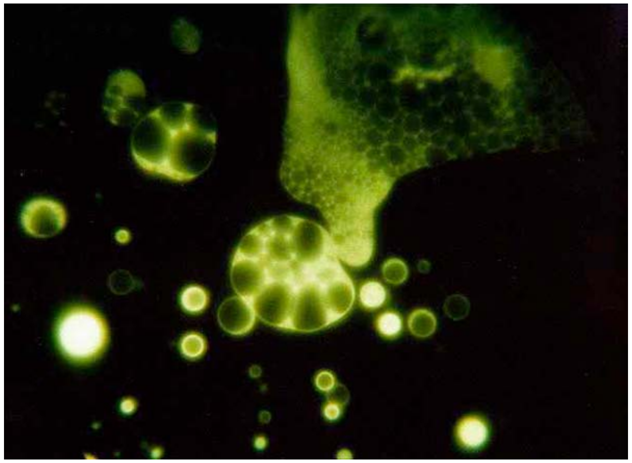
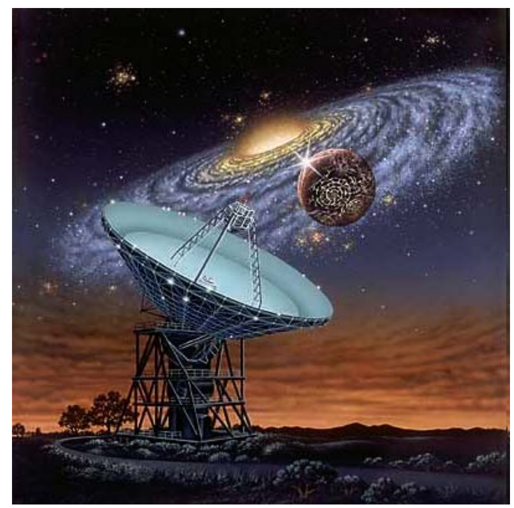


AST 309
part 2:
Extraterrestrial Life

The Origin and Evolution of Life on Earth



Overview

- The formation of Earth
- Pre-biotic chemistry (Miller-Urey exp.)
- First evidence for early life
- The evolution of life
- Extreme life on Earth: lessons for astrobiology

A timeline for the very early history of the Earth

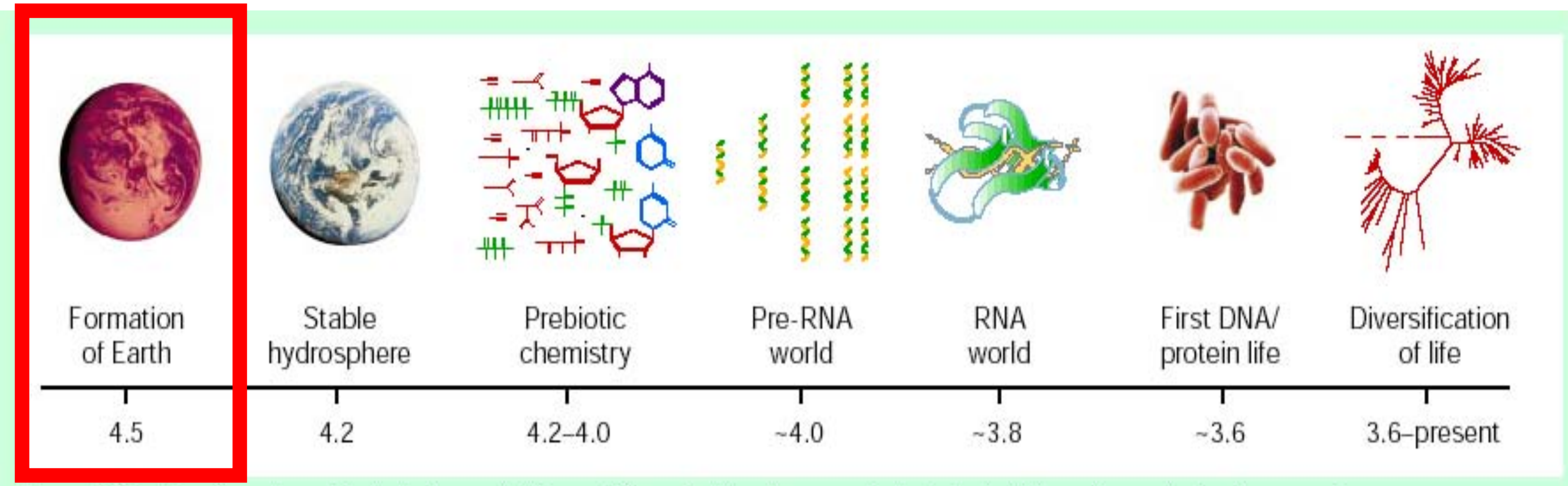
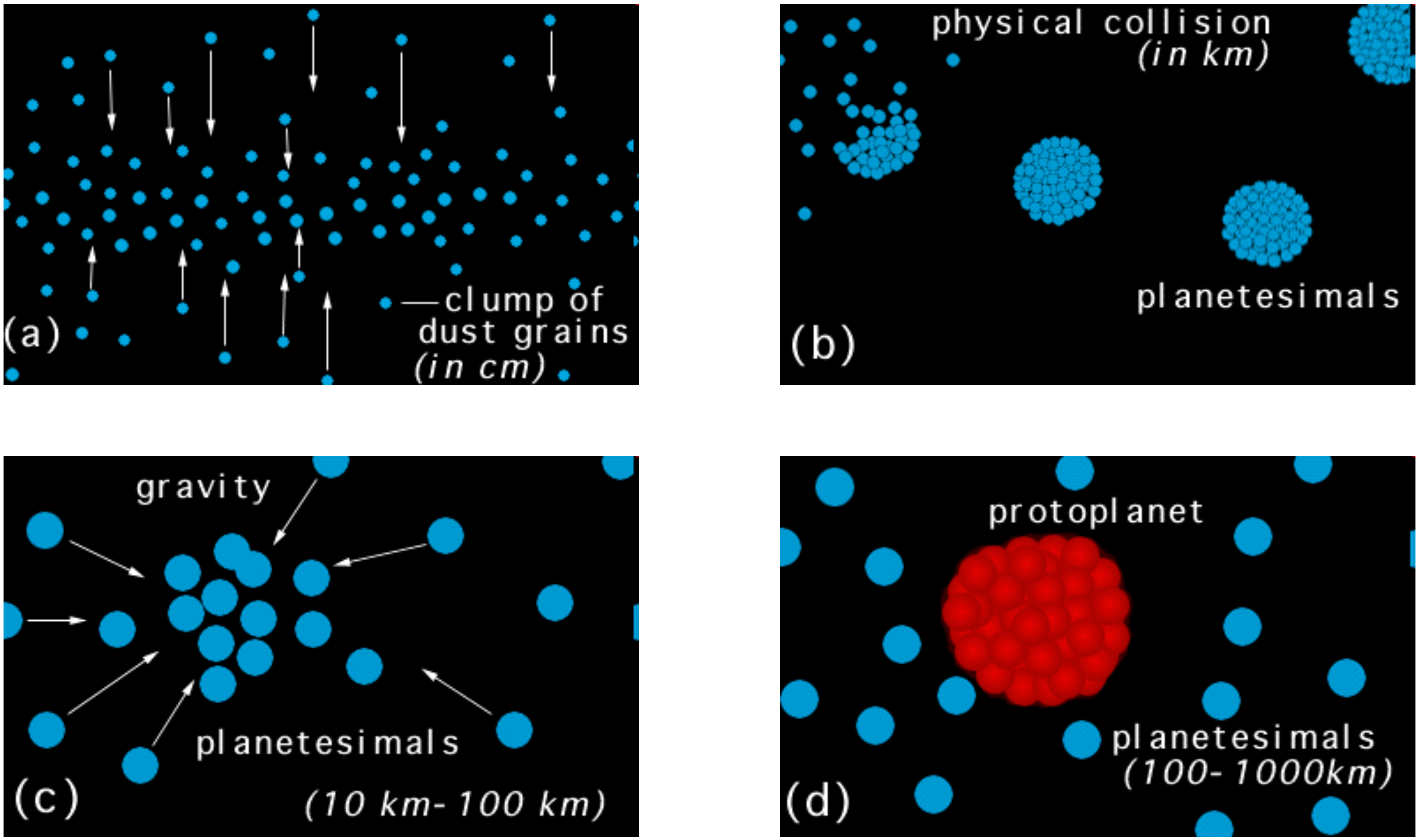


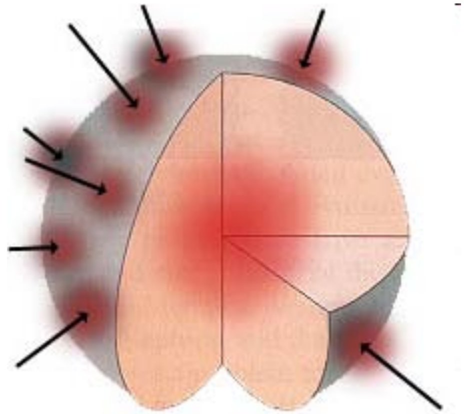
Figure 1 Timeline of events pertaining to the early history of life on Earth, with approximate dates in billions of years before the present.

The formation of Earth:



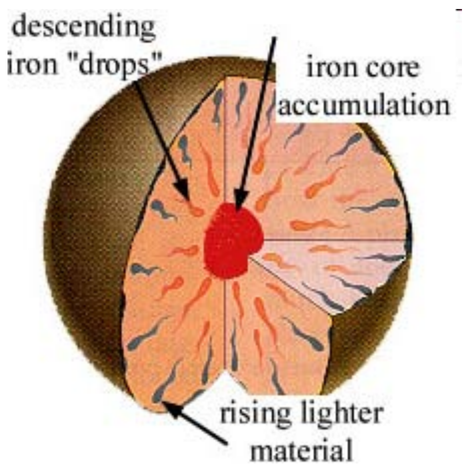
The Earth formed over ~50 Myr via planetesimal accretion

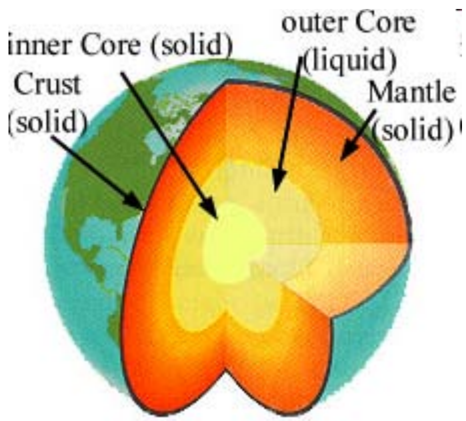
Earth differentiation:



The iron "drops" follow gravity and accumulate towards the core. Lighter materials, such as silicate minerals, migrate upwards in exchange. These silicate-rich materials may well have risen to the surface in molten form, giving rise to an initial **magma ocean**

Early Earth heats up due to radio-active decay, compression, and impacts. Over time the temperature of the planet interior rises towards the Fe-melting line.





After the initial segregation into a central iron (+nickel) core and an outer silicate shell, further differentiation occurred into an inner (solid) and outer (liquid) core (a pressure effect: solid iron is more densely packed than liquid iron), the mantel (Fe+Mg silicates) and the crust (K+Na silicates). Initially large portions of the crust might have been molten - the so called magma ocean. The latter would have cooled to form a layer of basaltic crust (such as is present beneath the oceans today). Continental crust would have formed later. It is probable that the Earth's initial crust was remelted several times due to impacts with large asteroids.

The formation of Earth:

Evolution of Our Atmosphere

Original Atmosphere of H/He Lost

- **Secondary Atmosphere liberated due to planetesimal collisions with proto-earth that released volatiles trapped in grains**
- **CO_2 + H_2O (liquid) $\Rightarrow H_2CO_3$ (acid rain)**
- **$H_2CO_3 + Ca^{++} \Rightarrow CaCO_3$ (limestone)**
- **$H_2CO_3 + CaMg(CO_3)_2 \Rightarrow$ dolomites**
- **$N_2 \Rightarrow$ chemically inert so it stays in atmosphere; N_2 cycle develops later**
- **$O_2 \Rightarrow$ not present in original atmosphere; gotta make some critters first!**

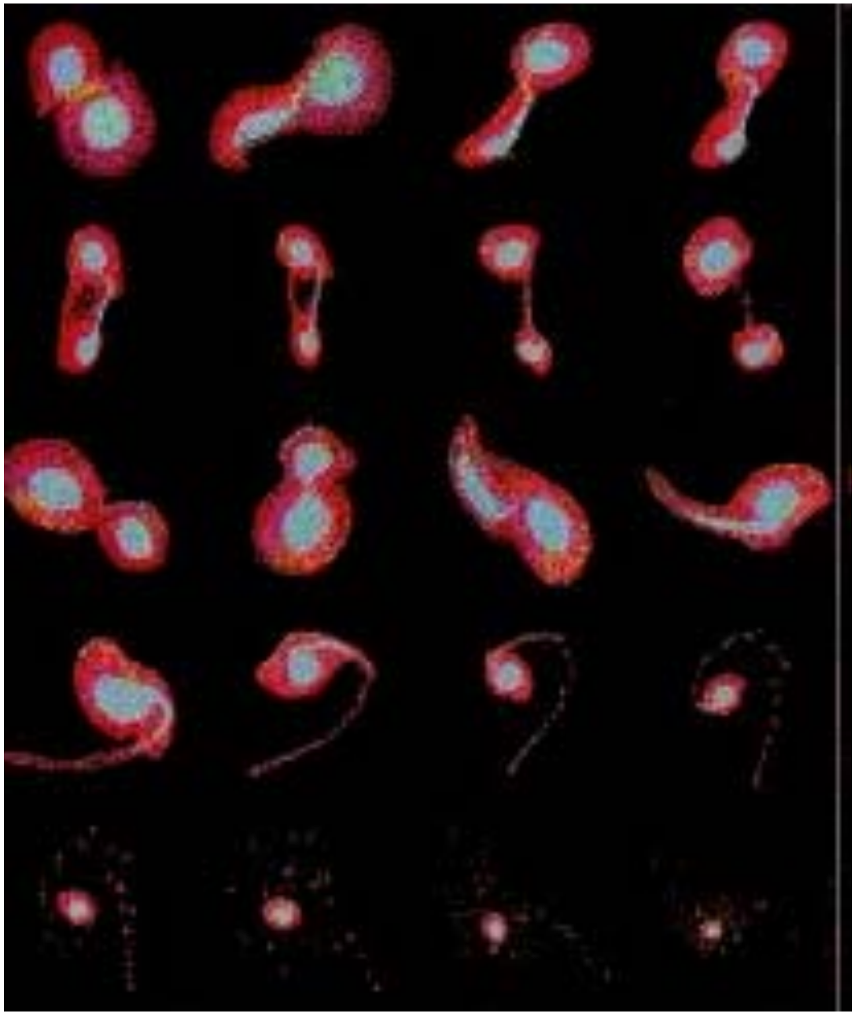
Delivery of water by icy planetesimals and comets?

After condensation of water vapor produced the earth's oceans, thus sweeping out the carbon dioxide and locking it up into rocks, our atmosphere was mostly nitrogen.

Kaboom! The formation of the Moon:

Currently favored hypothesis: Earth has a gigantic **grazing collision** with a Mars-size protoplanet!

It explains the Moon's lower density, lack of iron and oxygen isotope ratios that are identical to Earth's (Apollo).



A timeline for the very early history of the Earth

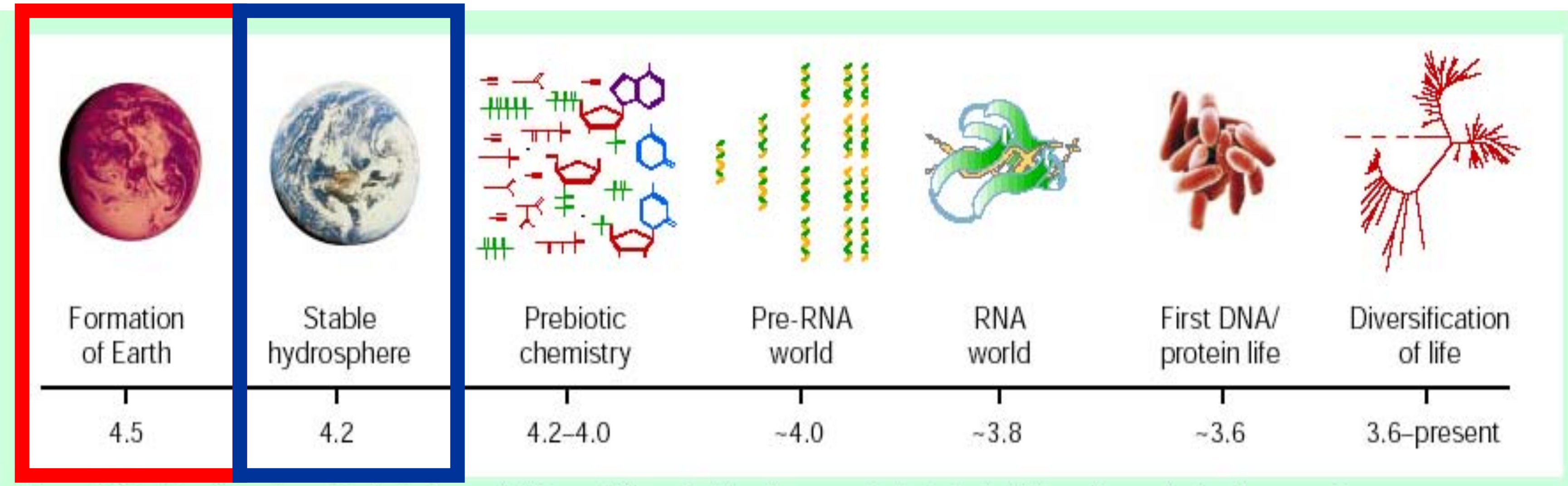
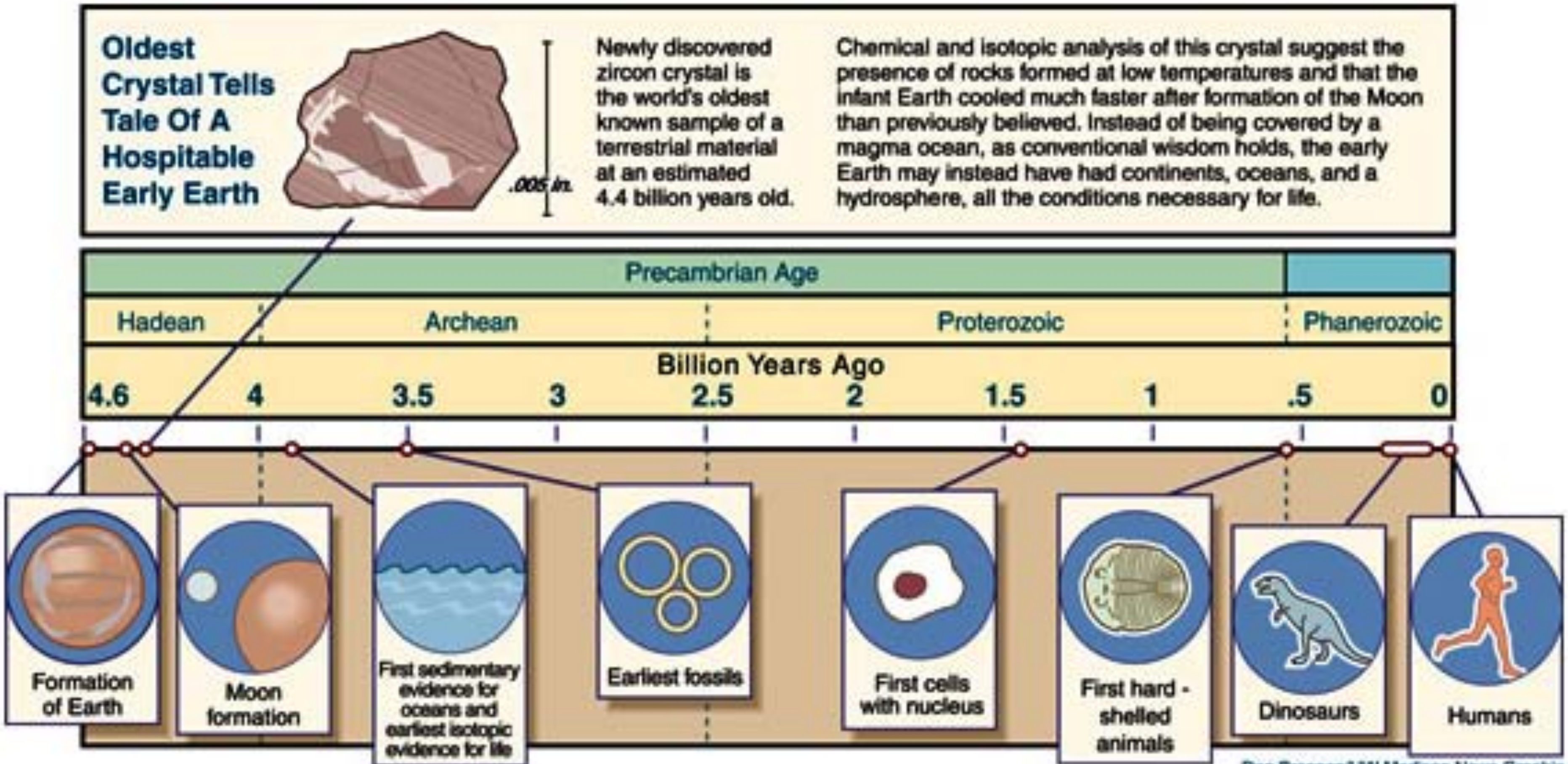


Figure 1 Timeline of events pertaining to the early history of life on Earth, with approximate dates in billions of years before the present.



Tiny zircons (zirconium silicate crystals) found in ancient stream deposits indicate that Earth developed continents and water -- perhaps even oceans and environments in which microbial life could emerge -- 4.3 billion to 4.4 billion years ago, remarkably soon after our planet formed. The presence of water on the young Earth was confirmed when the zircons were analyzed for oxygen isotopes and the telltale signature of rocks that have been touched by water was found: an elevated ratio of oxygen-18 to oxygen-16.

A timeline for the very early history of the Earth

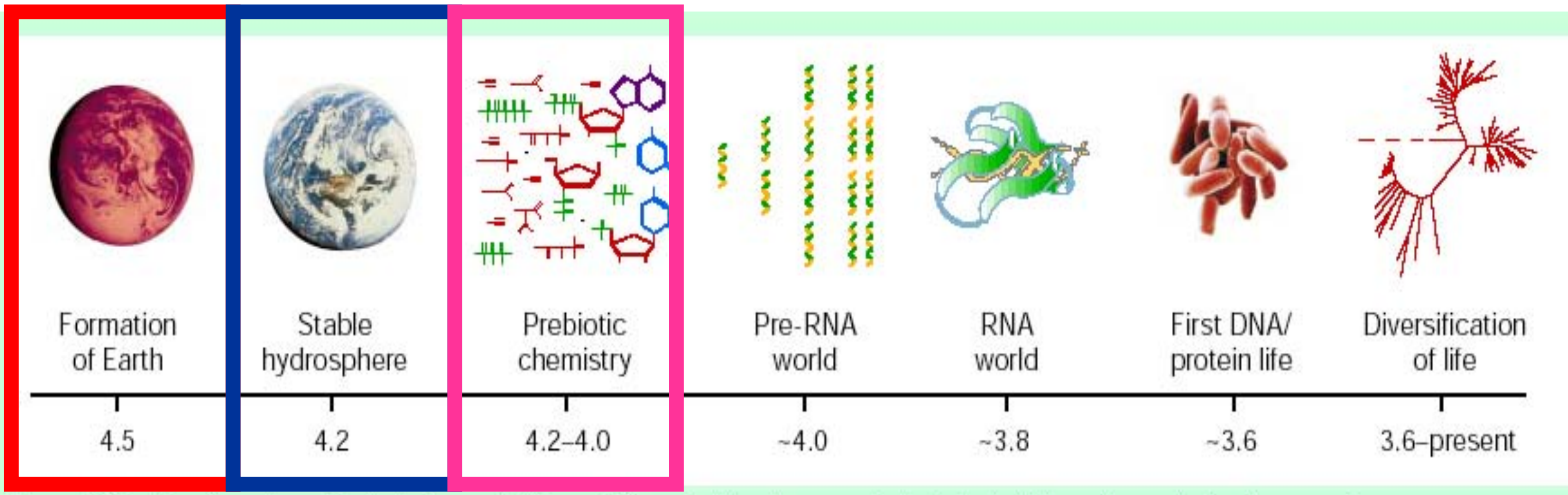


Figure 1 Timeline of events pertaining to the early history of life on Earth, with approximate dates in billions of years before the present.

How to understand an astrobiologist (or any microbiologist):

Monomer: usually a small molecule that can bind chemically to form a polymer (amino acids are monomers)

Polymer: a macro-molecule composed of repeating structural units. Proteins and nucleoacids (RNA & DNA) are polymers

Protein: a biochemical compound that facilitates a biological function

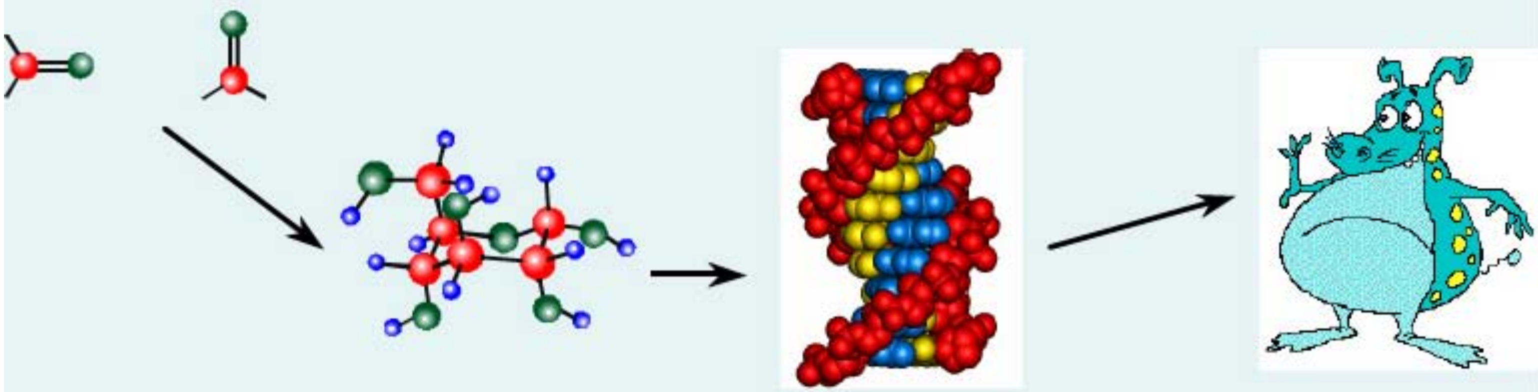
Encyme: are proteins that catalyze (e.g. increase rates) of chemical reactions

RNA: Ribonucleic acid, a macromolecule made of long chains of nucleotides (1 base, 1 sugar and a phosphate group). Single strand, can carry genetic info.

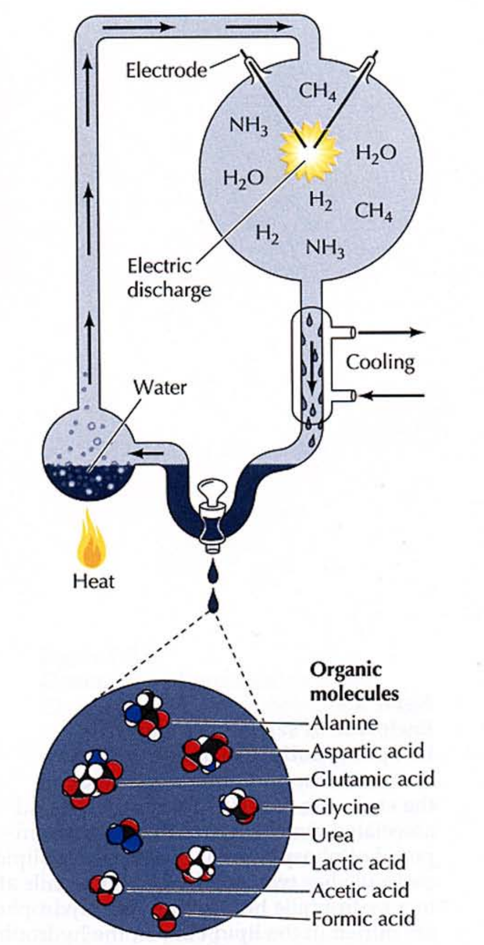
DNA: Deoxyribonucleic acid, double-helix shaped macromolecule made of nucleotides. Carries genetic information.

Basic prebiotic chemistry

Prebiotic chemistry is organic chemistry in aqueous solution, under plausible conditions of the primitive terrestrial environment, leading to compounds of biological interest. Elementary prebiotic chemistry uses simple and reactive organic compounds, such HCN, HC3N, HCHO or their oligomers.



The Miller-Urey experiment



Spontaneous formation of organic molecules Water vapor was refluxed through an atmosphere consisting of CH_4, NH_3, and H_2, into which electric sparks were discharged. Analysis of the reaction products revealed the formation of a variety of organic molecules, including the amino acids alanine, aspartic acid, glutamic acid, and glycine.

In the 1930s, Oparin and Haldane independently suggested that ultraviolet radiation from the sun or lightning discharges caused the molecules of the primordial atmosphere to react to form simple **organic** (carbon-containing) compounds. This process was replicated in 1953 by Stanley Miller and Harold Urey, who subjected a mixture of H_2O, CH_4, NH_3, and H_2 to an electric discharge for about a week. The resulting solution contained water-soluble organic compounds, including several amino acids (which are components of proteins) and other biochemically significant compounds.

Problem: The assumed atmospheric composition

The experiments only give large yields of interesting organics (amino acids, nucleic acids, sugars) if the gas is **H-rich** (highly reducing). If the early atmosphere was CO_2 + N_2 (mildly reducing), as many suspect, the yields are tiny.

Atmosphere from volcanic outgassing?

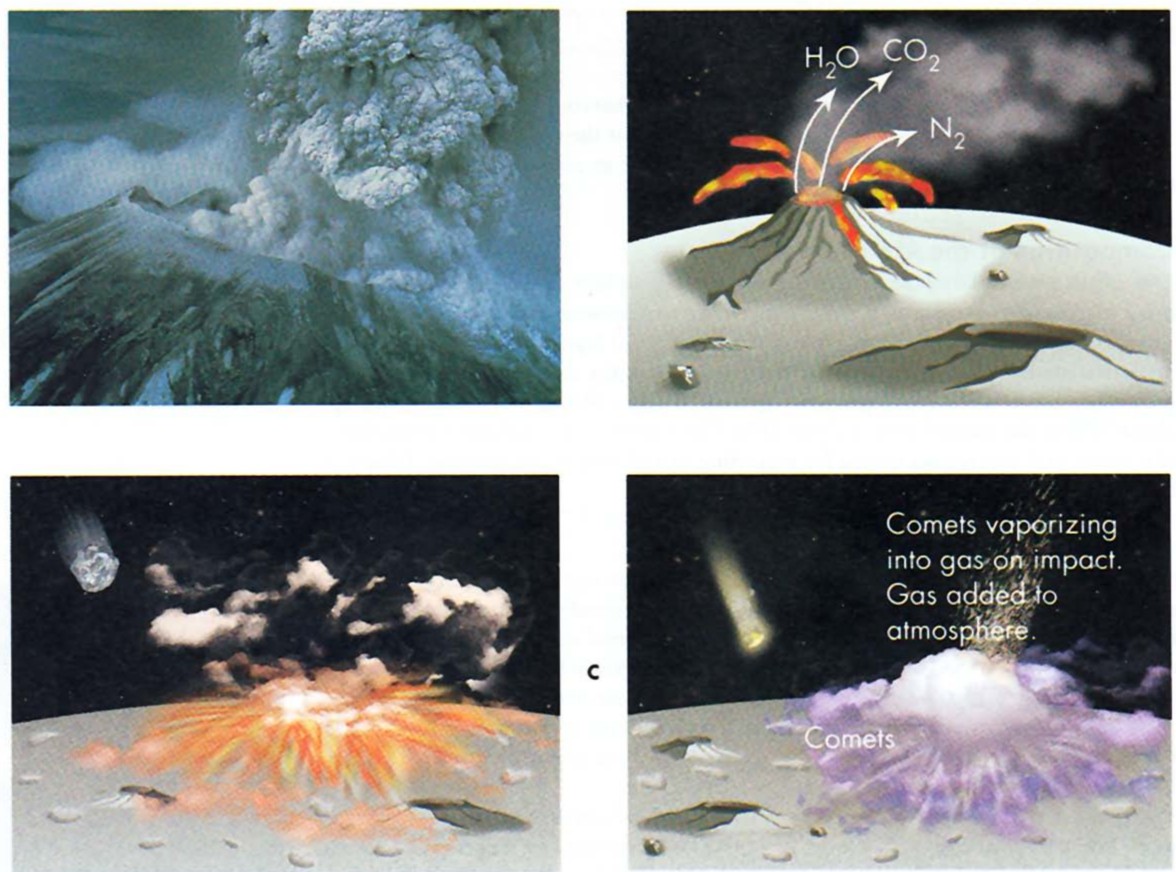
This would give atmosphere rich in CO_2, N_2, and H_2O.
Not the composition that favors Miller-Urey synthesis.

Could the original atmosphere have been delivered to the Earth from comets, asteroids, …? Perhaps then the composition would be H-rich.

What was the source of the early Earth's atmosphere? Not necessarily "endogenous" (there from the start). Outgassing from the crust due to volcanoes (top two), or planetesimal impact (lower left), or comet vaporization (lower right)? The point here is that a major alternative is ***exogenous delivery of organics by comets, asteroids, interplanetary dust…***

Endogenous

Exogenous



Another alternative: irradiation of ices, either extraterrestrial, or on a cold young Earth

Several groups have produced amino acids and other biologically-interesting molecules by ultraviolet irradiation of ices meant to resemble what we think interstellar ices are like. Munoz Caro et al. (2002) produced 16 amino acids this way. Hudson et al. (2008) et al. recently showed that irradiation of ice with high-energy protons produces amino acids, without any other gases present (I.e. doesn't depend on having hydrogen-rich atmosphere.

The key compound in the ices: Nitriles. In these experiments, it was acetonitrile
You may remember it from the "amino acid-like" molecule discovered in the interstellar medium: CH_3CN. It is also detected in comets and in Titan's atmosphere.

After condensation of water vapor produced the earth's oceans, thus sweeping out the carbon dioxide and locking it up into rocks, our atmosphere was mostly nitrogen.

How to Make Some Critters

Evolutionary Advantage Drives Everything!

Step 1: Rapid chemical synthesis of raw materials in the atmosphere produces amino acids:

$$NH_3 + 2CH_4 + 2H_20 + energy = C_2H_5O_2N + 5H_2$$

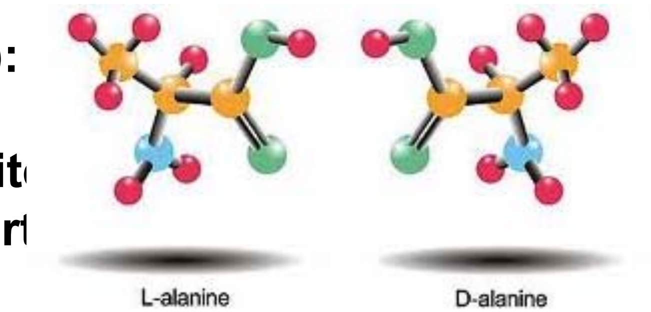
$$5H_2CO = Ribose(food)$$

$$5HCN + UV + NH_3 = Adenine(anotheraminoacid)$$

Most amino acids have a mirror image (L and D):

- L and D both found in meteorit
- L only in organisms on the eart

why is D selected against?(*)



So now we have some amino acids (monomers) loosely mixed in the oceans. Liquid medium is important:

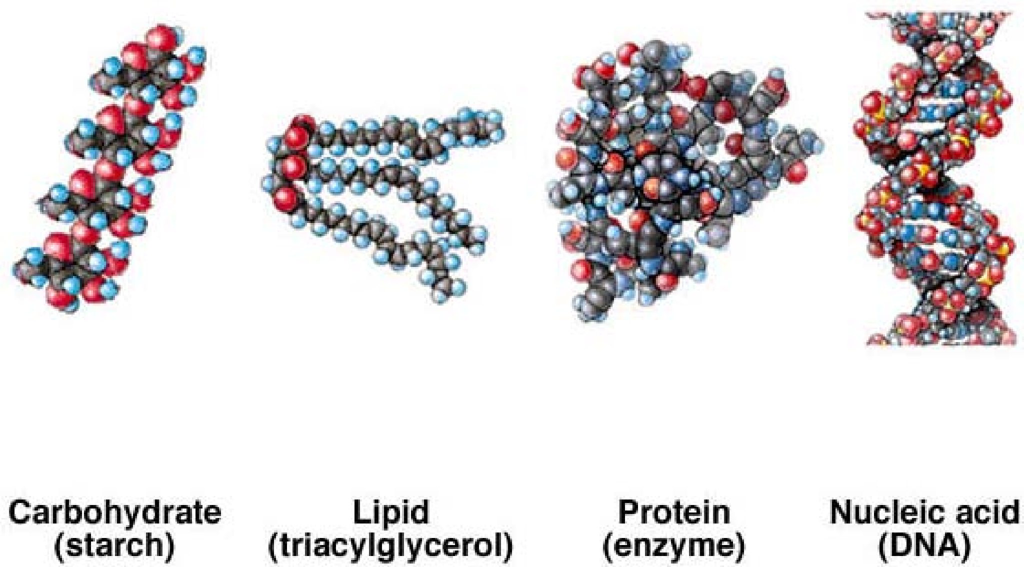
- Protects molecules from UV photon disruption
- Ease of transport and Interaction

Next goal is to combine Monomers into Polymers (peptide chains)

(*) We believe that Earth life's "choice" of chirality was purely random, and that if carbon-based life forms exist elsewhere in the universe, their chemistry could theoretically have opposite chirality.

Which monomer? Which polymer?

Monomers (building blocks) polymerized into ***four*** types of ***polymers.***

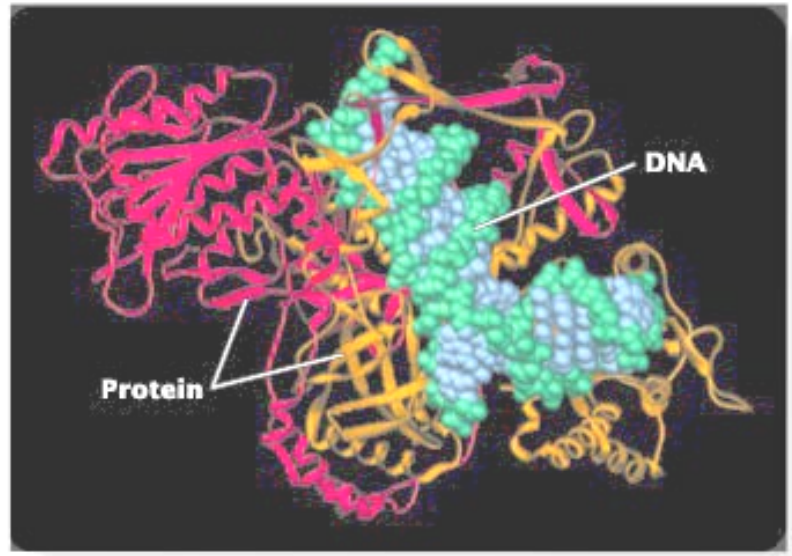


However, only two types seem crucial for primitive biological processes:
amino acids/proteins and nucleotides/nucleic acids

DNA-protein system: Too complex for first life
So which came first?

It is a temptation to think of “life" as a protein-making gene system. But this could **not** have been the origin of life. Not only is it far too complex to have developed spontaneously, there is a chicken-and-egg paradox:

No proteins without DNA to code for them, but
No reason for DNA without proteins to code for.



This protein is bending part of a DNA, something DNA is too stiff to do on its own. There are myriad other DNA-protein interactions, e.g. repair of DNA damage.

Could they somehow have developed simultaneously?

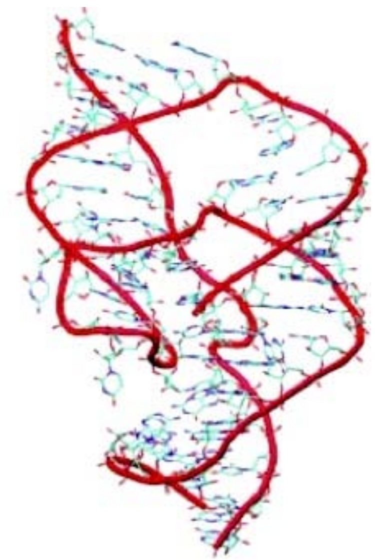
After all, nearly every DNA and RNA in today’s life operates only in connection with protein enzymes: protein-DNA interactions are the norm.

- The “chicken and the egg” problem is obvious: ***Neither DNA nor protein has any function without the other***. Yet their symbiosis is far too complex to have arisen from “nothing.”

=> So what preceded the DNA/protein system?

What came before DNA and proteins? Almost certainly: RNA

RNA looks a lot like DNA, but is single stranded. The big difference is that RNA is a molecule that can carry information like DNA, but can also fold itself into complex three-dimensional shapes like proteins, so RNAs can be their own enzymes (proteins). Because RNA is *ribo*nucleic acid, but can act like an enzyme (protein), these primordial RNAs are called "**ribozymes**" and are the most important candidate for the origin of life. *That* is why we are learning about DNA

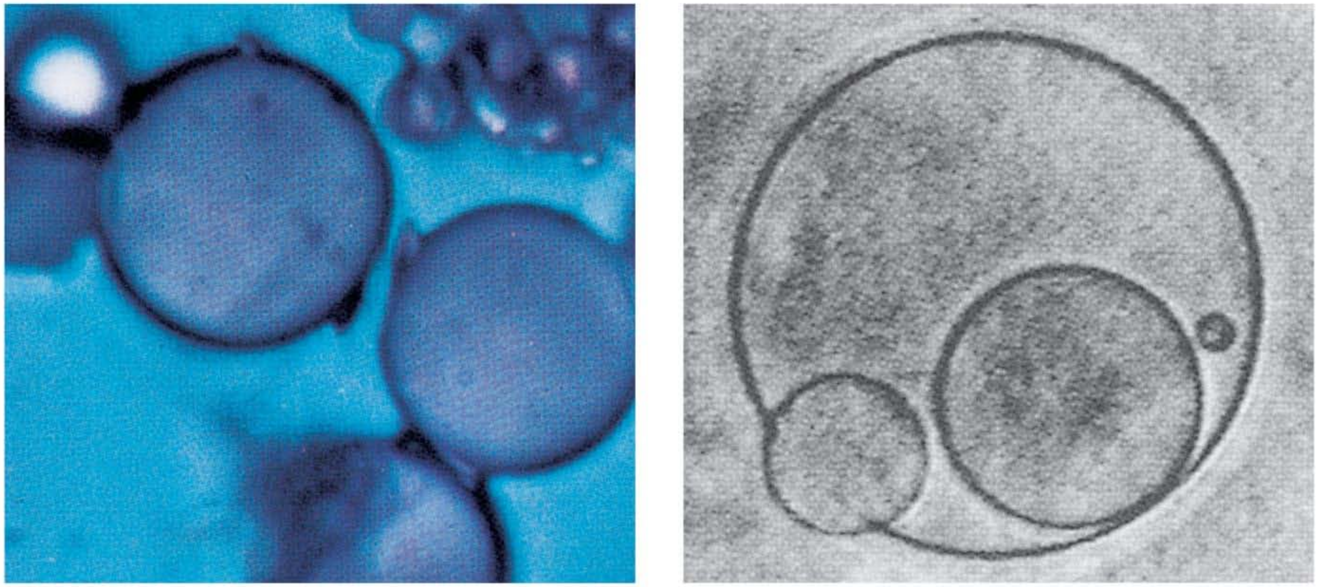


When naturally occurring ribozymes were discovered in present-day organisms (including humans), The idea that there was once an "RNA world" became easily the most plausible scenario for the transition to life.

Encapsulation: Prerequisite for RNA world?

The production of RNA polymers at fast enough rate is usually considered a problem, but there are many ways to enhance it. One is to confine the reactants to a compartment of some kind; a lipid vesicle, forerunner of today's lipid membranes.

Prebiotic membranes (vesicles) are easy

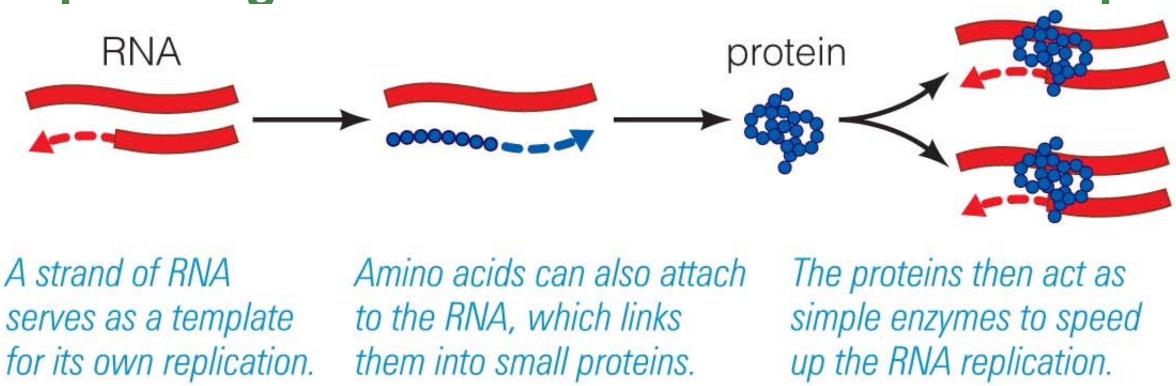


a These microscopic spheres were made by cooling a warm-water solution of amino acids. They are not alive, but they exhibit many lifelike properties.

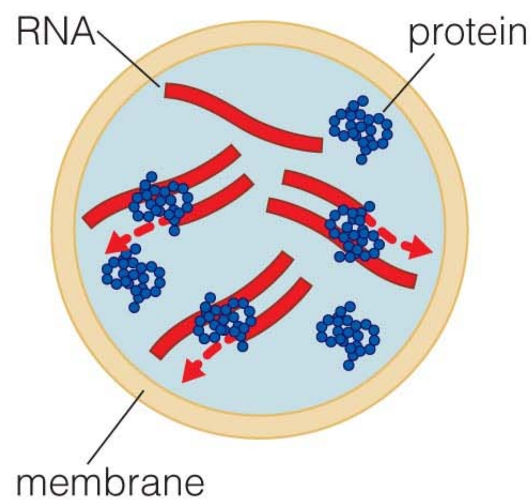
b These microscopic membranes are made from lipids that, when mixed with water, spontaneously form enclosed droplets.

What followed the RNA world?

How self-replicating RNA could have led to the DNA/protein world



a This diagram shows a self-replicating RNA molecule that has evolved the capability to produce a primitive enzyme that helps its own replication.



b If the RNA and the enzyme are isolated from the outside environment inside a pre-cell, then only the molecules in this particular pre-cell will benefit from the new enzyme, a fact that can speed up the molecular evolution.

But what preceeded RNA? How could an RNA be "alive"? Should we expect the same on habitable exoplanets? How different could life be if the basic polymer was not RNA? What if more bases, or more varied codons? What are the chances that life would occur again if we could "play back the tape"?

The lesson we learned so far was that nearly everything that we see today in living organisms is far too complex to have arisen spontaneously from some lifeless polymers.

That there are two ancient kingdoms, the **bacteria and archaea**, or that there are **prokaryotic and eukaryotic cells**, or that organisms can be classified according to their metabolic habits, are all interesting, but only shows us that all of these are too complex: They are the products of hundreds of millions of years of development and evolution.
We saw a glimmer of what might have come before in *ribozymes*.

A timeline for the very early history of the Earth

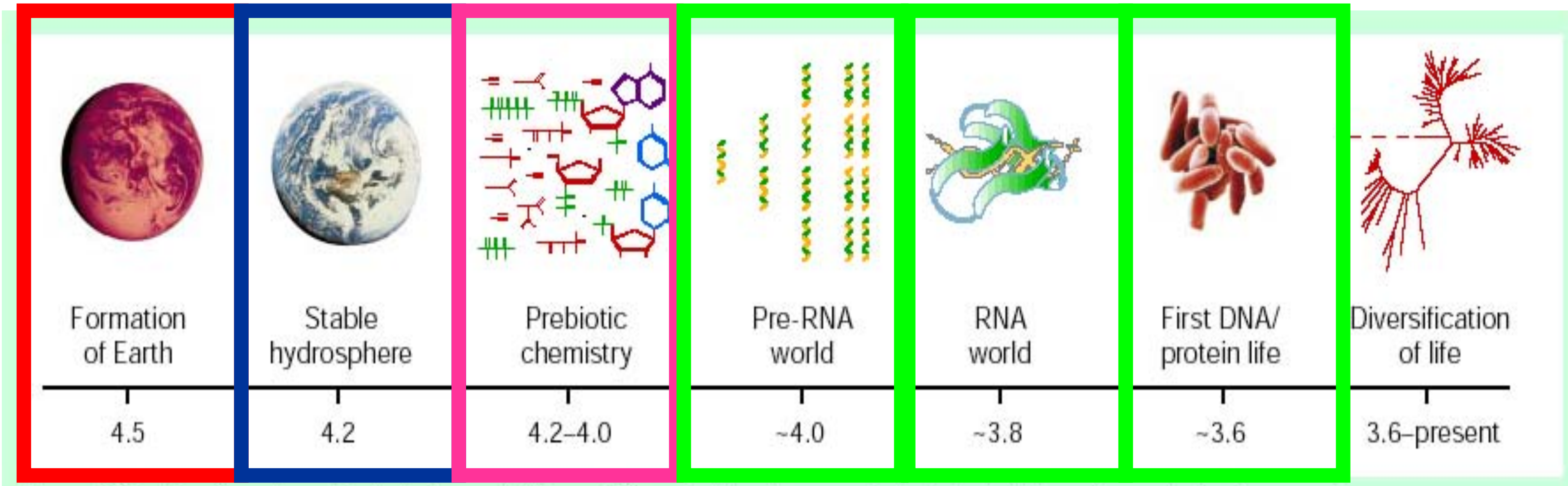
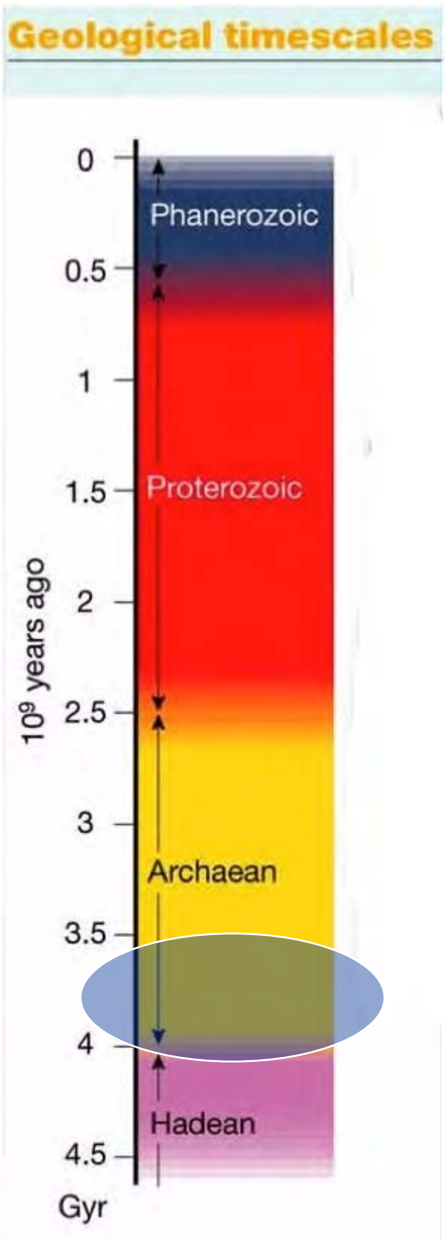


Figure 1 Timeline of events pertaining to the early history of life on Earth, with approximate dates in billions of years before the present.

When did life begin?



Stromatolites: Bacterial colonies that used photosynthesis

Microfossils: Difficult! Controversial….

Isotope ratios: carbon-12 to carbon-13 abundance is affected by metabolism in living things.

When organisms ingest carbon, they preferentially use 12C over 13C. (14C is radioactive, and thus won't remain over a long time period.) Carbon with a high ratio of 12C compared to 13C is therefore an indicator of living processes. Carbon enriched in 12C has been identified in rocks from Greenland dated at 3.85 billions of years ago. This is the earliest evidence for life on Earth.

Best estimate: 3.5 to 4.0 Gyr ago

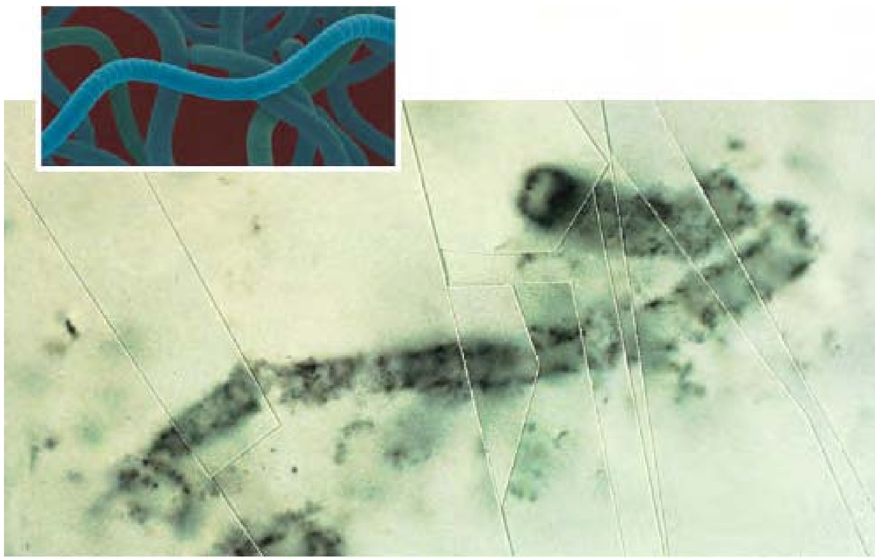
Establishing biological nature of fossils: stromatolites (below), …

Stomatolites: Mats of previous bacterial colonies that harvested sunlight for photosynthesis

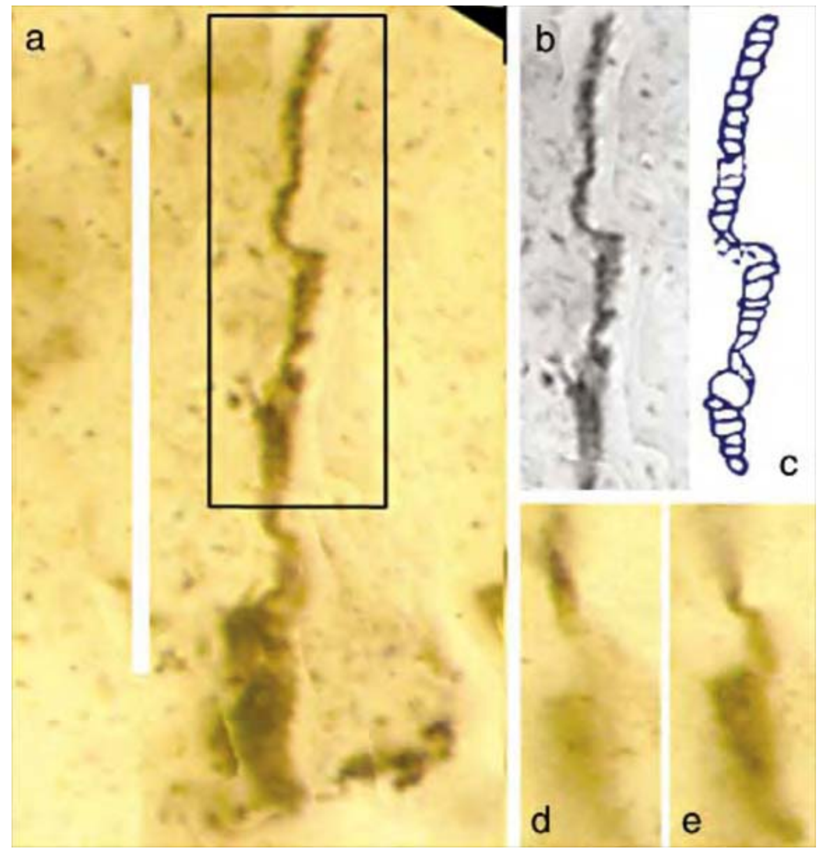
Stromatolites are a classic method for estimating when the Earth's atmosphere became oxygenated, and some think that the presence of stromatolites at such-and-such an age shows the Earth's atmosphere was oxygenated at that time. [Problem: Now clearer that many mat-building bacteria are not aerobic photosynthesizers.]

Oldest stromatolites are about 3 Gyr, but photosynthesis is so complex that it could not have been available near the beginning of life.

Ancient microfossils:

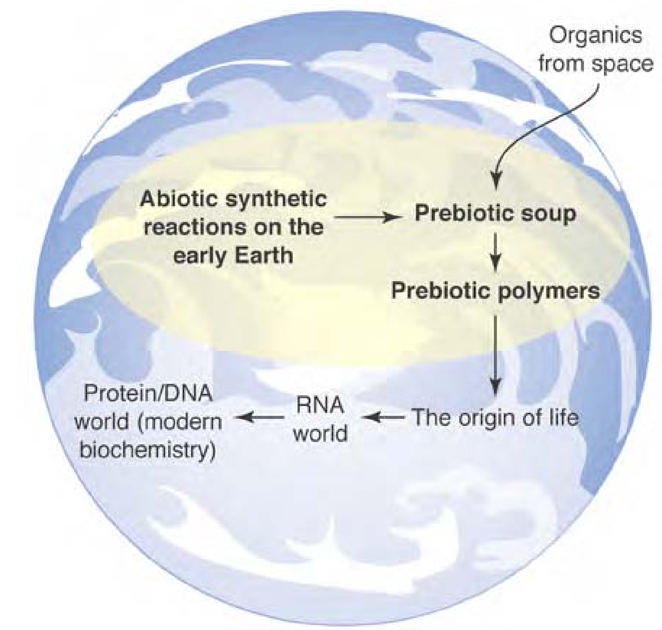


The Earliest Trace of Life? This fossil from Western Australia is 3.5 billion years old and shows carbon traces that indicate life. Its form is similar to that of modern filamentous cyanobacteria (inset).



Science 8 March 2002 :
“Earliest Signs of Life Just Oddly Shaped Crud?”

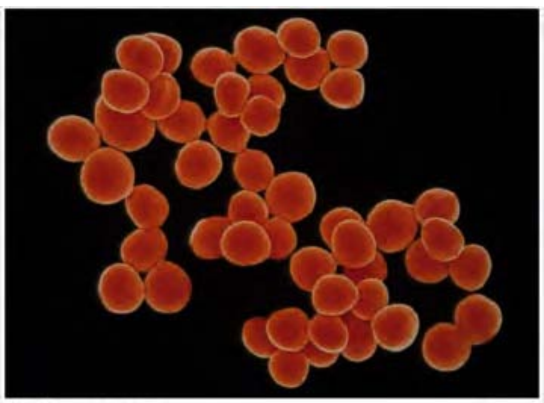
Where did life begin?



- **Land?**
  Problem: No protection from intense UV,
  or from sterilizing impacts.
  Additional reason for excluding origin on land:
  Hard to imagine life not in an aqueous solution.
- **Ocean?**
  How to concentrate the molecules so they
  polymerize in a reasonable time?
  One possibility: ***Encapsulation of molecules in cell-like membrane.***
- **In tidepools or lagoons?**
  Evaporation concentrates monomers, but unfortunately exposes to UV.
- **Hydrothermal deep-sea vents?**
  A present-day favorite.

The Hadean/Archean biological world

Prokaryotes: Most successful organisms on Earth. The only life for over 2 Gyr, many still with us. Essentially infinite lifetime for colonies. Note the complexity!
No organelles (eukaryotic cells only), smaller genome, no sex, but other abilities like extreme adaptation (see "extremophiles"), and *horizontal gene transfer*.

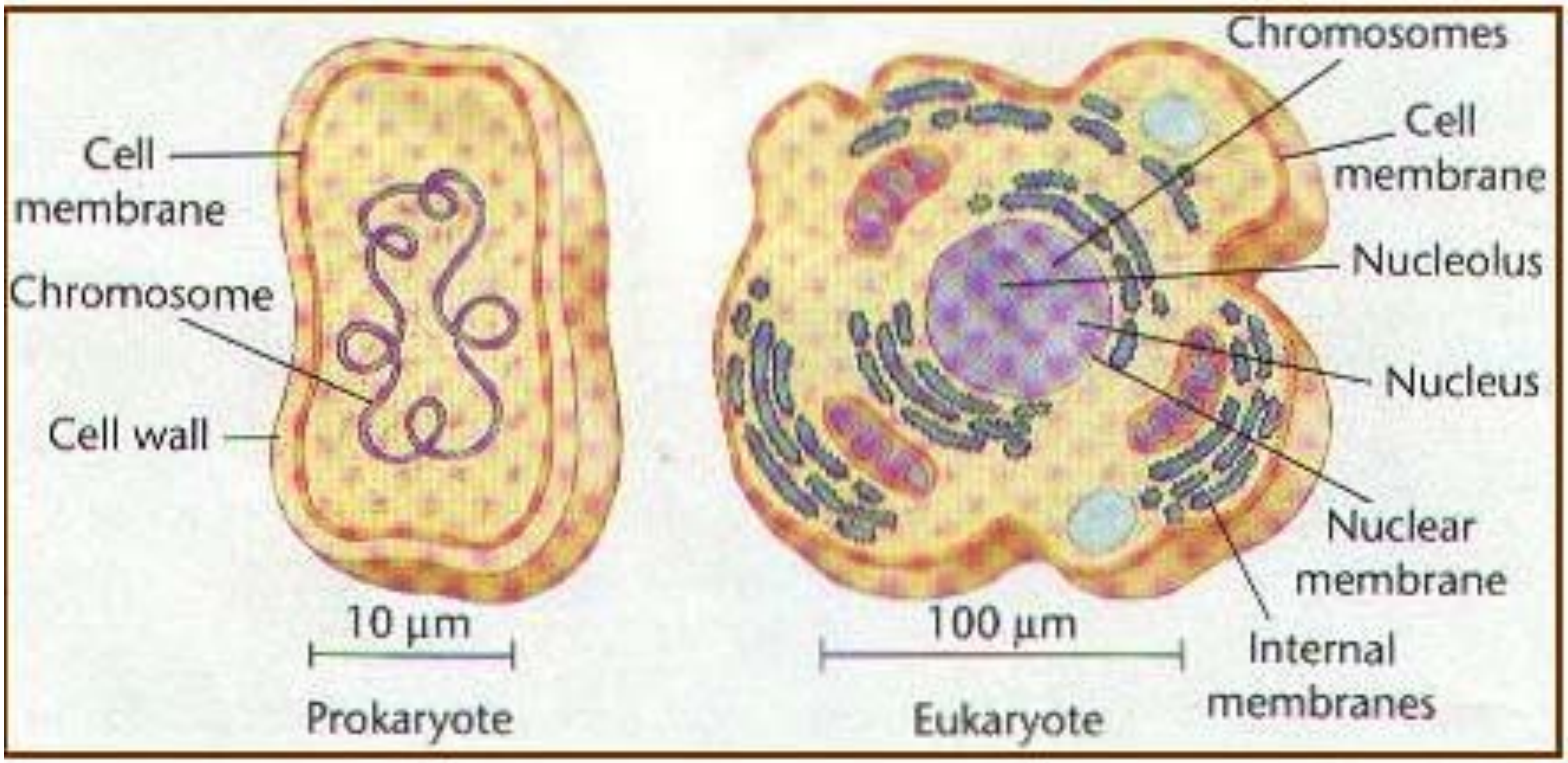


Staphylococcus aureus 1 µm

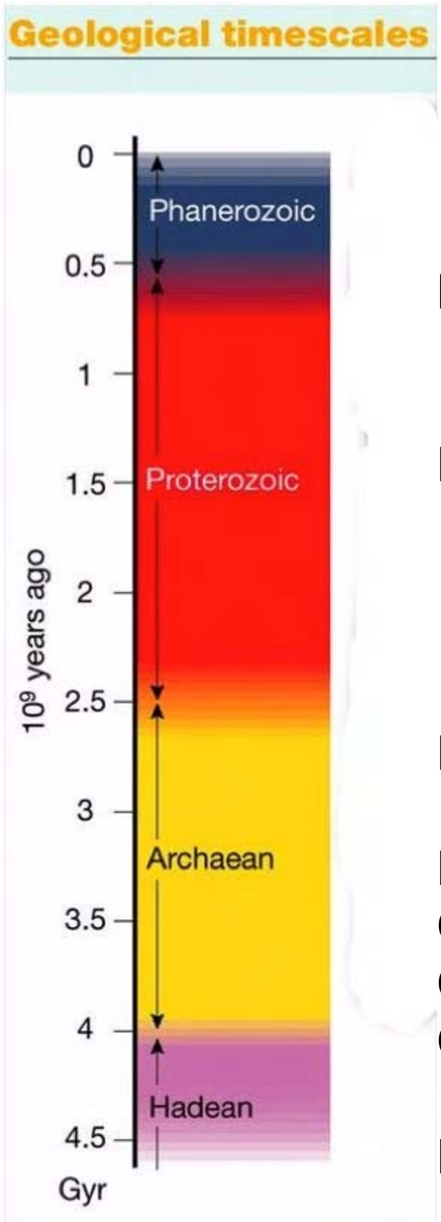
Actinomyces sp. 2 µm

Escherichia coli

Prokaryote vs. Eukaryote:



So what does the geological record show?



Multicellular life (Cambrian explosion)

Eukaryotes

Photosynthesis

Earliest confirmed microfossil
Oldest purported microfossils 3.5 Gyr
Oldest isotopic evidence for life 3.8 Gyr
Oldest zircons 4.2 Gyr

Earth forms

A timeline for the very early history of the Earth

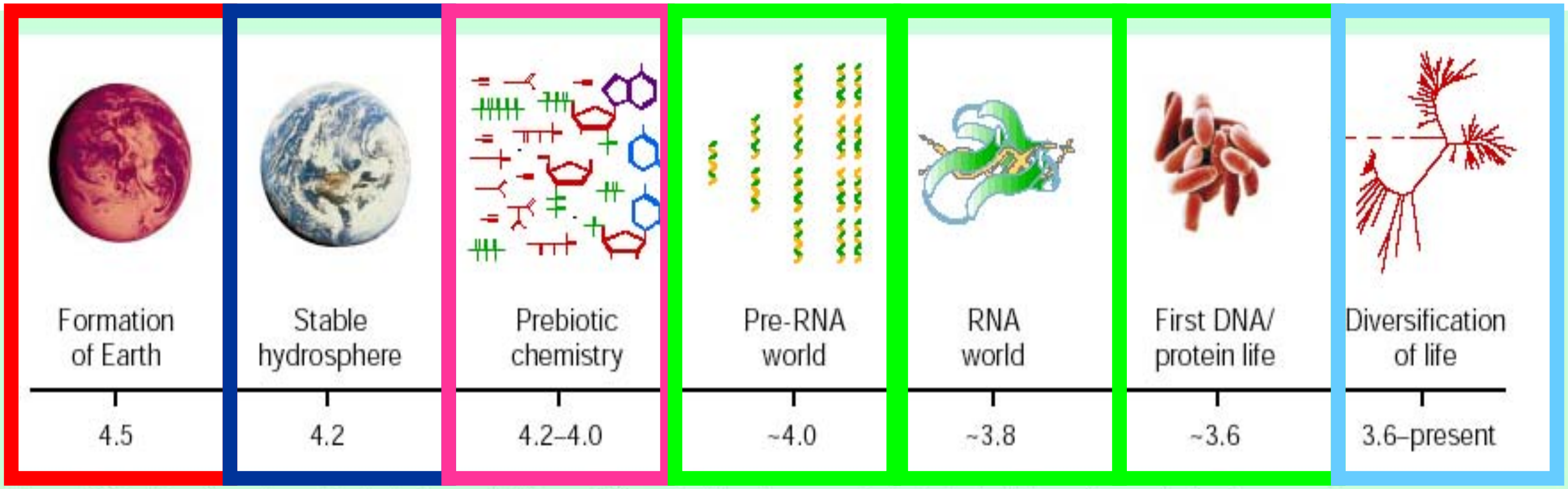
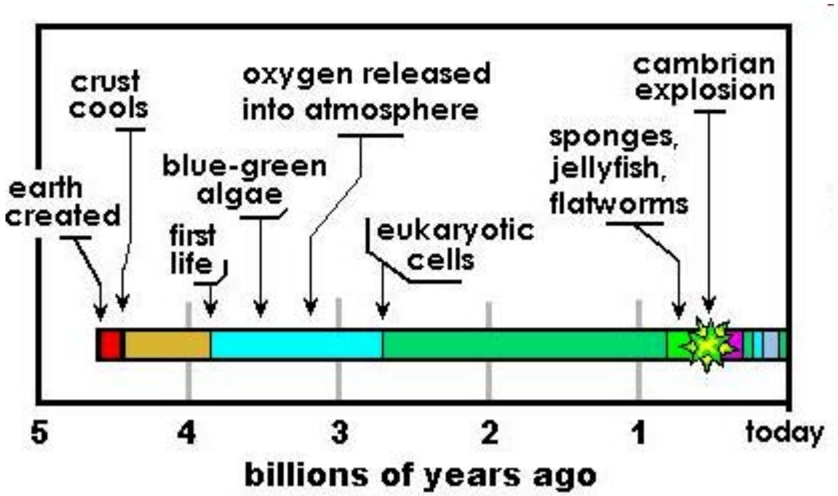
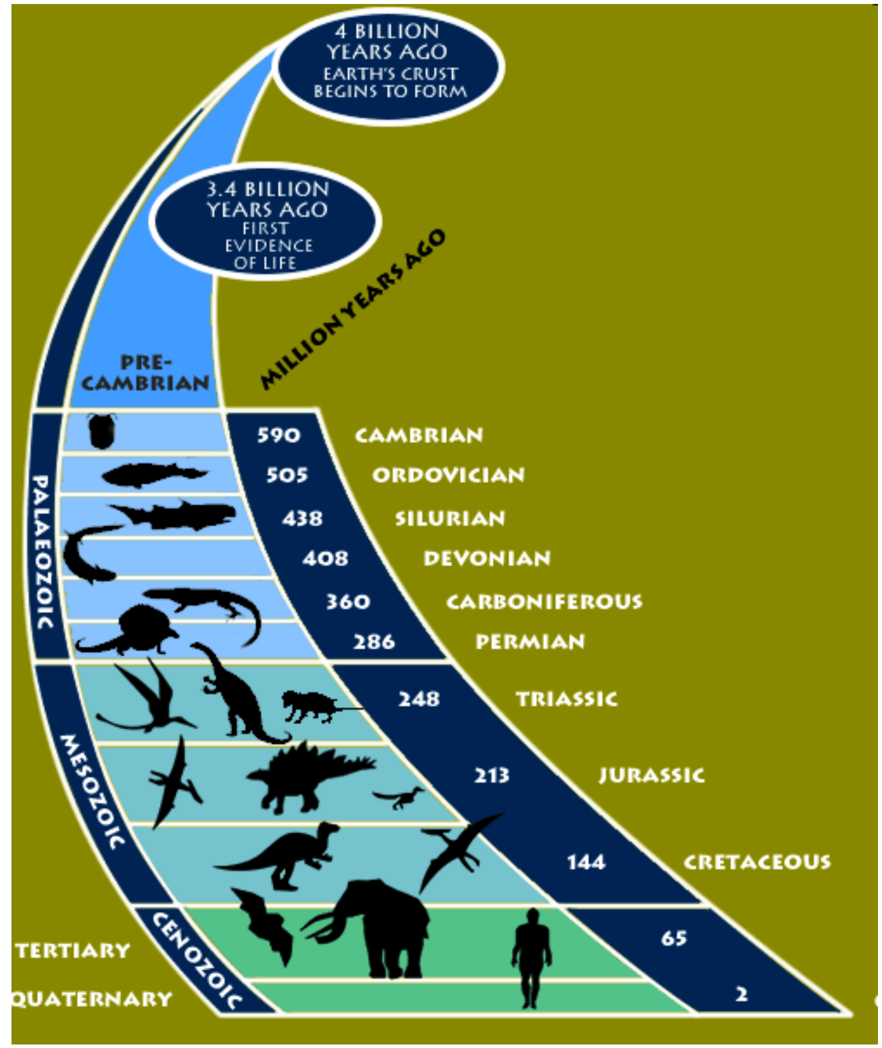


Figure 1 Timeline of events pertaining to the early history of life on Earth, with approximate dates in billions of years before the present.

Life on Earth





The Cambrian Explosion

- ~ 530 Myrs ago, fossil record of animals and other complex organisms “explodes”
- Major diversification of life on Earth
- Explosion took many millions of years (organisms before 580 Myrs were much simpler
- Several hypotheses:
  - Increased oxygen levels
  - Earth was recovering from a Snowball event
  - Evolution of eyes?
  - It wasn’t an explosion at all!

Life on Earth:

Escherichia coli

- Earth forms over a time of 50 Myr more than 4.5 Gyrs ago
- Pre-biotic chemistry somehow leads to first replicating macro-molecules (maybe RNA)
- RNA leads to DNA and first life form(s)
- Best estimate: life on Earth is between 3.5 and 4 Gyrs old!
- For >2 Gyrs we have simple prokaryotes, they start photosynthesis
- 1.5 Gyrs ago Eukaryotes evolve
- ~600 Myrs ago complex,
  multi-cellular life evolves