Early Earth and the Origin of Life

# Introduction

* Life is a continuum extending from the earliest organisms through various phylogenetic branches to the great variety of forms alive today.
* The diversification of life on Earth began over 3.8 billion ago.
* Geologic events that alter environments have changed the course of biological evolution.
* For example, the formation and subsequent breakup of the supercontinent Pangea had a tremendous impact on the diversity of life.
* Conversely, life has changed the planet it inhabits.
* The evolution of photosynthetic organisms that release oxygen into the air had a dramatic impact on Earth’s atmosphere.
* Much more recently, the emergence of *Homo sapiens* has changed the land, water, and air on a scale and at a rate unprecedented for a single species.
* Historical study of any sort is an inexact discipline that depends on the preservation, reliability, and interpretation of past records.
* The fossil record of past life is generally less and less complete the farther into the past we delve.
* Fortunately, each organism alive today carries traces of its evolutionary history in its molecules, metabolism, and anatomy.
* Still, the evolutionary episodes of greatest antiquity are generally the most obscure.

# **A. Introduction to the History of Life**

* One can view the chronology of the major episodes that shaped life as a phylogenetic tree.
* Alternatively, we can view these episodes with a clock analogy.

1. Life on Earth originated between 3.5 and 4.0 billion years ago

* For the first three-quarters of evolutionary history, Earth’s only organisms were microscopic and mostly unicellular.
* The Earth formed about 4.5 billion years ago, but rock bodies left over from the origin of the solar system bombarded the surface for the first few hundred million years, making it unlikely that life could survive.
* No clear fossils have been found in the oldest surviving Earth rocks, from 3.8 billion years ago.
* The oldest fossils that have been uncovered were embedded in rocks from western Australia from 3.5 billion years ago.
* The presence of these fossils, resembling bacteria, would imply that life originated much earlier.
* This may have been as early as 3.9 billion years ago, when Earth began to cool to a temperature at which liquid water could exist.

2. Prokaryotes dominated evolutionary history from 3.5 to 2.0 billion years ago

* Prokaryotes dominated evolutionary history from about 3.5 to 2.0 billion years ago.
* The fossil records supports the hypothesis that the earliest organisms were prokaryotes.
* Relatively early, prokaryotes diverged into two main evolutionary branches, the bacteria and the archaea.
* Representatives from both groups thrive in various environments today.
* Two rich sources for early prokaryote fossils are **stromatolites** (fossilized layered microbial mats) and sediments from ancient hydrothermal vent habitats.
* This indicates that the metabolism of prokaryotes was already diverse over 3 billion years ago.

3. Oxygen began accumulating in the atmosphere about 2.7 billion years ago

* Photosynthesis probably evolved very early in prokaryotic history.
* The metabolism of early versions of photosynthesis did not split water and liberate oxygen.
* Cyanobacteria, photosynthetic organisms that split water and produce O2 as a byproduct, evolved over 2.7 billion years ago.
* This early oxygen initially reacted with dissolved iron to form the precipitate iron oxide.
* This can be seen today in banded iron formations.
* About 2.7 billion years ago oxygen began accumulating in the atmosphere and terrestrial rocks with iron began oxidizing.
* While oxygen accumulation was gradual between 2.7 and 2.2 billion years ago, it shot up to 10% of current values shortly afterward.
* This “corrosive” O2 had an enormous impact on life, dooming many prokaryote groups.
* Some species survived in habitats that remained anaerobic.
* Other species evolved mechanisms to use O2 in cellular respiration, which uses oxygen to help harvest the energy stored in organic molecules.

**4. Eukaryotic life began by 2.1 billion years ago**

* Eukaryotic cells are generally larger and more complex than prokaryotic cells.
* In part, this is due to the apparent presence of the descendents of “endosymbiotic prokaryotes” that evolved into mitochondria and chloroplasts.
* While there is some evidence of earlier eukaryotic fossils, the first clear eukaryote appeared about 2.1 billion years ago.
* Other evidence places the origin of eukaryotes to as early as 2.7 billion years ago.
* This places the earliest eukaryotes at the same time as the oxygen revolution that changed the Earth’s environment so dramatically.
* The evolution of chloroplasts may be part of the explanation for this temporal correlation.
* Another eukaryotic organelle, the mitochondrion, turned the accumulating O2 to metabolic advantage through cellular respiration.

**5. Multicellular eukaryotes evolved by 1.2 billion years ago**

* A great range of eukaryotic unicellular forms evolved into the diversity of present-day “protists.”
* Multicellular organisms, differentiating from a single-celled precursor, appear 1.2 billion years ago as fossils, or perhaps as early as 1.5 billion years ago from molecular clock estimates.
* Recent fossil finds from China have produced a diversity of algae and animals from 570 million years ago, including beautifully preserved embryos.
* Geologic evidence for a severe ice age (“**snowball Earth**” hypothesis) from 750 to 570 million years ago may be responsible for the limited diversity and distribution of multicellular eukaryotes until the very late Precambrian.
* During this period, most life would have been confined to deep-sea vents and hot springs or those few locations where enough ice melted for sunlight to penetrate the surface waters of the sea.
* The first major diversification of multicellular eukaryotic organisms corresponds to the time of the thawing of snowball Earth.

6. Animal diversity exploded during the early Cambrian period

* A second radiation of eukaryotic forms produced most of the major groups of animals during the early Cambrian period.
* Cnidarians (the phylum that includes jellies) and poriferans (sponges) were already present in the late Precambrian.
* However, most of the major groups (phyla) of animals make their first fossil appearances during the relatively short span of the Cambrian period’s first 20 million years.

7. Plants, fungi, and animals colonized the land about 500 million years ago

* The colonization of land was one of the pivotal milestones in the history of life.
* There is fossil evidence that cyanobacteria and other photosynthetic prokaryotes coated damp terrestrial surfaces well over a billion years ago.
* However, macroscopic life in the form of plants, fungi, and animals did not colonize land until about 500 million years ago, during the early Paleozoic era.
* The gradual evolution from aquatic to terrestrial habitats required adaptations to prevent dehydration and to reproduce on land.
* For example, plants evolved a waterproof coating of wax on their leaves to slow the loss of water.
* Plants colonized land in association with fungi.
* Fungi aid the absorption of water and nutrients from the soil.
* The fungi obtain organic nutrients from the plant.
* This ancient symbiotic association is evident in some of the oldest fossilized roots.
* Plants created new opportunities for all life, including herbivorous (plant-eating) animals and their predators.
* The most widespread and diverse terrestrial animals are certain arthropods (including insects and spiders) and certain vertebrates (including amphibians, reptiles, birds, and mammals).
* Most orders of modern mammals, including primates, appeared 50-60 million years ago.
* Humans diverged from other primates only 5 million years ago.
* The terrestrial vertebrates, called tetrapods because of their four walking limbs, evolved from fishes, based on an extensive fossil record.
* Reptiles evolved from amphibians; both birds and mammals evolved from reptiles.
* Most orders of modern mammals, including primates, appeared 50-60 million years ago.
* Humans diverged from other primates only 5 million years ago.

# **B. The Origin of Life**

* Sometime between about 4.0 billion years ago, when the Earth’s crust began to solidify, and 3.5 billion years ago when stromatolites appear, the first organisms came into being.
* We will never know for sure, of course, how life on Earth began.
* But science seeks natural causes for natural phenomena.

**1. The first cells may have originated by chemical evolution on a young Earth: *an overview***

* Most scientists favor the hypothesis that life on Earth developed from nonliving materials that became ordered into aggregates that were capable of self-replication and metabolism.
* From the time of the Greeks until the 19th century, it was common “knowledge” that life could arise from nonliving matter, an idea called **spontaneous generation**.
* While this idea had been rejected by the late Renaissance for macroscopic life, it persisted as an explanation for the rapid growth of microorganisms in spoiled foods.
* In 1862, Louis Pasteur conducted broth experiments that rejected the idea of spontaneous generation even for microbes.
* A sterile broth would “spoil” only if microorganisms could invade from the environment.
* All life today arises only by the reproduction of preexisting life, the principle of **biogenesis**.
* Although there is no evidence that spontaneous generation occurs today, conditions on the early Earth were very different.
* There was very little atmospheric oxygen to attack complex molecules.
* Energy sources, such as lightning, volcanic activity, and ultraviolet sunlight, were more intense than what we experience today.
* One credible hypothesis is that chemical and physical processes in Earth’s primordial environment eventually produced simple cells.
* Under one hypothetical scenario this occurred in four stages.
* 1) The abiotic synthesis of small organic molecules.
* 2) The joining these small molecules into polymers.
* 3) The origin of self-replicating molecules.
* 4) The packaging of these molecules into “protobionts.”
* This hypothesis leads to predictions that can be tested in the laboratory.

2. Abiotic synthesis of organic monomers is a testable hypothesis

* In the 1920s, A.I. Oparin and J.B.S. Haldane independently postulated that conditions on the early Earth favored the synthesis of organic compounds from inorganic precursors.
* They reasoned that this cannot happen today because high levels of oxygen in the atmosphere attack chemical bonds.
* The reducing environment in the early atmosphere would have promoted the joining of simple molecules to form more complex ones.
* The considerable energy required to make organic molecules could be provided by lightning and the intense UV radiation that penetrated the primitive atmosphere.
* Young suns emit more UV radiation and the lack of an ozone layer in the early atmosphere would have allowed this radiation to reach the Earth.
* In 1953, Stanley Miller and Harold Urey tested the Oparin-Haldane hypothesis by creating, in the laboratory, the conditions that had been postulated for early Earth.
* They discharged sparks in an “atmosphere” of gases and water vapor.
* The Miller-Urey experiments produced a variety of amino acids and other organic molecules.
* The atmosphere in the Miller-Urey model consisted of H2O, H2, CH4, and NH3, probably a more strongly reducing environment than is currently believed to have existed on early Earth.
* Other attempts to reproduce the Miller-Urey experiment with other gas mixtures also produced organic molecules, although in smaller quantities.
* The Miller-Urey experiments still stimulate debate on the origin of Earth’s early stockpile of organic ingredients.
* Alternate sites proposed for the synthesis of organic molecules include submerged volcanoes and deep-sea vents where hot water and minerals gush into the deep ocean.
* Another possible source for organic monomers on Earth is from space, including via meteorites containing organic molecules that crashed to Earth.

3. Laboratory simulations of early-Earth conditions have produced organic polymers

* The abiotic origin hypothesis predicts that monomers should link to form polymers without enzymes and other cellular equipment.
* Researchers have produced polymers, including polypeptides, after dripping solutions of monomers onto hot sand, clay, or rock.
* Similar conditions likely existed on the early Earth at deep-sea vents or when dilute solutions of monomers splashed onto fresh lava.

**4. RNA may have been the first genetic material**

* Life is defined partly by inheritance.
* Today, cells store their genetic information as DNA, transcribe select sections into RNA, and translate the RNA messages into enzymes and other proteins.
* Many researchers have proposed that the first hereditary material was RNA, not DNA.
* Because RNA can also function as an enzyme, it helps resolve the paradox of which came first, genes or enzymes.
* Short polymers of ribonucleotides can be synthesized abiotically in the laboratory.
* If these polymers are added to a solution of ribonucleotide monomers, sequences up to 10 bases long are copied from the template according to the base-pairing rules.
* If zinc is added, the copied sequences may reach 40 nucleotides with less than 1% error.
* In the 1980s Thomas Cech discovered that RNA molecules are important catalysts in modern cells.
* RNA catalysts, called **ribozymes**, remove introns from RNA.
* Ribozymes also help catalyze the synthesis of new RNA polymers.
* In the pre-biotic world, RNA molecules may have been fully capable of ribozyme-catalyzed replication.
* Laboratory experiments have demonstrated that RNA sequences can evolve in abiotic conditions.
* RNA molecules have both a genotype (nucleotide sequence) and a phenotype (three-dimensional shape) that interacts with surrounding molecules.
* Under particular conditions, some RNA sequences are more stable and replicate faster and with fewer errors than other sequences.
* Occasional copying errors create mutations and selection screens these mutations for the most stable or the best at self-replication.
* RNA-directed protein synthesis may have begun as weak binding of specific amino acids to bases along RNA molecules, which functioned as simple templates holding a few amino acids together long enough for them to be linked.
* This is one function of rRNA today in ribosomes.
* If RNA synthesized a short polypeptide that behaved as an enzyme helping RNA replication, then early chemical dynamics would include molecular cooperation as well as competition.

**5. Protobionts can form by self-assembly**

* Living cells may have been preceded by **protobionts,** aggregates of abiotically produced molecules.
* Protobionts do not reproduce precisely, but they do maintain an internal chemical environment different from their surroundings and may show some properties associated with life, metabolism, and excitability.
* In the laboratory, droplets of abiotically produced organic compounds, called liposomes, form when lipids are included in the mix.
* The lipids form a molecular bilayer at the droplet surface, much like the lipid bilayer of a membrane.
* These droplets can undergo osmotic swelling or shrinking in different salt concentrations.
* They also store energy as a membrane potential, a voltage cross the surface.
* Liposomes behave dynamically, growing by engulfing smaller liposomes or “giving birth” to smaller liposomes.
* If enzymes are included among the ingredients, they are incorporated into the droplets.
* The protobionts are then able to absorb substrates from their surroundings and release the products of the reactions catalyzed by the enzymes.
* Unlike some laboratory models, protobionts that formed in the ancient seas would not have possessed refined enzymes, the products of inherited instructions.
* However, some molecules produced abiotically do have weak catalytic capacities.
* There could well have been protobioints that had a rudimentary metabolism that allowed them to modify substances they took in across their membranes.

6. Natural selection could refine protobionts containing hereditary information

* Once primitive RNA genes and their polypeptide products were packaged within a membrane, the protobionts could have evolved as units.
* Molecular cooperation could be refined because favorable components were concentrated together, rather than spread throughout the surroundings.
* As an example: suppose that an RNA molecule ordered amino acids into a primitive enzyme that extracted energy from inorganic sulfur compounds taken up from the surroundings
* This energy could be used for other reactions within the protobiont, including the replication of RNA.
* Natural selection would favor such a gene only if its products were kept close by, rather than being shared with competing RNA sequences in the environment.
* The most successful protobionts would grow and split, distributing copies of their genes to offspring.
* Even if only one such protobiont arose initially by the abiotic processes that have been described, its descendants would vary because of mutation, errors in copying RNA.
* Evolution via differential reproductive success of varied individuals presumably refined primitive metabolism and inheritance.
* One refinement was the replacement of RNA as the repository of genetic information by DNA, a more stable molecule.
* Once DNA appeared, RNA molecules would have begun to take on their modern roles as intermediates in translation of genetic programs.

**7. Debates about the origin of life abound**

* Laboratory simulations cannot prove that these kinds of chemical processes actually created life on the primitive Earth.
* They describe steps that *could* have happened.
* The origin of life is still subject to much speculation and alternative views.
* Among the debates are whether organic monomers on early Earth were synthesized there or reached Earth on comets and meteorites.
* Major debates also concern *where* life evolved.
* The prevailing site until recently was in shallow water or moist sediments.
* However, some scientists, including Günter Wachtershäuser and colleagues, have proposed that life originated in deep-sea vents.
* Modern phylogenetic analyses indicate that the ancestors of modern prokaryotes thrived in very hot conditions and may have lived on inorganic sulfur compounds that are common in deep-sea vent environments.
* These sites have energy sources that can be used by modern prokaryotes, produce some organic compounds, and have inorganic iron and nickel sulfides that can catalyze some organic reactions.
* As understanding of our solar system has improved, the hypothesis that life is not restricted to Earth has received more attention.
* The presence of ice on Europa, a moon of Jupiter, has led to hypotheses that liquid water lies beneath the surface and may support life.
* While Mars is cold, dry, and lifeless today, it was probably relatively warmer, wetter, and with a CO2-rich atmosphere billions of years ago.
* Many scientists see Mars as an ideal place to test hypotheses about Earth’s prebiotic chemistry.
* Debate about the origin of terrestrial and extraterrestrial life abounds.
* The leap from an aggregate of molecules that reproduces to even the simplest prokaryotic cell is immense, and change must have occurred in many smaller evolutionary steps.
* The point at which we stop calling membrane-enclosed compartments that metabolize and replicate their genetic programs protobionts and begin calling them living cells is as fuzzy as our definition of life.
* Prokaryotes were already flourishing at least 3.5 billion years ago and all the lineages of life arose from those ancient prokaryotes.

**C. The Major Lineages of Life**

**1. The five-kingdom system reflected increased knowledge of life’s diversity**

* In 1969, R.H Whittaker argued for a five-kingdom system: Monera, Protista, Plantae, Fungi, and Animalia.
* The five-kingdom system recognizes that there are two fundamentally different types of cells: prokaryotic (the kingdom Monera) and eukaryotic (the other four kingdoms).
* Three kingdoms of multicellular eukaryotes were distinguished by nutrition, in part.
* Plants are autotrophic, making organic food by photosynthesis.
* Most fungi are decomposers with extracellular digestion.
* Most animals digest food within specialized cavities.
* In Whittaker’s system, the Protista consisted of all eukaryotes that did not fit the definition of plants, fungi, or animals.
* Most protists are unicellular.
* However, some multicellular organisms, such as seaweeds, were included in the Protista because of their relationships to specific unicellular protists.
* The five-kingdom system prevailed in biology for over 20 years.

2. Arranging the diversity of life into the highest taxa is a work in progress

* During the last three decades, systematists applying cladistic analysis, including the construction of cladograms based on molecular data, have been identifying problems with the five-kingdom system.
* One challenge has been evidence that there are two distinct lineages of prokaryotes.
* This data led to the **three-domain system**: Bacteria, Archaea, and Eukarya, as superkingdoms.
* Many microbiologists have divided the two prokaryotic domains into multiple kingdoms based on cladistic analysis of molecular data.
* A second challenge to the five kingdom system comes from systematists who are sorting out the phylogeny of the former members of the kingdom Protista.
* Molecular systematics and cladistics have shown that the Protista is not monophyletic.
* Some of these organisms have been split among five or more new kingdoms.
* Others have been assigned to the Plantae, Fungi, or Animalia.
* Clearly, taxonomy at the highest level is a work in progress.
* It may seem ironic that systematists are generally more confident in their groupings of species into lower tax than they are about evolutionary relationships among the major groups of organisms.
* Tracing phylogeny at the kingdom level takes us back to the evolutionary branching that occurred in Precambrian seas a billion or more years ago.
* There will be much more research before there is anything close to a new consensus for how the three domains of life are related and how many kingdoms there are.
* New data will undoubtedly lead to further taxonomic modeling.
* Keep in mind that phylogenetic trees and taxonomic groupings are hypotheses that fit the best available data.