1. Big Bang (13.7 Ga)
2. Hydrogen and helium atoms created
3. Our galaxy forms (10 Ga)
4. As material collects to form the protosun, rotation flattens nebula
5. Solar nebula begins to contract (4.7 Ma)
6. Continual bombardment and the decay of radiogenic elements produce magma ocean
7. Chemical differentiation produces Earth’s layered structure
8. Outgassing produces Earth’s primitive atmosphere and oceans
9. Formation of Earth-Moon system (4.5 Ma)
10. Debris orbits Earth and accretes
11. Mars-size object impacts young Earth (4.5 Ma)
12. Heavy elements synthesized by supernova explosions
Timeline for the Sun, Earth, and Moon

- Oldest meteorite ages
- Oldest Moon rocks
- Oldest Earth rocks

4.6 billion years ago: Earth aggregates
4.5 billion years ago: Giant Impact
4.4 billion years ago: Molten Earth cools
4.1 billion years ago: Earth differentiates

How did we get here?

- Life appears in the oldest rocks
- It took 2 billion years for the first cells with internal structure.
Diversification of Life

Any measure of the total number of species shows an increase through time.

Diversification of Life

This is not so much progress as diversification into new ecological niches.
Fossils

- Tangible remains or signs of ancient organisms
- Found in sedimentary rocks or sediments, especially marine sediments
- Thousands to billions of years old

Fossils

- Most fossils are hard parts of organism
  - Teeth, skeleton
  - Crinoid
Fossils

- Hard parts may be completely replaced by minerals

Fossils

- Fossilization of soft parts is rare
  - Requires oxygen-poor environment
  - Burial in fine-grained sediment
- Permineralization
  - Infilling of woody tissue by inorganic materials
  - Petrified wood
Chemical Fossils - Biomarkers

- Complex organic compounds found in oil, rocks, and sediments
- Linked with and distinctive of a particular source
  - For example, algae, bacteria, or vascular plants
- Useful for
  - Dating indicators in stratigraphy
  - Molecular paleontology

Fossils

- Fossil need not be skeletal
- Mold
  - 3-D negative imprint
Fossils

- Impressions
  - 2-D preservation of outlines and surface features
- Carbonization
  - Concentrated residue of remaining carbon

Fossils

- Trace fossils
  - Tracks/trackways
  - Trails
  - Burrows
- Provides behavioral information about extinct animals
Fossils

- Fossils provide biased view of biota
  - Not all organisms are preserved
    - Rare
    - Lack hard parts
  - Not all skeletal material is preserved
    - Scavengers
    - Transport and abrasion
    - Post-burial alteration of rock
  - Not all fossils are exposed at the surface
  - Some form fossil fuels

Taxonomic Groups

- Six kingdoms
  - Prokaryotes
    - Archaeobacteria
    - Eubacteria
  - Eukaryotes
    - Plantae
      - Producer
    - Fungi
      - Consumer
    - Animalia
      - Consumer
      - Protista
  - Woese
    - Bacteria
    - Archaea
    - Eukaryota
Phylogenetic Tree of Life

- Classification introduced by Woese et al. (1990, PNAS 87, 4576-4579)
  - Divides cellular life forms into archaea, bacteria, and eukaryote domains
    - Based on differences in 16S rRNA genes
    - Archaea, bacteria and eukaryotes each arose separately from an ancestor with poorly developed genetic machinery (progenote)

Extinction

- Caused by extreme impacts of limiting factors
  - Predation
  - Disease
  - Competition
- Pseudoextinction
  - Species evolutionary line of descent continues but members are given a new name
- High rates of extinction make useful index fossil
  - Ammonoids
Extinction

- Rates
  - Average rate has declined through time
- Mass extinctions
  - Many extinctions within a brief interval of time
  - Largest events peak at extinction of > 40% genera
  - Rapid increase follows

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Single-celled life: Prokaryotes

The first prokaryotes showed up on Earth more than 3.5 billion years ago

Prokaryotes = organisms without a cell nucleus, or indeed any other membrane-bound organelles; mostly unicellular organisms
Prokaryotes generally accepted as first living cells and most primitive organisms
Origins of the Atmosphere

- Some geologists believe that most of the air and water on Earth came from volatile-rich matter of the outer solar system that impacted Earth as it formed
  - Countless comets may have bombarded Earth bringing water and gas that gave us our oceans and atmosphere
- The very hot young Earth would also have lots of volcanic activity leading to outgassing of volatile gases from within the magma
  - Originally water and gases were locked up in minerals
  - There is evidence that the hot outgassing that occurred during the first billion years also led to the first atmosphere of the Earth

Interacting Earth Systems
Volcanoes contribute gases to the atmosphere and solids to the crust
Atmospheric Gases

- Did not inherit all our atmosphere from ancestral bodies
  - Water vapor and other gasses released from rocks by outgassing
- Outgassing by volcanic emission occurs today
  - Water vapor, H, HCl, CO, CO₂, N₂
- Early atmosphere higher H content
  - Possibly also ammonia and methane
- Gasses from modern volcanoes from recycled rocks
- Reasonably sure early atmosphere not from accretion
  - i.e., accumulation of light volatiles from nebula
- Relative scarcity of inert gasses in modern atmosphere
  - Ar, Ne, Krypton
  - Too heavy to escape from earths gravity
  - Less abundant than in atmosphere of stars
- Our atmosphere not residue of gasses from nebula

Rapid Degassing

- Rapid degassing must have produced much water vapor
- Condense to form seas when earth cooled sufficiently
- Know oceans formed early
  - Water laid sediments
    - Metamorphosed sediments date 3.8 by
    - Detrital grains 4.4 by
Archean Life

- Earth is best suited known planet
  - Conditions right by 4.2 B years
- Western Australia organic compounds
  - 3.5 B years
- Mars
  - Water flowed once
  - Life may have evolved separately

Archean Life

- South African cherts contain possible mold of prokaryotic cell
  - 3.4 B years
- Oldest unquestionable life form
  - 3.2 B years old
  - Australia
  - Intertwined filaments
Archean Life

- Stromatolites
  - 3.5 B years
  - Suggest photosynthesis
- Biomarkers for cyanobacteria
  - 2.7 B years

Stromatolites - the first abundant photosynthesizers

Glacier National Park, Montana (~1.3 by)
Still alive in a few isolated places

Shark Bay, Western Australia
Cyanobacteria (algae) trap particles to build mounds

Proterozoic Events

- Widespread glaciation
  - 2.3 Ga
- Stromatolites
  - Proliferate
  - Diverse shapes 1.2 B years ago
- Early Eukaryotes
**Archean Life**

- Stanley Miller and Harold Urey
  - Produced amino acids found in proteins
  - Modeled primitive atmosphere
  - Added lightning
    - Included oxygen
  - Amino acids found on meteorites

- RNA world
  - Nucleic acid
  - Can replicate itself
  - May have been catalyst for production of key proteins
  - Foundation for DNA world
Archean Life

- Mid-ocean ridges
  - High heat
  - Chemosynthetic organisms
- Hydrogen oxidation
  - \(2H_2 + O_2 \rightarrow 2H_2O + \text{energy}\)
- Sulfur reduction
  - \(S + H_2 \rightarrow H_2S + \text{energy}\)
- Methane production
  - \(CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O + \text{energy}\)

**How did it begin?**

**Current thinking:**

- Organic molecules polymerize with inorganic semi-permeable membranes.
- Driven by the chemical energy of submarine hot springs – chemosynthesis.
How did it begin?

Current thinking is probably wrong:
- High temperatures of mid-ocean ridge springs are too high for long-chain organic molecules to be stable.

How did it begin?

- Cold seeps in subduction zones, however, provide abundant organic compounds.
Archean Life

- Deep-sea vents offer wide range of temperatures
- Organic compounds readily dissolve in warm water
- Protection from ultraviolet radiation
- Protection from O₂
- Abundant phosphorous
- Contain metals
- Contain clays

Single-celled life: Prokaryotes

Bacteria are prokaryotes.

There are still more prokaryotes, by any measure: number, mass, volume, than all other forms of life combined.
Single-celled life: Eukaryotes

- Organisms with complex cells
- The first eukaryotes probably resulted from symbiotic relationships between two prokaryotes

Eukaryotes = organism with complex cell or cells, in which genetic material is organized into membrane-bound nucleus or nuclei; mostly multicellular.

Eukaryotes larger than prokaryotes, and have a variety of internal membranes and structures, called organelles and a cytoskeleton; DNA in chromosomes

Evolution of Eukaryotes

- Union of 2 prokaryotic cells
  - Mitochondrion
    - Allow cells to derive energy from their food by respiration
    - Evolved from 1 prokaryotic cell
  - Chloroplast
    - Site of photosynthesis
    - Protozoan consumed, retained cyanobacterial cell

Nuclear DNA and genetic machinery of eukaryotes closely related to archaea but membrane composition closely related to bacteria
Algae

- Multicellular protists
- Algal ribbons wound into loose coils
  - 2.1 B years ago

Algae

- Prokaryotic forms
  - Gunflint flora 2 B years ago
  - Lake Superior
- Acritarchs
  - Multicellular forms abundant after 2 B years
Proterozoic Life

- Trace fossils provide evidence for past life in Neoproterozoic
- Increasingly complex and varied

An Earth without oxygen: Banded Iron Formation

- Iron in solution precipitates in oxygen-rich water
- If atmosphere is oxygen rich, iron would not be available for BIF formation
An Earth without oxygen:
Banded Iron Formation

- All the oceans were rich in iron (from hot springs at mid-ocean ridges).
- Implies that there was little oxygen except where the iron was deposited.

Banded Iron Formations

- Stopped forming 1.9 B years ago
  - Chert contaminated by iron
    - Red or brown color
  - Alternate with iron-rich layers (magnetite)
    - Oxygen-poor ocean waters
    - Iron was not oxidized
Red Beds

- Never found in terranes older than 2 B years

Earth *with* oxygen: No Banded iron formation

- The banded iron formation stopped ~2 billion years ago
- Photosynthesis increased the oxygen levels
- But BIF came back again ~800 myBP
Snowball Earth

- Neoproterozoic glacial deposits

Banded iron and glaciation

Snowball earth: anoxic ocean

Deglaciation: ocean ventilation

The Snowball Earth.
As Earth warmed up ~590 myBP, multi-cellular animals evolved

Similar to living jellyfish
The Cambrian: Explosion of Life

All modern phyla present, plus a few weird ones.

- Large animals with skeletons
  - Trilobites
  - Arthropods with calcified segmented skeletons
Cambrian Explosion

- Bottom-dwelling forms create scratch marks
  - Similar to some Neoproterozoic tracks

Cambrian Explosion

- Other abundant Early Cambrian animal groups
  - Monoplacophoran mollusks
  - Inarticulate brachiopods
  - Echinoderms
The Cambrian: Explosion of Life

WHY?

- Sea level rise – new nearshore environments?
- Change in sea water chemistry?
- Or just inevitable consequence of multicelld animals?

Late Paleozoic Life in the Sea

- Crinoid meadows
  - Significant contribution to early Carboniferous (Mississippian) limestone
The Paleozoic: Life Leaves the Oceans

- Pangea was forming
- Many new life forms emerged, others died out
- Climate/atmosphere controls evolution

Late Paleozoic Life on Land

- Extensive swamps developed
- Coal swamps dominated by lycopsids
  - *Lepidodendron*
    - Up to 30 m tall
  - *Sigillaria*
Late Paleozoic Life on Land

- Seed ferns
  - Abundant
  - Small bushy plants
  - Large and treelike
    - *Glossopteris*

Late Paleozoic Life on Land

- Cordaites
  - Upland plants
- Gymnosperms
  - Naked seed plants
  - Formed woodlands
  - Conifers
    - Cone bearing plants
Late Paleozoic Life on Land

- Winged insects
  - Dragonflies
  - Mayflies

Late Paleozoic Life on Land

- Amphibians
- Reptiles
Late Phanerozoic Life

- Rates of Origination and Extinction

![Graph showing rates of origination and extinction over time.](image)

Late Permian Anoxia

- Japan
- Uplifted rocks
- Gray chert replaced oxidized hematite
The end of the Paleozoic: Permian mass extinction

- Greatest single catastrophe in the history of life on Earth
- Low sea levels, lots of volcanoes
- Major turning point in evolution of life

The Mesozoic: Rise of the dinosaurs

- Climate began to warm up
- Sea level rose
- Flowering plants evolved
Life of the Cretaceous

- **Plankton**
  - Diatoms radiated
  - Foraminifera diversified
  - Calcareous nannoplankton radiated
  - Ammonoids and belemnoids persisted

Life of the Cretaceous

- **Teleost fish**
  - Dominant modern group
  - Symmetric tail
  - Specialized fins
  - Short jaws
Life of the Cretaceous

- Marine reptiles still important
  - Mosasaurs
  - Up to 15 m
  - *Hesperornis*
  - Marine turtles

Life of the Cretaceous

- Surface-dwelling bivalve mollusks
  - Rudists
  - Formed large tropical reefs
    - Up to 1 m height
- Predators led to reduction in brachiopods and stalked crinoids
Life of the Cretaceous

- Flowering Plants
  - Angiosperms appear
    - Flowering plants
    - Hardwood trees
  - Increase in complexity and form
  - Gymnosperms still dominant

Life of the Cretaceous

- Vertebrate faunas
  - Community analogous to modern African savannah
  - Duck-billed dinosaurs
Life of the Cretaceous

- *Tyrannosaurus rex*
- Flying vertebrates
  - Reptiles
  - Birds

Life of the Cretaceous

- Mammal evolution
  - Pointed teeth
  - Endothermic
  - Large brains
  - Suckled their young
  - Rear feet for grasping
    - Tree climbing
One day, 65 million years ago

- A huge meteorite (10 km) hit the Earth
- 180 km diameter crater on Yucatan Peninsula (Chicxulub, Mexico)

One day, 65 million years ago

- Dust thrown up into atmosphere blocked sunlight
- Firestorms raged
Cretaceous Mass Extinction

- Dinosaurs
- Ammonoids
- Mosasaurs and other marine reptiles
- Reductions in gymnosperms and angiosperms
- 90% calcareous nannoplant and foraminifera went extinct
- Meteor impact
  - Iridium anomaly
  - Extinction patterns

World-wide extinction

- Dinosaurs may have already been disappearing
- Cool climate killed many other species
The Impact

- Chicxulub Crater
  - Gravity anomalies

Tertiary

- Rise of the Mammals
- Evolution of humans
Paleogene Life

- Paleogene
  - Paleocene
  - Eocene
  - Oligocene

Recovery from Cretaceous extinctions

- Modern life forms
- New animals
  - Whales
  - Sharks
Paleogene Life

- Sandy coasts offer new niches
  - Sand dollars evolved from sea biscuits
- Flowering plants expanded
  - Grasses originated

Mammals diversified
- Most modern orders present by Early Eocene
Paleogene Life

- Bats present by early Eocene

Paleogene Life

- Primates evolved in Paleocene
  - Climbing by Early Eocene
Paleogene Life

- Mammalian carnivores evolved by mid-Paleogene

Paleogene Life

- Earliest horses by end of Paleocene
  - Size of small dogs
Paleogene Life

- Carnivores evolved in Eocene
  - Saber tooth tiger
  - Bearlike dogs
  - Wolflike animals

Paleogene Life

- Primates modernized in Oligocene
  - Monkeys
  - Apelike primates
  - *Aegytopithecus*
Neogene Life

- Marine life
  - Miocene ancestral whales
    - Sperm whale
    - Baleen whales
    - Dolphin

- Terrestrial Life
  - Grasses
  - Herbs and weeds
  - Requires arid climate
    - Cooler climate linked to Antarctic glaciation
Neogene Life

- Mammals
  - Groups of large mammals
  - Many adapted to open terrain
    - Even-toed ungulates
      - Bovidae
      - Elephants
    - Carnivorous mammals
  - New world primates

Human Evolution

- Miocene apes radiated in Africa and Eurasia
  - Most were arboreal
- Earliest apes
  - 6-7 M year old fossil skull
    - *Sahelanthropus*
    - Resembles both apes and humans
Human Evolution

- Australopithecines
  - Intermediate between humans and apes
  - Only slightly larger brain than chimp
  - Broad pelvis