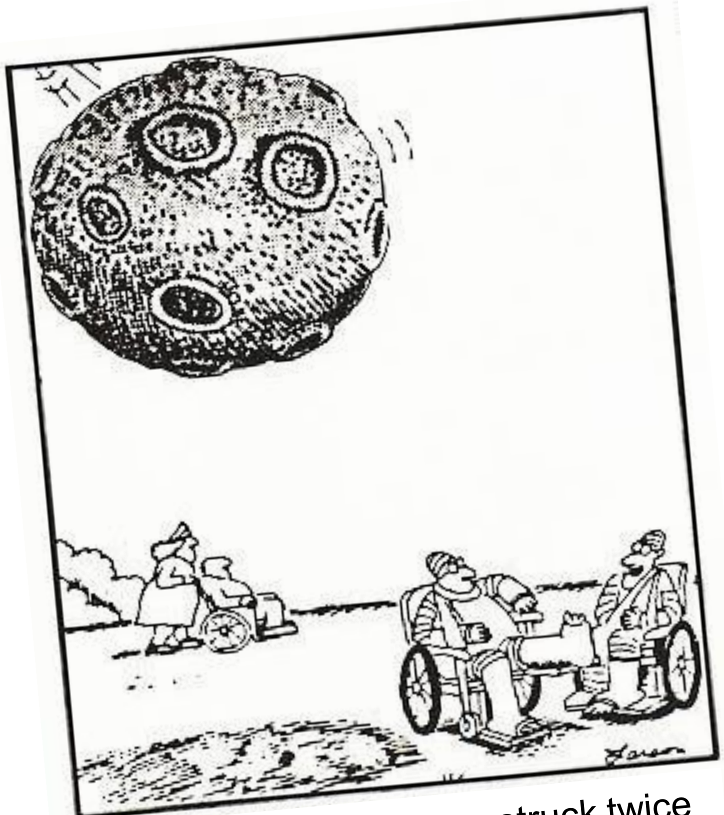
Earth: The Early Years



You're kidding! … I was struck twice by lightning too.

We discuss ...

- What happened to the Earth during the first few billion years?
- How did the core and mantle form?
- What was is the origin of the atmosphere and ocean (water)?
- What is the relationship to (early) life?

Age of Earth

James Ussher (17th C)
biblical account: 6,000 years (10/23/4004 BC, at 9am GMT)

Herman von Helmholtz and William Thompson (Lord Kelvin)
cooling sun: 20-40 m.y. (million years!)

Archean of Australia

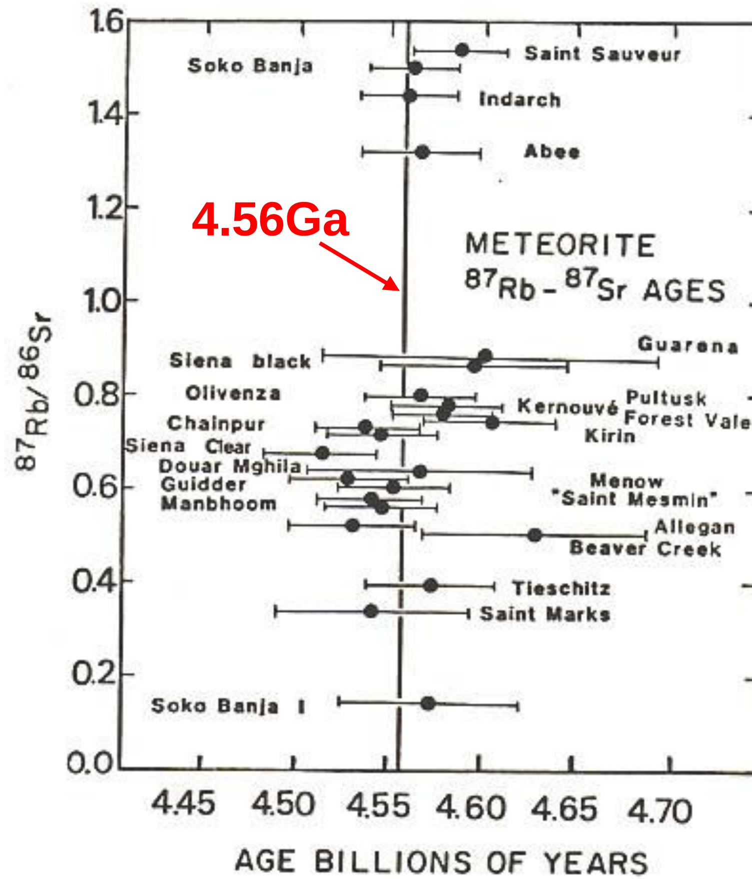
Charles Darwin
evolution >300 m.y.

Lord Kelvin (1880's)
cooling Earth: 50-100 m.y.

Lord Rutherford; Boltwood and Strutt (early 1900's)
radioisotopes: 2 b.y. (billion years!)
Arthur Holmes
isotopic dating: ~3.3 b.y.

Age of meteorites: 4.56 (+/- 0.1) b.y.
Oldest fossil (Australia): 3.5 b.y
Oldest rock (gneiss; Slave, N. Canada): 3.96 b.y
Oldest mineral (zircon; NW Australia): 4.3 b.y

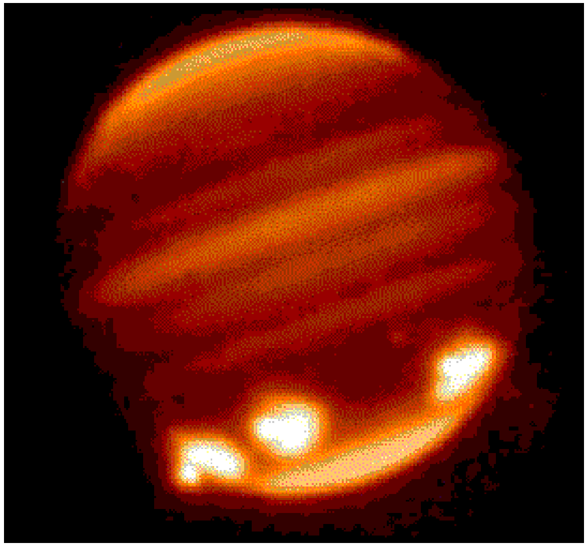
Age of meteorites



- Most (stony) meteorites are ~4.56 billion years old (Ga), which dates beginning of our solar system.
- This contrasts with the age of ~14 Ga for our Universe, meaning that we occupy a recent solar system.
- The atoms on and in Earth (incl. life) are mostly older than birth of our solar system.

Heat Sources of Early Earth

Accretion/Impacts:
Impacting bodies bombard Earth and convert energy of motion (kinetic energy) into heat.
Also, surface magma ocean and sinking Fe droplets



Comet Schoemaker-Levy 9 on Jupiter (Hubble infrared image, July 1994)

Self-compression
As Earth gets bigger, more gravity forces mass to contract, producing heat

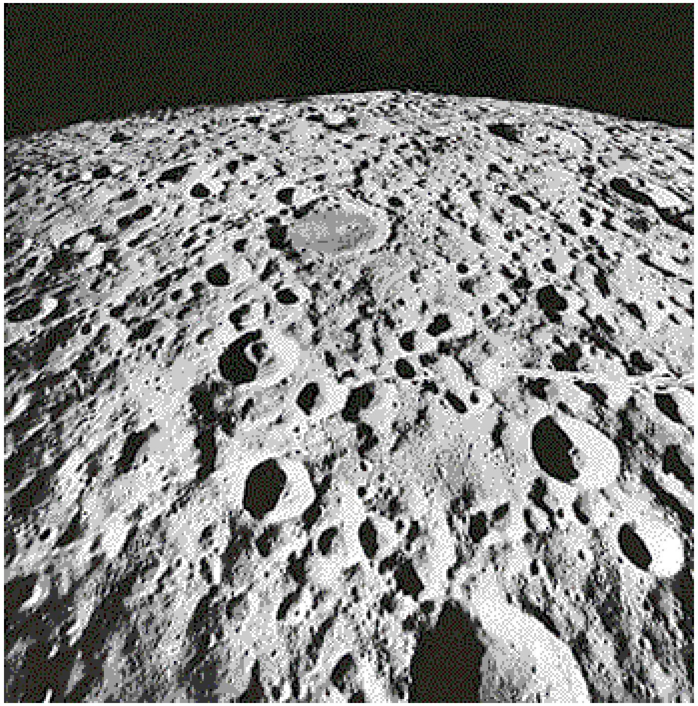
Short-lived isotopes
The surrounding material absorbs energy released in radioactivity, heating up.

Differentiation
Conversion of gravitational potential energy to heat during core formation

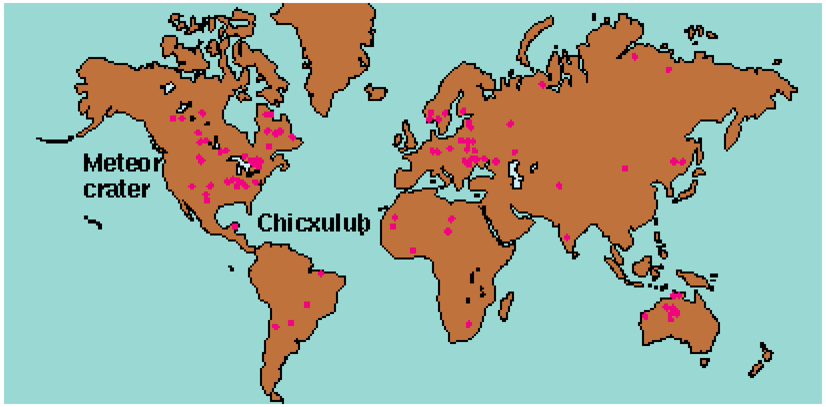
Early Earth >7000K (fully molten planet)
Today's Earth ~5000K (partially molten core)

Note:
$0^oC = 32^oF = 273K$
$0K = -460^oF = -273^oC$

Impacts (craters) and Earth



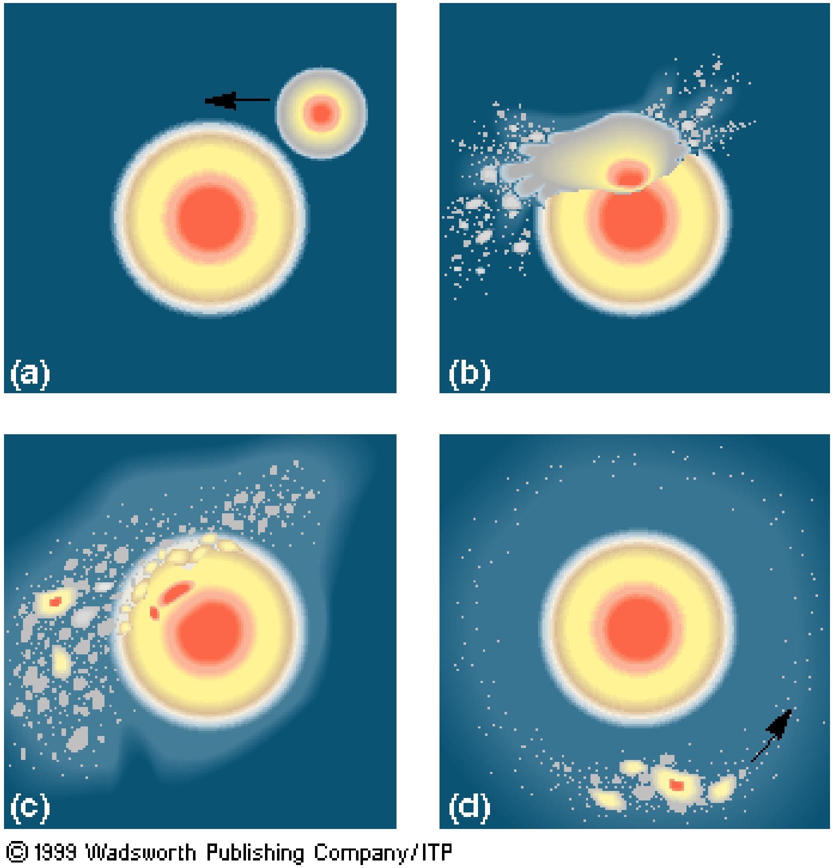
Moon



Meteor crater, AZ
1.2 km, 49,000y

Impacts and the Moon

Moon:
radius ~3500 km
distance ~385,000 km
synchronous ccw rotation
(facing same side)



Collision around 4.5Ga
(around 50 million year after formation)

Heat Sources of Early Earth

Accretion/Impacts:
Impacting bodies bombard the solid Earth (formed by condensation) and convert their energy of motion (kinetic energy) into heat.
Also, surface magma ocean and sinking Fe droplets

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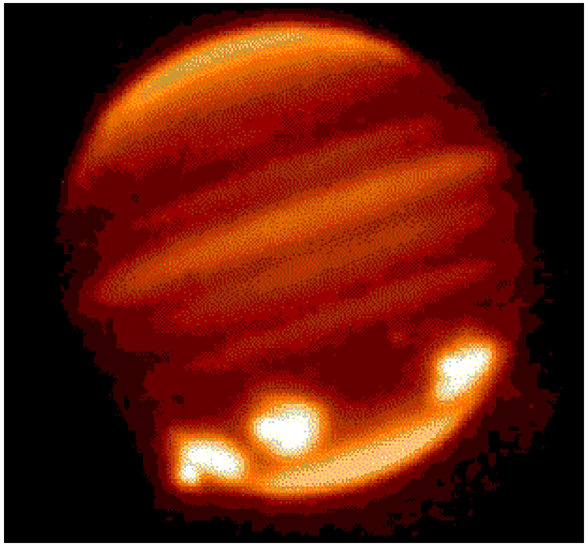

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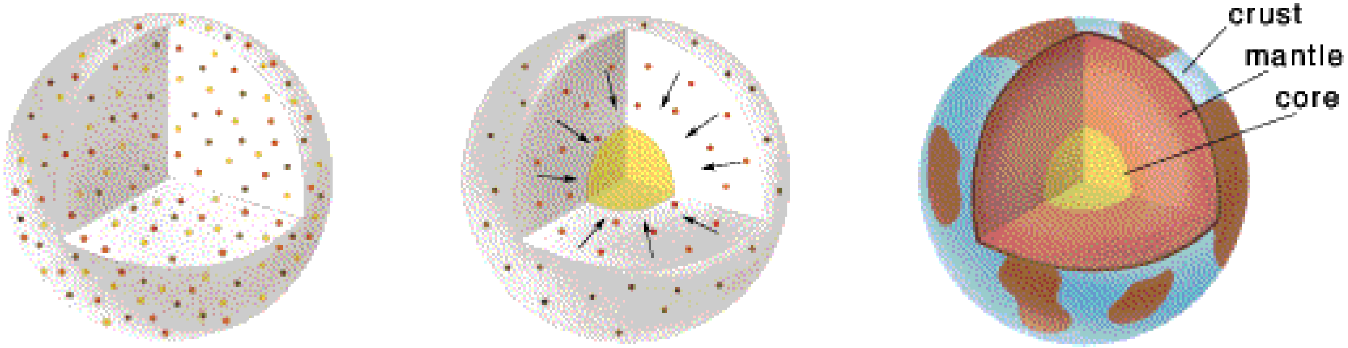
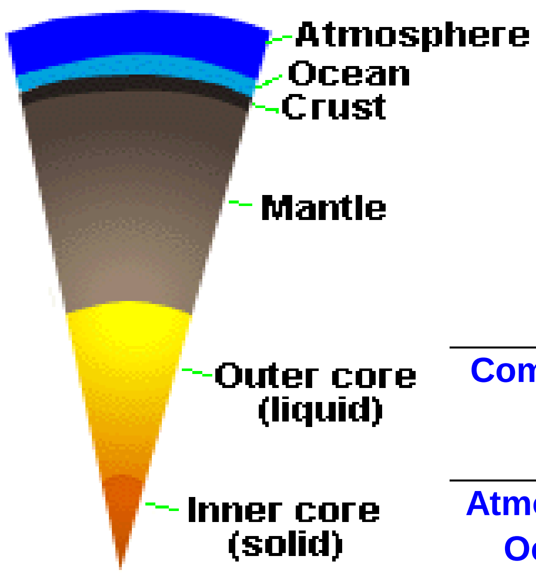
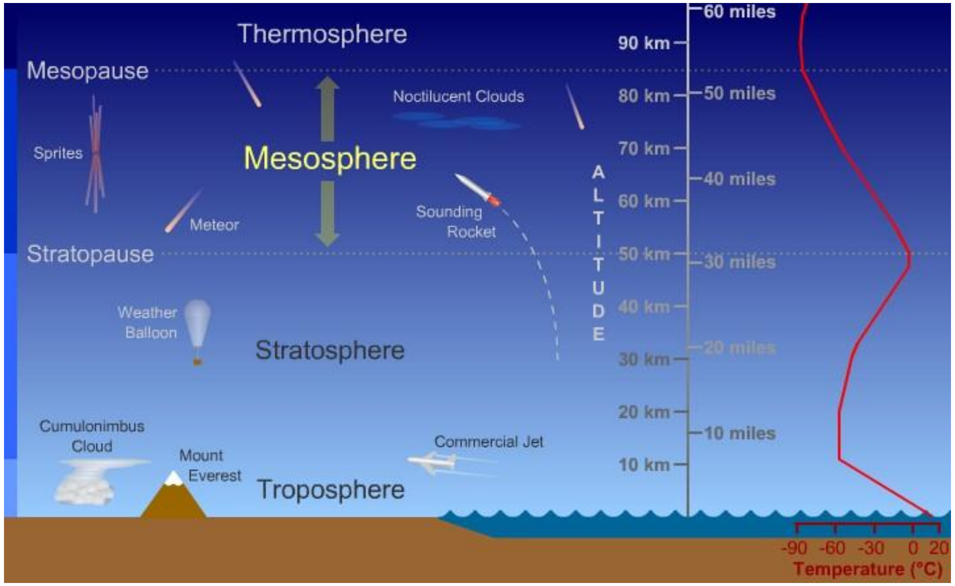
Early Earth: Differentiation



- Early Earth has uniform composition and density.
- Today's layered structure requires "liquid stage" of early planet.
- Heating of early Earth reached melting point of iron which, being dense, settled to Earth's center (core).
- At surface of hot early Earth (7000K?) a (100+ km deep) magma ocean.
- Mantle convection ("overturn") and surface cooling eventually produced proto-crust. Continued mantle convection and melting differentiated today's continental crust (light minerals) from mantle (heavier minerals), creating today's layered Earth.

Layered Earth



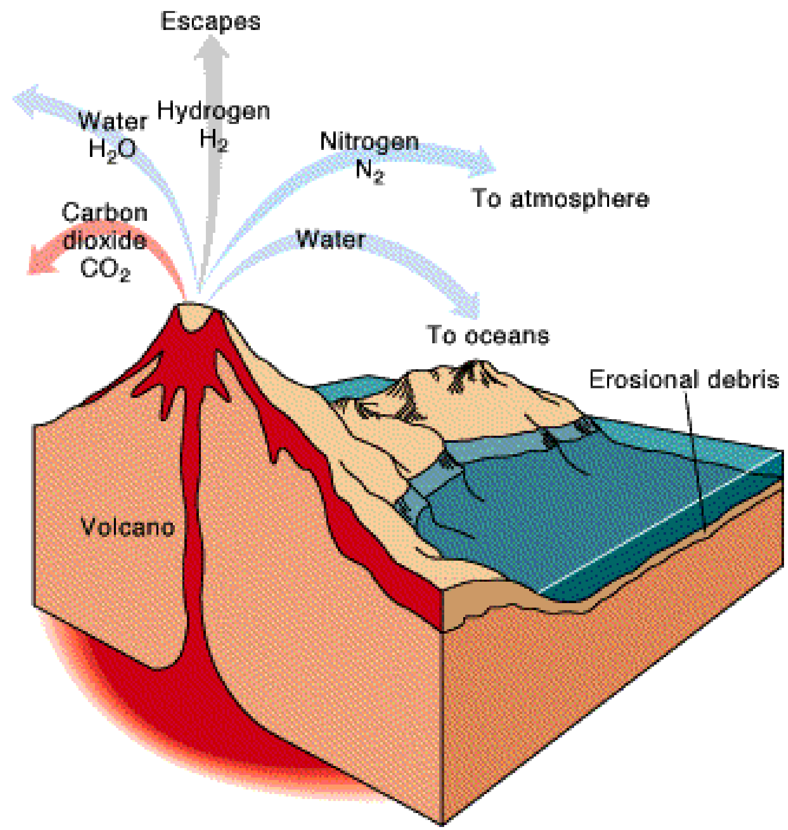


Component	Average thickness (km)	Average density (10^3 kg/m^3)	Fraction of total (%)	Principal constituents
Atmosphere	-	-	0.00009	N_2, O_2
Oceans	4	1.03	0.024	H_2O
Crust	45	2.8	0.5	Silicates and other oxides
Mantle	2900	4.5	67	Mg silicates
Core	3400	11.0	30	Fe, S (liquid)
			2	Fe, Ni (solid)

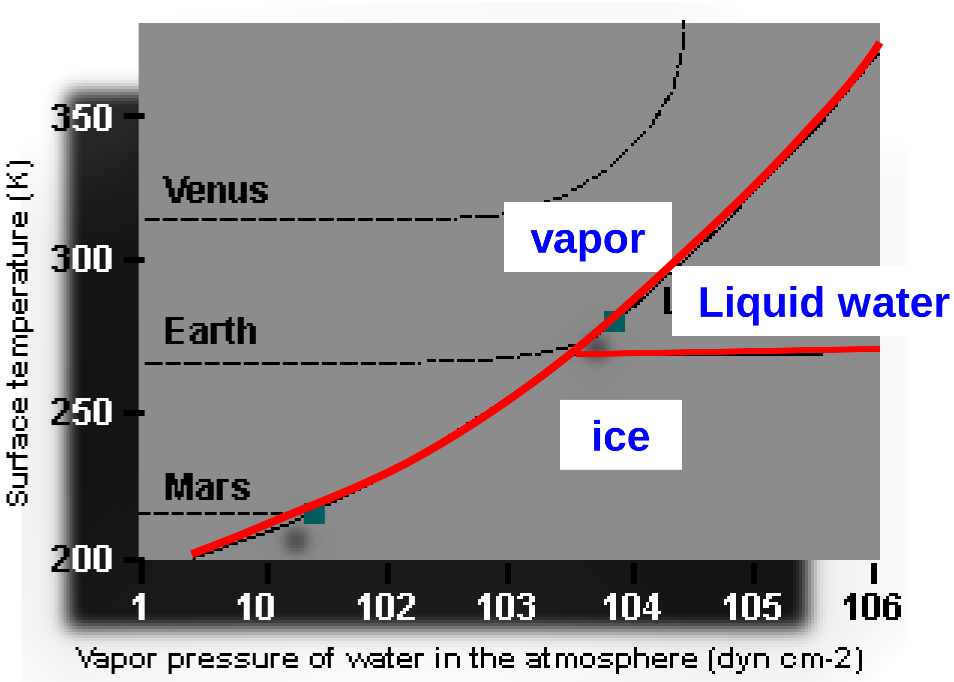
… what about Atmosphere and Ocean?

Early Earth's Atmosphere: Volcanic Outgassing

- Volcanic outgassing during convection forms early atmosphere, composed of several gases, especially H_2O vapor and N_2, and CO_2.
- Chemical reactions in atmosphere also yielded methane (CH_4) and ammonia (NH_4). Building blocks for amino acids (part of life's proteins).
- H_2O saturation, the dominant phase, leads to rain and early oceans when temperature dropped (see next).



Early Greenhouse Effect – Water Vapor



- Early “greenhouse” warming on inner planets as water vapor accumulates in atmosphere.
- Increase halted by condensation into ice for Mars.
- Increase halted by condensation into water (ocean) for Earth.
- On Venus, water saturation never achieved, producing *runaway greenhouse effect* (positive feedback).

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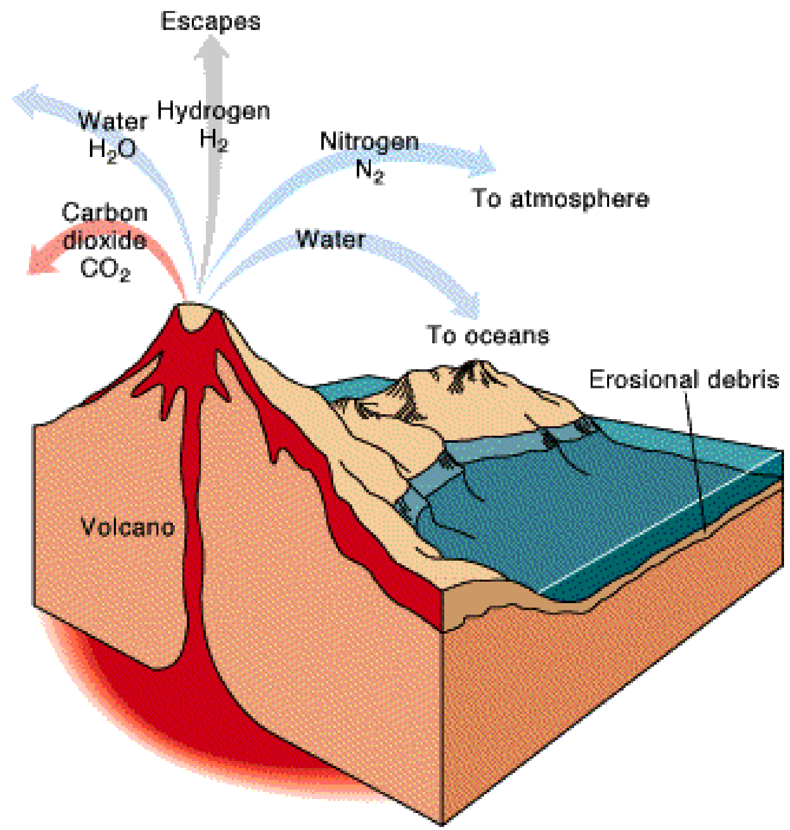
- H_2O, dominant species, leading to rain and early oceans when temperature dropped.
- Atmospheric CO_2 becomes dissolved in water and removed by limestone ($CaCO_3$). Further lowers atmospheric temperature, producing more rain.



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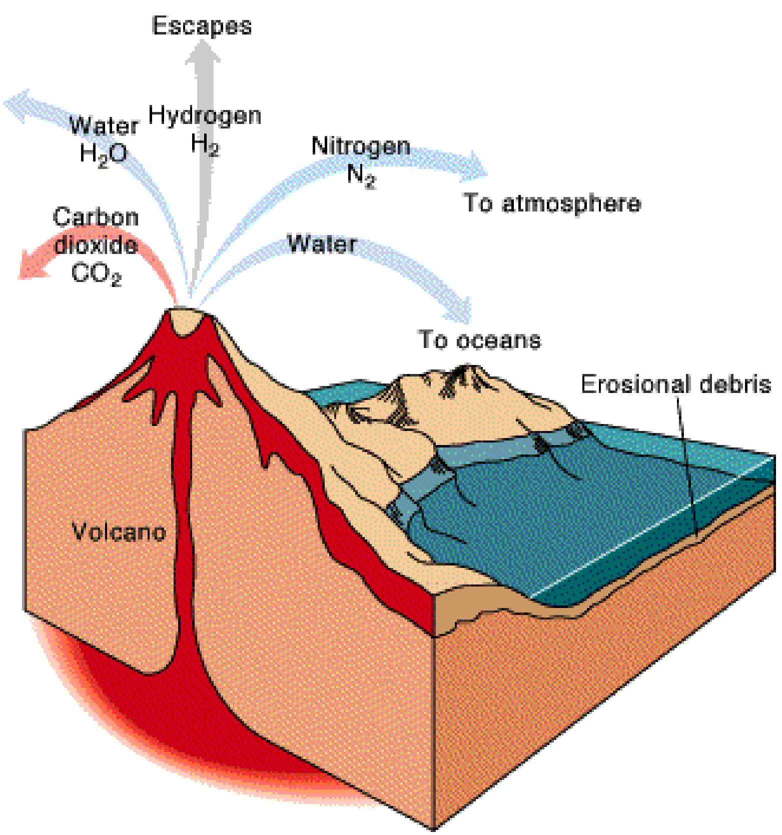
- LIFE becomes player. Role of oxygen !



Stages of Atmospheric Formation

1. Beginning

   In early years atmosphere was composed of H and He.

2. Chemical/ pre-biological era

   Atmosphere formed from volcanic outgassing, dominated by water vapor, CO_2, SO_2 and others.

3. Microbial era

   Initial O_2 from photolysis formed ozone layer, early microbes emitted O_2 as waste product.

4. Biological era

   Simultaneous decrease in atmospheric CO_2 (calcite) and the increase in O_2 (waste) due to life processes.

Redox Reactions, Early Earth and Life

Redox systems: Main energy capture and energy release mechanisms of life

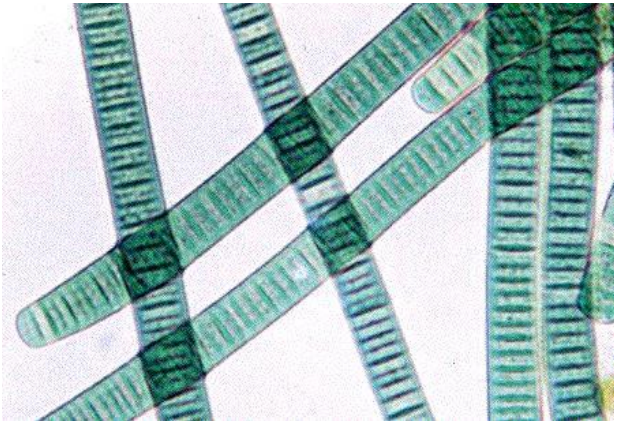
Oxidation is removal of electrons - releases energy (e.g. fire, rusting); $Fe^{2+} \rightarrow Fe^{3+}$
Reduction is the addition of electrons - takes energy; $Fe^{3+} \rightarrow Fe^{2+}$

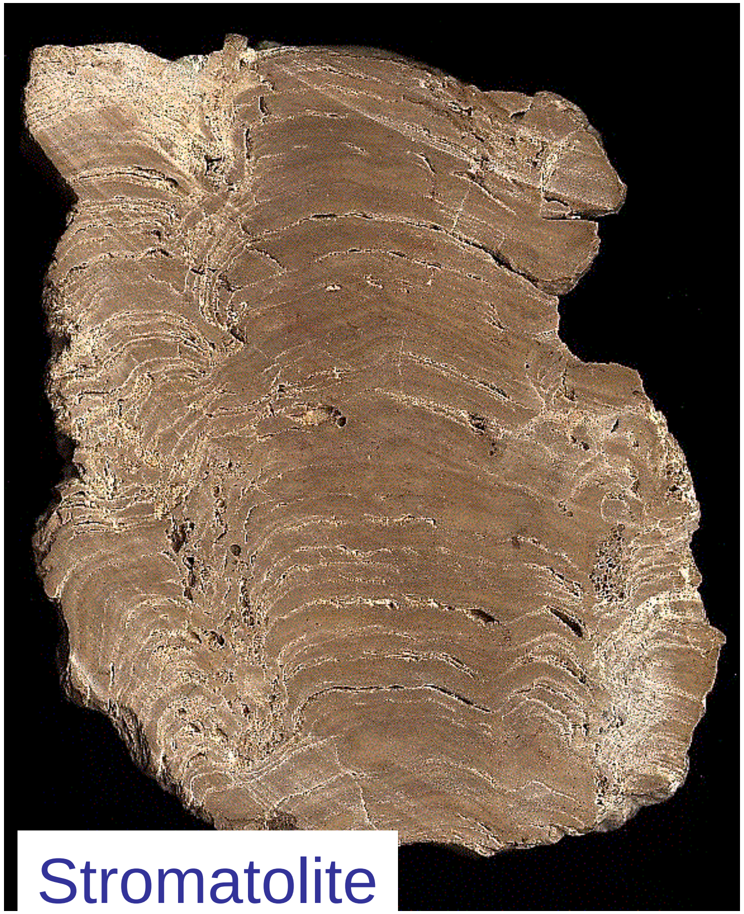
Photosynthesis is a Redox reaction (reduction):
$CO_2 + H_2O + e^- \rightarrow CH_2O + O_2$; CO_2 is the electron acceptor
Respiration is a Redox reaction (oxidation):
$CH_2O + O_2 \rightarrow CO_2 + H_2O + e^-$; CH_2O (formaldehyde) is oxidized by oxygen (cf. $C_6H_{12}O_6$)

Presence of ferrous ("reduced"; Fe^{2+}) Fe requires O-free atmosphere:
Banded Iron Formations contain magnetite, Fe_3O_4 (before ~2.5Ga)

Oxidization of ferrous (soluble) Fe makes ferric (insoluble) iron:
Redbeds contain hematite (Fe_2O_3) indicate free O in atmosphere after ~2.5Ga

Biotic O_2: Cyanobacteria



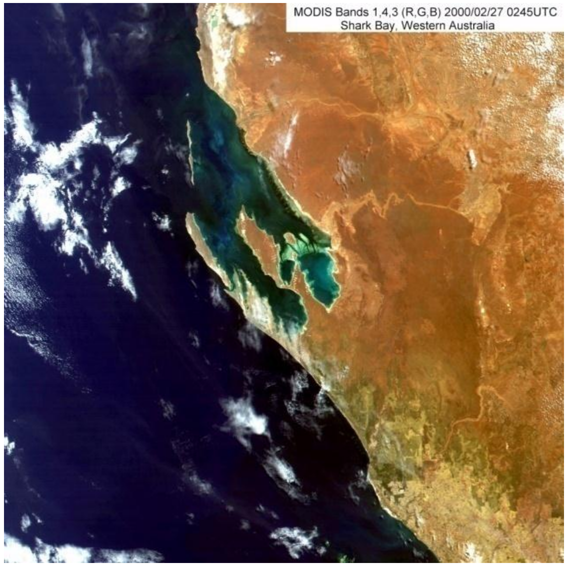


- Early photosynthetic aquatic organisms called "blue-green algae". *Not* eukaryotes (cells with nucleus) like today's algae, but relatives of bacteria (**prokaryotes**; cells without nucleus) and chloroplast in plant/algae cells

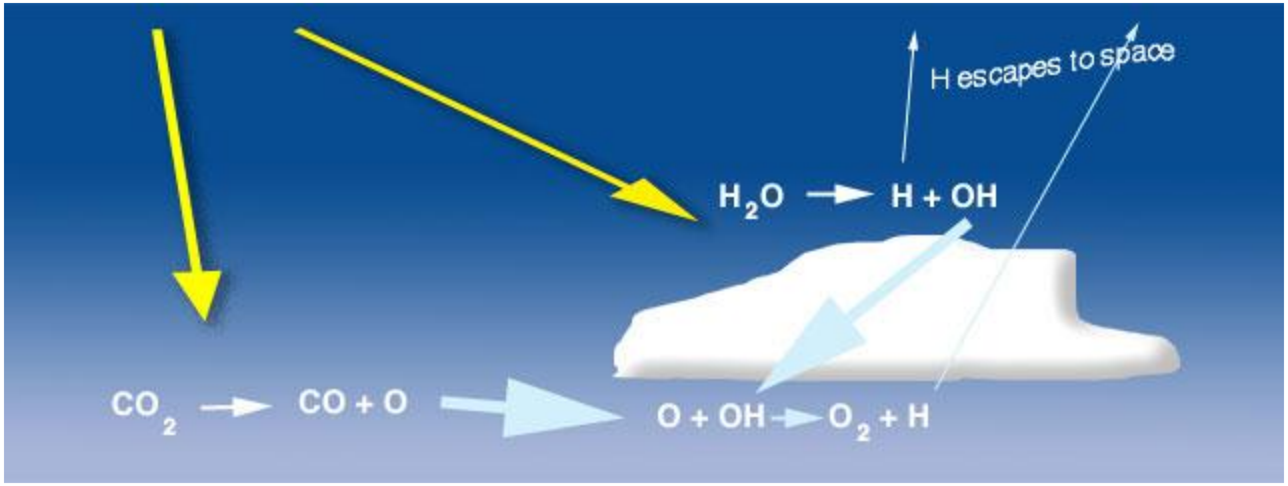
- O produced by blue-green algae (in BIFs (reduced, dissolved Fe^{2+}); starting around 3.8Ga (no free O!)

- Eventually enough free O in atmosphere to form continental redbeds (oxidized Fe^{3+}); after 2.5Ga

Stromatolites in Shark Bay, W. Australia
(World Heritage Site)



(Stratospheric) Ozone Layer



Photolysis or photodissociation (UV) in early years

$H_2O \rightarrow H + OH$ and

$CO_2 \rightarrow CO + O$

$O + OH \rightarrow O_2 + H$

But, O_2 reacts to form CO_2 and H_2O, so, O-starved early atmosphere

With more abundant oxygen (from marine life):

$O_2 \rightarrow O + O$

$O_2 + O \rightarrow O_3$ (ozone)

Stratospheric ozone shields solar UV radiation, allowing life on land: the "good" ozone