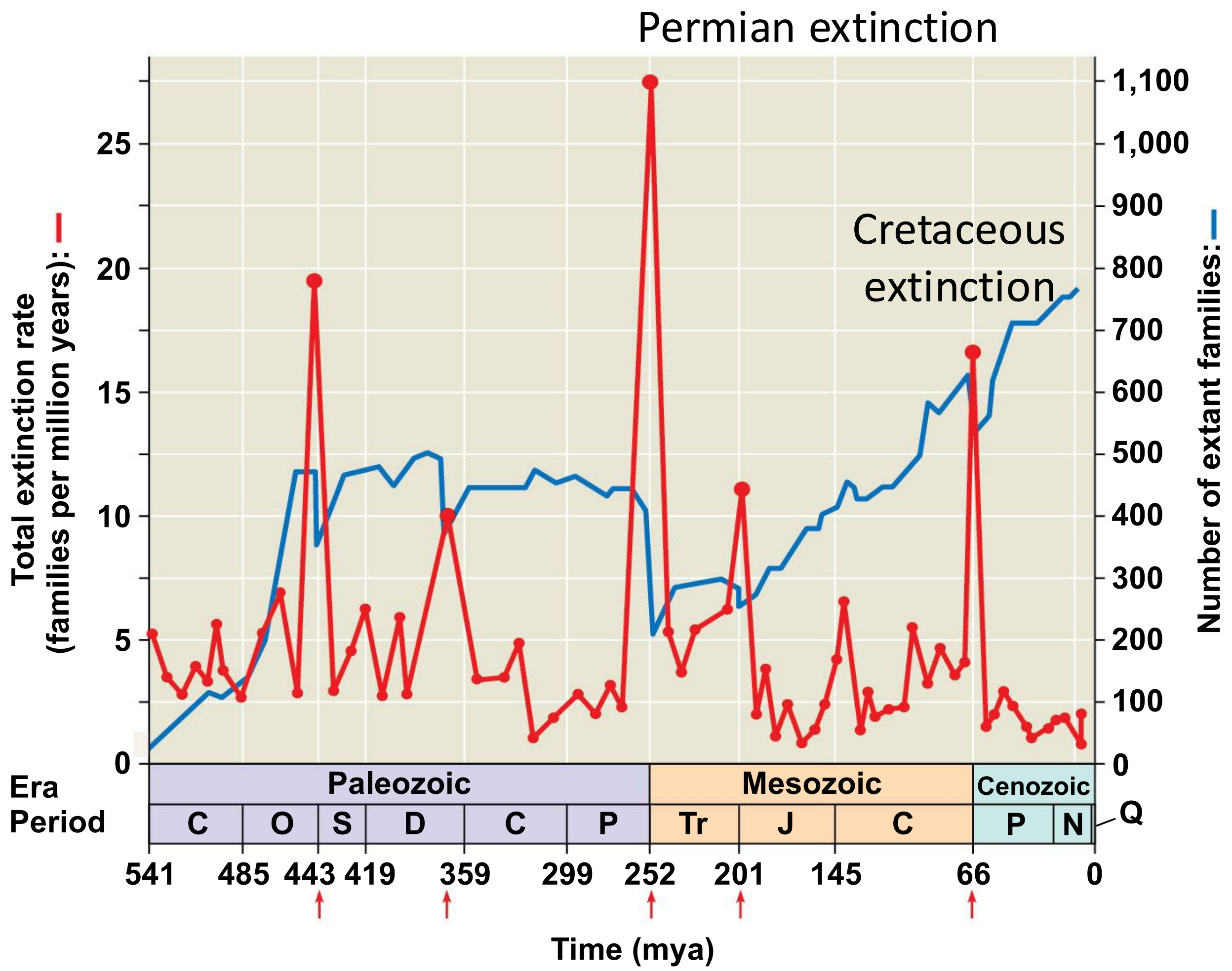
- Continental drift has many effects on living organisms
  - Organisms must adapt, move, or risk extinction as the climate changes in response to continents moving toward or away from the equator
  - Separation of landmasses can lead to allopatric speciation
- The distribution of fossils and living groups reflects the historic movement of continents
  - For example, the similarity of fossils in parts of South America and Africa is consistent with the idea that these continents were formerly attached

Mass Extinctions

- The fossil record shows that most species that have ever lived are now extinct
- Extinction can be caused by changes to a species' biotic or abiotic environment
- At times, the rate of extinction has increased dramatically and caused a **mass extinction**

The "Big Five" Mass Extinction Events

- In each of the five mass extinction events, 50% or more of marine species became extinct



Permian extinction

- The Permian extinction defines the boundary between the Paleozoic and Mesozoic eras 252 million years ago
- This mass extinction occurred in less than 500,000 years and caused the extinction of about 96% of marine animal species
- A number of factors might have contributed to this mass extinction
  - Extreme volcanism in what is now Siberia
  - Global warming and ocean acidification resulting from the emission of large amounts of CO_2 from volcanoes
  - Anoxic conditions resulting from nutrient enrichment of ecosystems

Cretaceous extinction

- The Cretaceous mass extinction occurred 66 million years ago
- More than half of all marine species, many families of terrestrial plants and animals, and all of the dinosaurs, except birds, went extinct during this event

- The presence of iridium in sedimentary rocks from that time period suggests a meteorite impact
- Dust clouds caused by the impact would have blocked sunlight and disturbed the global climate
- The Chicxulub crater off the coast of Mexico is evidence of a massive meteorite collision that dates to the same time

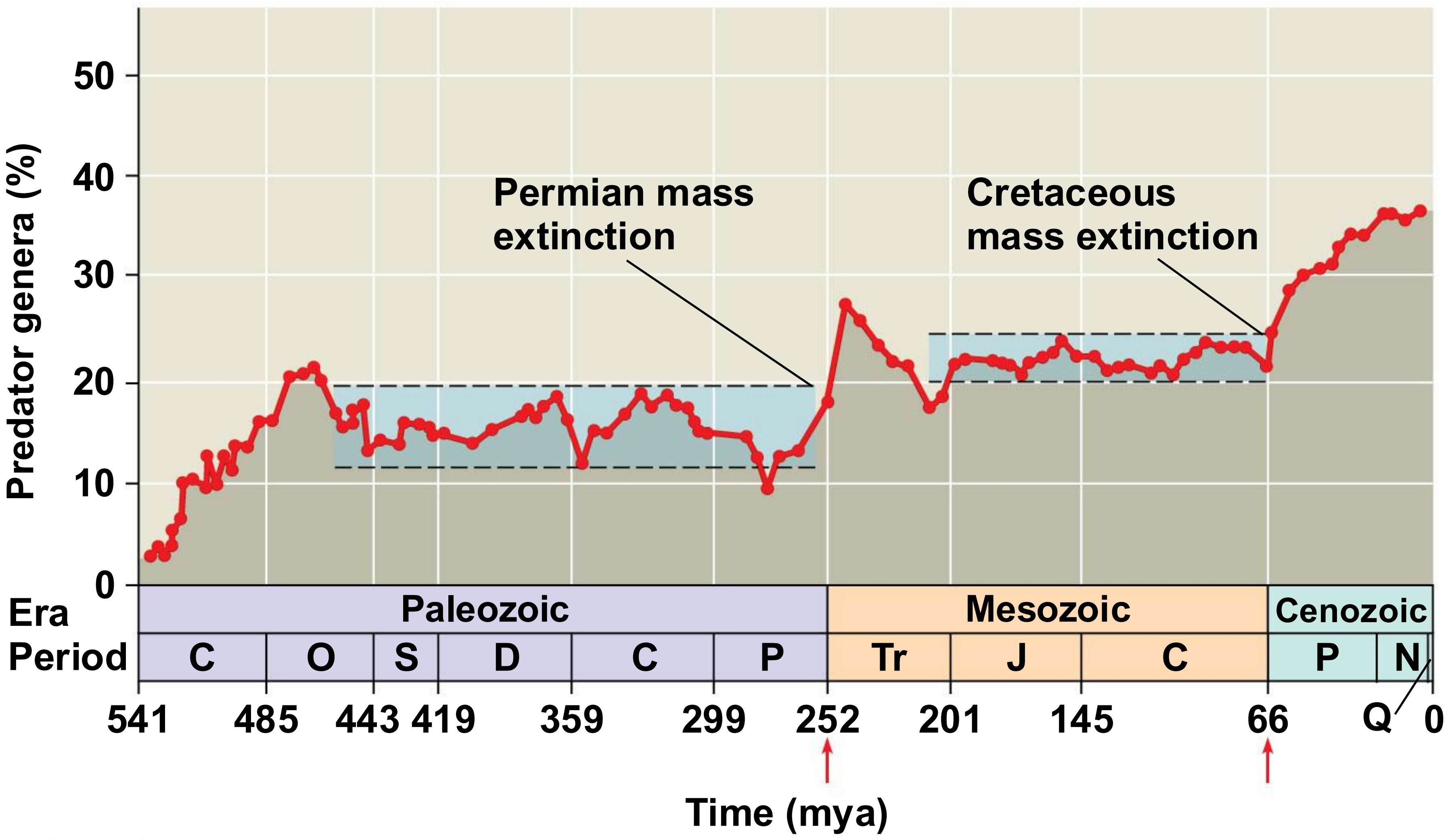
Is a Sixth Mass Extinction Under Way?

- Scientists estimate that the current rate of extinction is 100 to 1,000 times the typical background rate seen in the fossil record
- It is difficult to estimate current extinction rates because many undiscovered species may be lost through destruction of the tropical rain forest

- Many species are declining rapidly due to habitat loss, introduced species, overharvesting, and other factors
- Climate change may hasten declines; extinction rates historically have tended to increase when global temperatures were high
- Data suggest that a sixth, human-caused mass extinction is likely to occur unless dramatic action is taken

Consequences of Mass Extinctions

- It typically takes 5–10 million years for diversity to recover following a mass extinction; in some cases up to 100 million years
- Mass extinctions can change the types of organisms found in ecological communities
  - For example, the proportion of predators increased in marine communities after the Permian and Cretaceous mass extinctions



Predator genera (%)
50
40
30
20
10
0
Permian mass extinction
Cretaceous mass extinction
Era
Paleozoic
Mesozoic
Cenozoic
Period
C
O
S
D
C
P
Tr
J
C
P
N
Q
541
485
443
419
359
299
252
201
145
66
0
Time (mya)

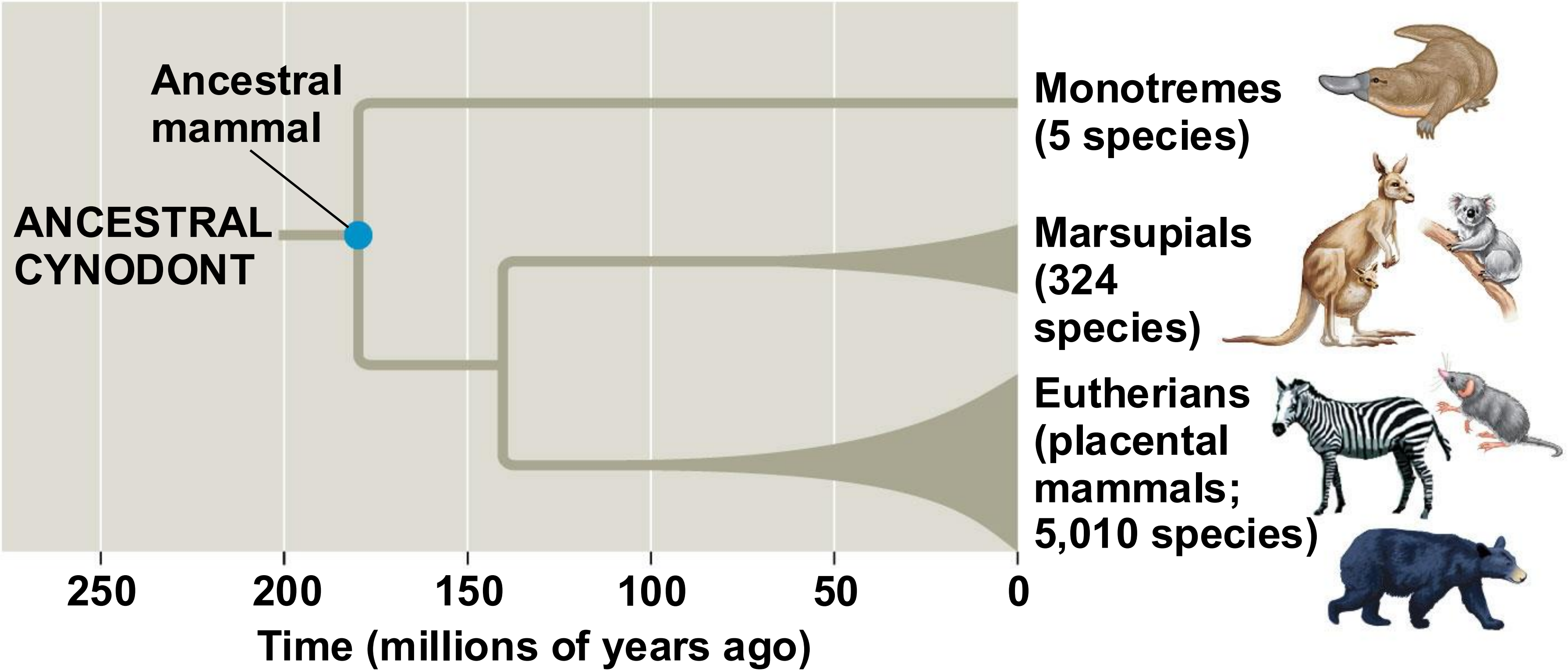
- Mass extinctions can also eliminate lineages with novel and advantageous features
  - For example, shell-drilling gastropods were lost in the extinction at the end of the Triassic and did not reappear for 120 million years

Adaptive Radiations

- **Adaptive radiation** is the rapid evolution of diversely adapted species from a common ancestor
- Adaptive radiations may follow
  - mass extinctions
  - the evolution of novel characteristics
  - the colonization of new regions

Examples of Adaptive Radiations

- Mammals underwent an adaptive radiation after the extinction of terrestrial dinosaurs
- The disappearance of dinosaurs (except birds) opened ecological niches, allowing for the expansion of mammals in diversity and size
- Other notable radiations include photosynthetic prokaryotes, large predators in the Cambrian, land plants, insects, and tetrapods



Ancestral mammal
ANCESTRAL CYNODONT
Monotremes (5 species)
Marsupials (324 species)
Eutherians (placental mammals; 5,010 species)
250
200
150
100
50
0
Time (millions of years ago)

Regional Adaptive Radiations

- Adaptive radiations can occur when organisms colonize new environments with little competition
- The Hawaiian Islands are one of the world's great showcases of adaptive radiation
  - For example, the "silversword alliance" is a diverse group of plants descended from an ancestral tarweed that arrived about 5 million years ago

Adaptive radiation on the Hawaiian Islands