Chapter 25: The Origin and Evolutionary History of Life on Earth

1. What is the best current estimate of the age of the Earth, and what is the evidence for that estimate?

2. What are considered to be the four requirements for life to begin on Earth?

3. Describe the contributions of Oparin and Haldane and of Miller and Urey to models of the origin of life on Earth.

4. Briefly discuss at least three different models for how life began on Earth.

5. What are protobionts and microspheres, and what does their existence imply about how cellular life began?

6. Explain the RNA world hypothesis and how in vitro evolution tests it.

7. What are microfossils, and to what age do the oldest ones found on Earth date?

8. What are stromatolites?

9. What are banded iron formations, and why are they important?

10. When did oxygenation of Earth’s atmosphere occur, and what were the key consequences of it?

11. When do eukaryotic cells appear in the fossil record?

12. When was Precambrian time and what were the major events during that time period?

13. For each of the “big five” mass extinctions, give when they occurred, their likely causes if known, and key consequences of them.

14. Outline the relative history, dominant organisms, and key events of each of the periods of the Paleozoic, Mesozoic, and Cenozoic eras.

15. What is the sixth extinction?
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I. Chemical conditions of the early Earth that could have fostered the origin of life

A. The Earth is about 4.6 billion years old (time of the first likely solid surface)
   1. Supported by radioisotope dating of
      - Oldest known Earth minerals (date to 4.4 billion years ago, or 4.4 bya)
      - Oldest known rocks on Earth (4.1 bya)
      - Oldest known meteorites (4.6 bya; for the age of the solar system)
   2. Some models go out to 6 billion years, it is hard to make a rule for a definitive starting point of planet formation

B. Earth’s early atmosphere (when life first appears in the fossil record) most likely consisted of CO$_2$, H$_2$O, CO, H$_2$, N$_2$, and small amounts of NH$_3$, H$_2$S, and CH$_4$ – note the lack of O$_2$, which is a major constituent of today’s atmosphere

C. Four requirements for the current chemical evolution model were likely met in the early Earth
   1. Little or no free oxygen
   2. Abundant energy sources (volcanism, thunderstorms, and bombardment with particles and radiation from space were all likely present as energy sources; especially important is more UV radiation than today)
      - The sun was hotter, producing more UV light
      - The Earth had no ozone layer to filter out most of the UV light coming in
   3. Chemical building blocks of water, dissolved mineral ions, and atmospheric gases
   4. Time (there was plenty of time before the first traces of life from 3.8 bya]

D. Attempts to mimic the early Earth’s atmosphere and chemical profile have led to production of organic molecules from simpler materials after energy is added
   1. 1920s – Oparin and Haldane independently proposed that organic molecules could form spontaneously from simpler raw materials when sufficient energy is supplied in a reducing (energy-rich, electron-adding) environment
   2. 1950s – Miller and Urey made a “reducing atmosphere” of H$_2$O, H$_2$, NH$_3$, CH$_4$ in a spark chamber; after sparking, they found that amino acids and other organic compounds had formed
      - Designed to mimic what was thought at the time to have been Earth’s early atmosphere
      - Later experiments with different “reducing atmospheres” that were thought to be better matches to the likely atmosphere of the early Earth produced all 20 amino acids used in proteins, various sugars and lipids, and components of DNA and RNA nucleotides
      - Current models of the Earth’s early atmosphere are that in general the atmosphere was not reducing, but that there were likely many local environments that were reducing – especially near volcanic activity
   3. Organic polymers can form spontaneously from monomer building blocks on some sand, clay, or rock surfaces

E. There are several models for exactly where and how life as we know it on Earth began
   1. Prebiotic broth hypothesis – life began from an “organic soup” in the oceans
   2. Bubble hypothesis – a variation on the prebiotic broth, with “oily bubbles” from an organic soup interacting with land surfaces at shallow seas or seashores
   3. Iron-sulfur world hypothesis – life began from an “organic soup” interacting with mineral surfaces at hydrothermal vents in the ocean floor, with abundant iron and sulfur there impacting the early metabolism that developed
   4. Deep-hot biosphere hypothesis – life began in an “organic soup” deep within the Earth
5. **exogenesis** – Earth was seeded with life from an extraterrestrial source

II. A model for how the first cells could have originated and functioned

A. **protobionts** have been produced that resemble living cells
   1. **microspheres**, a type of protobiont, form spontaneously when liquid water is added to abiotically produced polypeptides
   2. microspheres can grow, divide, and maintain internal chemistry different from their surroundings
   3. microspheres show that some spontaneous production and maintenance of organization is possible, but are incomplete as a model for formation of the first cells

B. genetic reproduction was crucial in the origin of true cells
   1. RNA likely was first (**RNA world hypothesis**)
      - RNA can catalyze a variety of reactions, including some self-catalytic reactions
      - RNA can also store genetic information
      - **in vitro evolution** of RNA has shown that the RNA world hypothesis is feasible – selection can act on self-replicating RNA molecules in vitro
   2. DNA likely came later and had the selective advantage of greater stability

III. First life, however it came to be (or, Enough theory, Dr. Bowling, give me some dates to learn for the test!)

A. the first evidence of life in the fossil record are isotopic carbon “fingerprints” in rocks from ~3.8 bya
B. the first evidence of cells are **microfossils** of prokaryotic cells in fossils of **stromatolites** dated to ~3.5 bya
   1. **stromatolites** are rocklike structures made up of layers of bacteria and sediment
   2. in some areas stromatolites are still being formed today
C. the first cells were most likely anaerobic heterotrophs
   1. there was likely an abundance of organic molecules available for food early on
   2. later, as organic molecules became scarcer, photosynthetic organisms were favored
D. the first photosynthetic organisms were likely the purple and green sulfur bacteria, which use H\textsubscript{2}S as a hydrogen donor

IV. Life changes the planet: oxygenating Earth’s oceans and atmosphere

A. cyanobacteria were likely the first photosynthetic organisms to use H\textsubscript{2}O as a hydrogen donor, releasing O\textsubscript{2} into the environment
   1. stromatolites from as old as 3.5 bya containing what appear to be fossil cyanobacteria
   2. many stromatolites with what appear to by fossil cyanobacteria date to about 2.5 bya
B. **banded iron formations** from about 2.5 bya indicate the release of O\textsubscript{2} into the oceans
C. by 2 bya, O\textsubscript{2} levels began to build up in the atmosphere
D. the presence of O\textsubscript{2} had a profound impact on life on Earth
   1. O\textsubscript{2} is toxic to organisms that don’t have protective mechanisms; many died as O\textsubscript{2} levels built up
      - creates an oxidizing atmosphere, which can destroy precious reduced organic molecules
      - some anaerobic organisms survive (even today) only in environments with little to no oxygen
      - some evolved adaptations to the presence of oxygen
      - some organisms developed means to use O\textsubscript{2} in respiration to extract more energy from foods (aerobic respiration)
   2. the formation of the **ozone layer** (O\textsubscript{3}) soon after oxygenation of the atmosphere provided protection from UV radiation and allowed life to expand to regions at and near the Earth’s surface
V. Eukaryotic cells descended from prokaryotic cells
   A. eukaryotes first appear in the fossil record about 2 bya, long after prokaryotic cells
   B. DNA sequencing provides evidence of common ancestry of life on Earth, with eukaryotes splitting from Archaea about 2 bya
   C. recall the endosymbiotic theory – model for how at least some of the eukaryotic cell organelles came to exist

VI. History of life on Earth (organized by divisions of geological time)
   A. basis for the divisions
      1. divisions of geological time are based major changes in types of organisms found in the fossil record (each division has its own characteristic set of commonly found fossils and unique fossil forms)
      2. many of the transitions between the divisions are marked by major extinction events, where many organisms apparently died out over a short period of time because they disappear from the fossil record from that point on
      3. although there are many major extinction events in the fossil record, by most measures five stand out above the rest; you need to know these “big five” mass extinction events
   B. Precambrian time, from 4.6 bya up to 542 million years ago (mya); the fossil record is very spotty prior to 542 mya
      1. we have already covered some of the major events of that time period (origin of life, oxygenation of the oceans and atmosphere)
      2. Snowball Earth??? 800 mya – 635 mya
      3. ended with the Ediacaran Period (635-542 mya), which is widely recognized as having the oldest animal fossils
   C. Paleozoic era (542-251 mya)
      1. Cambrian period (542-488 mya)
         • Cambrian explosion - fossils of multicellular organisms are abundant in this period
         • all contemporary animal phyla are represented in Cambrian fossils, as well as many extinct groups
         • this is the biggest expansion in diversity found in the fossil record
         • Burgess shale – most famous example of Cambrian fossils
      2. Ordovician period (488-444 mya)
         • abundant numbers and diversification of trilobites, brachiopods, and molluscs
         • first coral reefs
         • first terrestrial plants
         • Ordovician period ended in a mass extinction event (1st of the big five)
            • likely due to an ice age, perhaps in conjunction with a gamma ray burst
            • decimated the trilobites and brachiopods, along with many other groups of marine organisms
      3. Silurian period (444-416 mya) – first vascular plants; first true terrestrial animals
      4. Devonian period (416-359 mya) – jawed fishes, amphibians, insects, and vascular plants first appear; jawed fishes diversify and dominate the seas (Age of Fishes), and vascular plants diversify and dominant the land
         • Devonian period ended in a mass extinction event (2nd of the big five)
      5. Carboniferous period (359-299 mya) – reptiles first appear; amphibians diversify and are the dominant terrestrial carnivores (Age of Amphibians); most of today’s major coal deposits are the remains of organisms that lived in this period
      6. Permian period (299-251 mya) – by the end of this period, the continents have merged as the Pangaea supercontinent
      7. the era ended (251 mya) with a mass extinction event (3rd of the big five)
         • the largest mass extinction on record
         • more than 90% of the marine species and 70% of land vertebrates that are in the fossil record at the end of the Permian never appear in the fossil record again
         • the mass extinction event apparently took place in a time span of only a few hundred thousand years, which is fast in the geological time scale
   D. Mesozoic era (251-65 mya)
1. Diversification and dominance by reptiles – the whole era is often called the **Age of Reptiles** (sometime called the Age of Dinosaurs, many non-dinosaur reptiles were prominent)

2. **Triassic period** (251-200 mya)
   - Dinosaurs and mammals first appear
   - Gymnosperms are the dominant land plants
   - Ended with a **mass extinction event** (4th of the big five) that paved the way for the dinosaurs to rise to prominence

3. **Jurassic period** (200-146 mya)
   - Dinosaurs dominate the land (and other large reptiles dominate the seas and the skies)
   - Birds evolve from a dinosaur lineage

4. **Cretaceous period** (146-65 mya)
   - Flowering plants evolved around the early Cretaceous and diversified quickly
   - Many animals (especially insects) appear to have **coevolved** with flowering plants (different species affecting each other’s evolution)

5. The era ended (65 mya) with a **mass extinction event** (5th of the big five)
   - Dinosaurs essentially all died out (unless you count birds as dinosaurs, which some scientists do)
   - Most gymnosperms also died out, as did many marine organisms
   - Evidence points to the impact of a large extraterrestrial body as a likely cause of the extinction event
     - Major impact almost certainly occurred at this time; iridium layers worldwide and deposits from tsunamis around the Gulf of Mexico coast of the time provide clear evidence of this
     - A large crater site (**Chicxulub crater**) in the Yucatán Peninsula of Mexico is likely the result of this impact
     - The extent to which such an impact could affect the biosphere is still debated, but is accepted by more and more scientists as at least a contributing factor to this massive extinction event

E. **Cenozoic era** (65 mya – present)
   1. Usually called the **Age of Mammals**, but birds, insects, and flowering plants have also undergone massive diversification and have all achieved some measure of “dominance” in the biosphere during this era
   2. Two periods, **Paleogene** (65-23 mya) and the **Neogene** (23 mya – present), although an older division into **Tertiary** (65-~2 mya) and **Quaternary** (~2 mya – present) is still often referred to
   3. The Neogene has been marked by many ice ages, the rise of humans, and mass extinctions; most of these mass extinctions may have been caused by the ice age climate, humans, or both; the **current mass extinction event** (we are in one now, **the sixth extinction**) is mostly caused by humans