The Hadean Earth

4.5 - 3.9 Gyr
Impacts melt the surface.
Volatile escape to space

Source of atmosphere, oceans: outgassing and impacts
Early atmosphere: CO₂, H₂O, N₂, H₂S, SO₂, H₂

Oceans exist by 4.4 Gyr

Impacts:
• 4.5 Gyr
• Late Heavy Bombardment at 3.9 Gyr
Lunar crater counts give this dating
The Hadean Earth

Details:

• Large impacts (200+ km) occurred ~ every 100 million years.
  • These will melt the surface and strip the atmosphere.
• Atmospheres (H₂O + CO₂) regenerated
• As surface cools, rain replenished oceans

Life appeared with 100 Myr of end of great bombardment

Did life reform many times?
Crater Counts
The Archean Era
3.9 Gya - 2.5 Gya

- Oceans had formed and stabilized
- Atmosphere had stabilized
First Life

What was the first life on Earth?

• The first living things must have been simple
• All existing life is advanced.
• The fossil record is incomplete.

Where do we look?
Rocks

The fossil evidence is preserved in rocks.

- **Igneous** rock: solidified lava
- **Sedimentary** rock: sediment laid down and compressed into rock.
- **Metamorphic** rock: sedimentary rock that has been modified by heat and/or pressure (but not melted).

Fossils are not found in igneous rock.
The Oldest Rocks (<2.5Gya)
The Oldest Fossil Evidence

• >3.85 Gya: isotopic evidence. 
  $C^{12}/C^{13} > 89$ suggests biochemical processes. 
  Other isotopic evidence agrees (Fe, N, S).
• 3.5 Gya: fossil stromatolites
• 3.5 Gya: possible fossil micro-organisms
• 3.2-3.5 Gya: fossil cells

Fossil Cyanobacteria
~1 Gyr
Bitter Springs Chert, Australia
http://www.ucmp.berkeley.edu/precambrian/bittersprings.html
Stromatolites

Layered mats of bacteria and other micro-organisms

Now ➔
Shark’s Bay,
Australia

←Then
Implications
Life formed very early on - probably within 100 Myr of the Earth’s surface becoming inhabitable.
Last Universal Common Ancestor (LUCA)

- Used **DNA** with 4 bases to encode information
- Had a cell wall
- Metabolized something, perhaps $\text{H}_2\text{S}$
- Used **19 left-handed amino acids**

- Nature inferred from evolutionary relationships
- Results in the Tree of Life
- LUCA may be a *Thermophile*

- Possibly more complex than some existing life
The Tree of Life
The Archaea

Archaea often inhabit extreme environments. Archaea superficially resemble bacteria, but are genetically distinct. Archaea are anaerobic (don't use oxygen).

- Acidophiles - acidic environs (pH~0)
- Alkalophiles - inhabit alkaline lakes (pH~10)
- Barophiles - high pressure
- Thermophiles - hot environments (>45°C)
- Lithophiles - live in/metabolize igneous rock
- Methanogens - metabolize hydrogen
- Halophiles - live in salty environs
- Psychrophiles - adapted to cold (<0°C)

Extremophiles all!
Why?

• Originated under extreme conditions?
• Crowded out by better adapted latecomers?
Life on the Fringe

Life on Earth
• Does not need Oxygen or CO$_2$
• Does not need to metabolize Carbon
• Does not need Sunlight
• Can thrive at 110°C
• Can survive in ice
• Can lie dormant for millions of years
• Needs H$_2$O
Origin of Life

Raw ingredients (CHON) are available in space.

Complex organic molecules can be produced in a reducing atmosphere, given energy (UV photons or lightning).

Life probably began in water, not on land.
Black Smokers

Mid-ocean hydrothermal vents (geysers)
• Temperature >100C (to 400C)
• Spew iron and sulfides (metabolized by *thermophiles*)
Origin in the Ocean

• Water protects against UV radiation
• Water is needed for biochemistry
• Hydrothermal vents provide nutrients
• Protected from surface impacts
Earliest Life

• May have used RNA (a self-catalyzing molecule)

• First cell wall may have been a *coacervate*
  • *lipids* have hydrophobic and hydrophilic ends.
  • surface tension will draw it into a sphere.
  • *coacervates* exhibit osmotic pressure

• DNA replaces RNA.
  • DNA is more robust, but requires *ribozymes* (enzyme catalysts) to function
Metabolism

Anaerobic photosynthesis:
\[ 12\text{H}_2\text{S} + 6\text{CO}_2 \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{H}_2\text{O} + 12\text{S} \]
(what some anaerobes and archaea [chemoautotrophs/photohertotrophs] do)

Aerobic photosynthesis:
\[ 6\text{H}_2\text{O} + 6\text{CO}_2 \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \]
(what plants [photoautotrophs] do)

Respiration:
\[ \text{C} + \text{O}_2 \rightarrow \text{CO}_2 \]
(what animals [chemoheterotrophs] do)

(\text{C}_6\text{H}_{12}\text{O}_6 \text{ is glucose, a common sugar})
Prokaryotes

Archaea and Bacteria

- no cell nucleus
- single strand of DNA
- no cell structure
- asexual/sexual reproduction (gene swapping by transduction)
- earliest record: **stromatolites** and fossil cells at 3.5 Gya
Eukaryotes

• DNA segregated in a cell nucleus
• double strands of DNA
• organelles - symbiotes of bacteria
• sexual reproduction
• earliest record: fossil protists at 2.4 Gya


Eukaryotes likely evolved when a large prokaryote with a cytoskeleton, perhaps similar to *Magnetobacter*, engulfed but failed to digest, a smaller prokaryote.
Oxygen

Highly reactive
Deleterious to organic molecules

Oxidation offers very efficient metabolism
$3O_2 \rightarrow 2O_3$ (ozone) in presence of UV

First indications of $O_2$ in atmosphere: 2.35 Gya

Enough $O_2$ (10%) to support fire: 200 Mya