AST 309L Part IV
Evolution of Earth and Complex Life

*The major question underlying every topic in this section of course: How likely is it that __**complex**__ life is common in our Galaxy?*

*Goal: Piece together the co-evolution of Earth and complex life, ask which significant events ("innovations") might be **convergent**, which **contingent**, on previous low-probability events.*

Topics we will cover:

A. Geological processes, radiometric ages, evolutionary history of Earth, paleoclimatology **Textbook, Ch. 4.1-4.5 (not 4.6)**

Major topics:
Moon-forming, ocean-boiling, impact degassing, bombardment.
Origin of atmosphere, later oxygenation of atmosphere, Snowball Earth episodes and less severe environmental variations, late bolide impacts and mass extinctions, …

B. History of life on Earth: Major evolutionary transitions; mass extinctions Textbook, Ch. 6.3, 6.4

Major topics:
Horizontal (lateral) transfer, development of eukaryotes, endosymbiosis, meiosis, Cambrian explosion, mass extinctions, land colonization, … cognition, "intelligence"…

Your job: Un-separate these two sets of topics and understand:

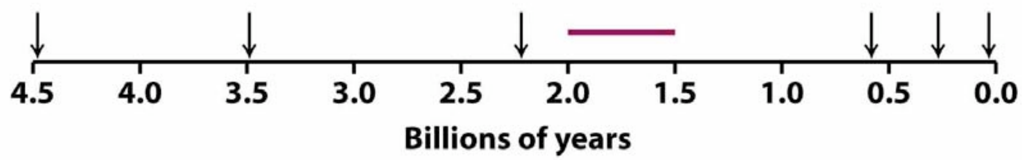
1. The coupled chronology of Earth and life.
   "Timelines" (numbers not so important as what they imply)

2. How the development of many features in biological world may have been determined by events in the environment; and

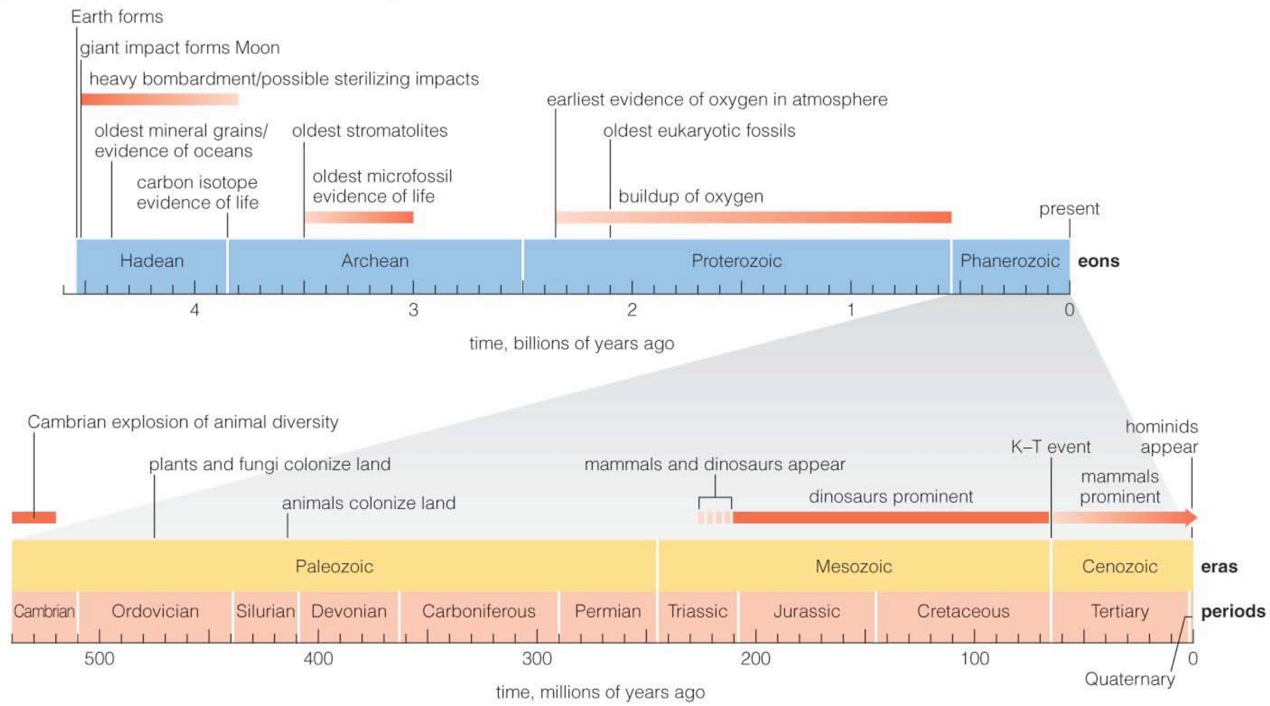
3. Whether there are some features that might be more intrinsic to living organisms under any conditions. Might complex life be "convergent," so common on extrasolar planets?

We want to fill this timeline with events, both for Earth and life on Earth

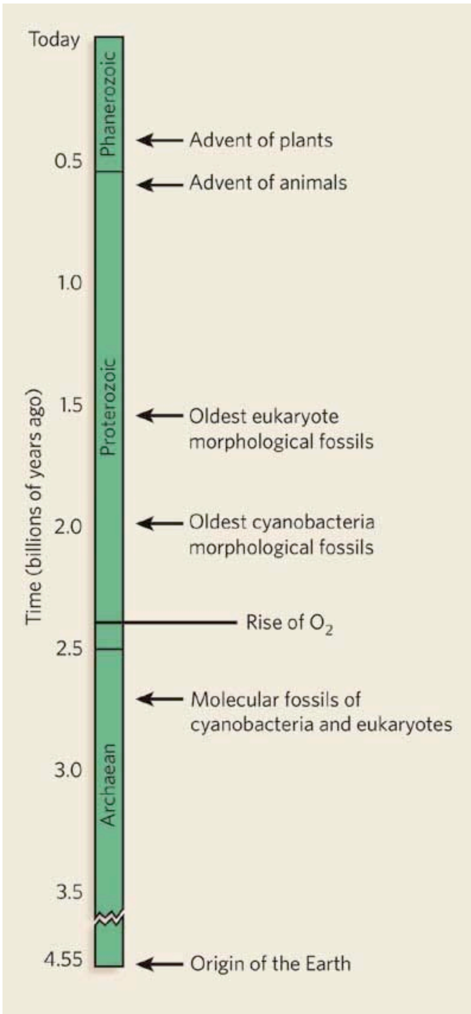
Needed: Ages of rocks, minerals in rocks, fossils, molecular signatures



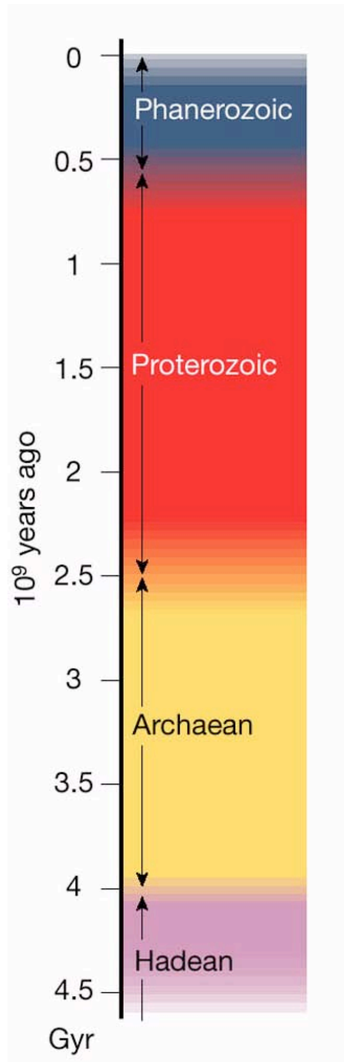
We are trying to fill in at this level of detail (This is illustration from your textbook)



New timeline for earliest life and oxygenation of the atmosphere (Oct 2008 Nature)



Geological eons



Four eons

Hadean: oceans, atmosphere; possible origin of life, but punctuated by sterilizing impacts

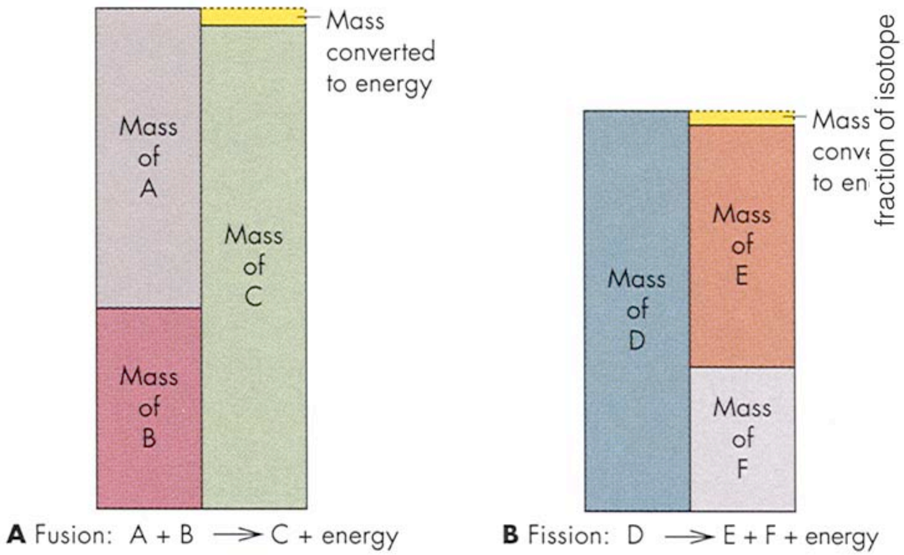
Archean: probable origin of life; age of prokaryotes (bacteria and archaea). Probably no UV shield (since no ozone because very little oxygen)

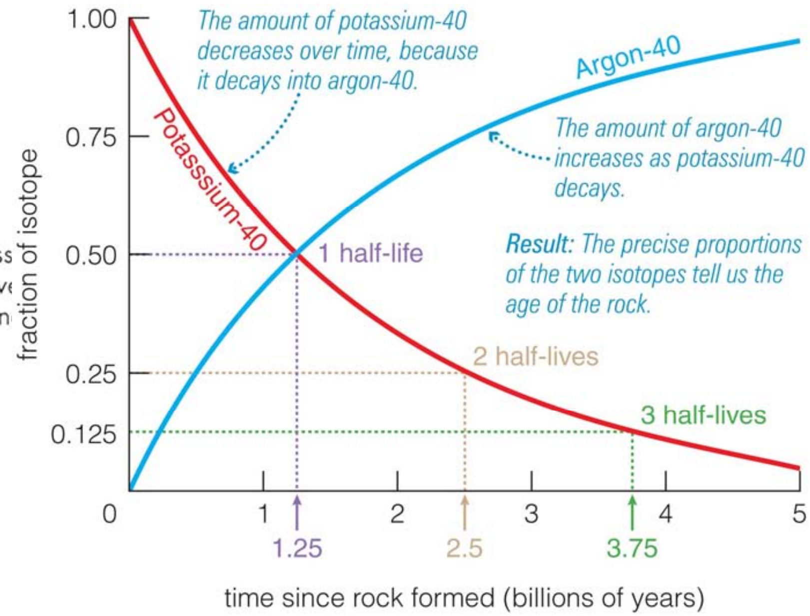
Proterozoic: oxygenation, UV shield; Snowball Earth; rise of the eukaryotes, meiosis, beginning of "Cambrian explosion."

Phanerozoic: "Cambrian explosion" then development of all modern body plans, and many more, most of which must have gone extinct (because we don't see them anywhere today, or even in the fossil record). Then colonization of land, … We discuss "modern times" separately.

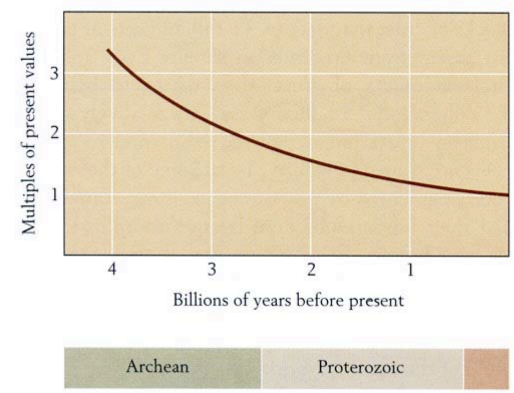
Radiometric Ages

Fusion vs. Fission





Radioactive decay important not only for estimating rock ages!
rate of production of heat by radioactive decay in Earth's Interior. [recall explanation of why small planets cool fastest…]

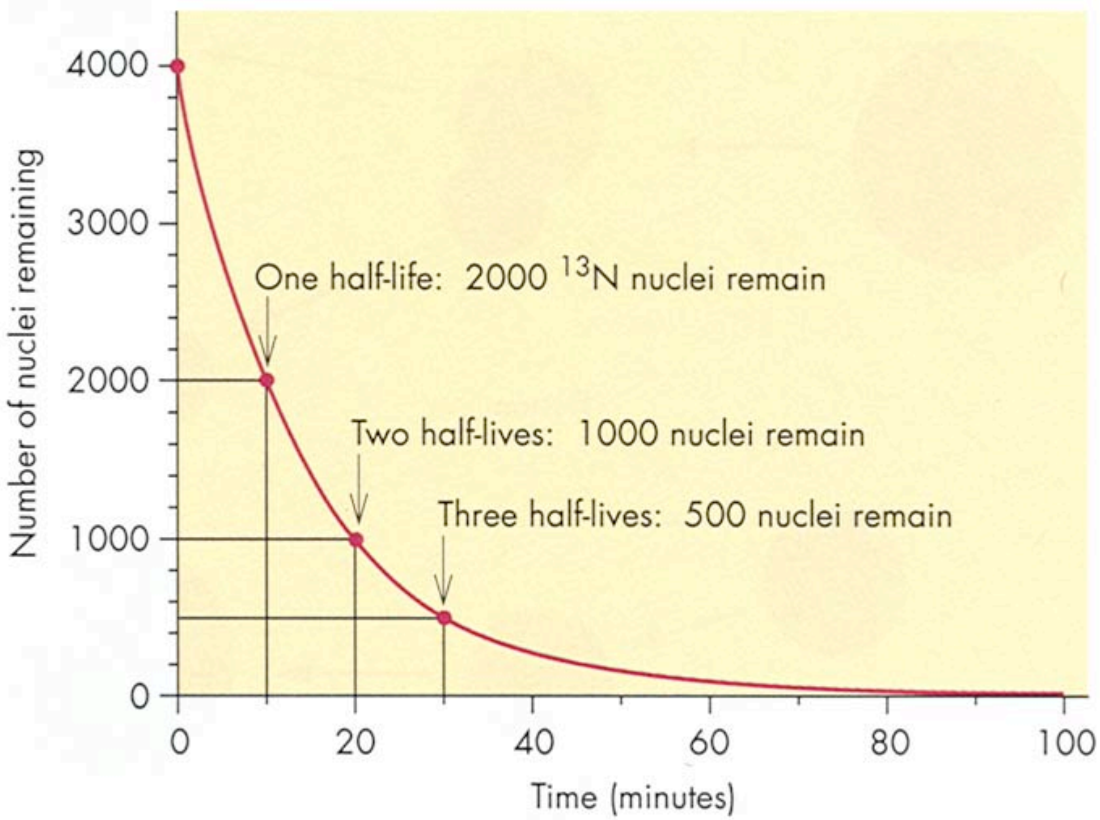


The decline of heat production by radioactive decay in Earth's interior. Heat production values are relative to those of the present, which is assigned a value of 1.

^{13}N radioactive decay: idea of half-life

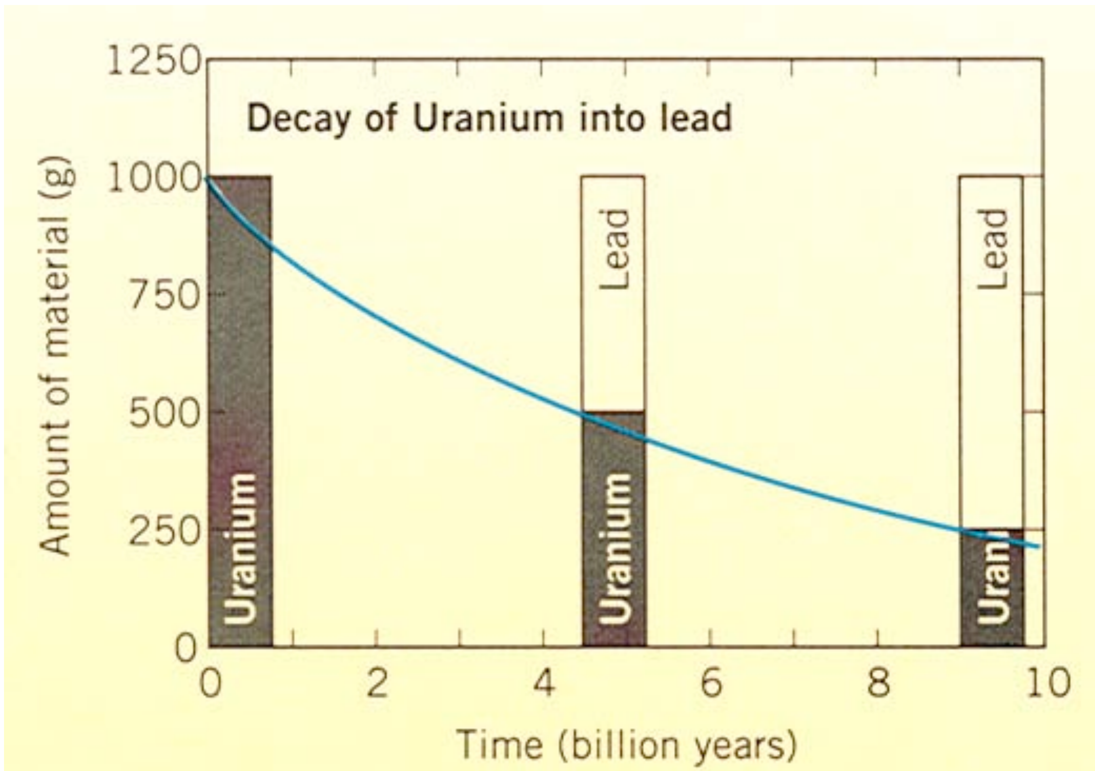
The Number of Remaining ^{13}N Nuclei Declines with Time

^{13}N is an unstable isotope with a half-life of 10 minutes. After one half-life, only half of the original 4000 nuclei remain. During each succeeding half-life, the number of remaining nuclei drops by half.



Uranium radioactive decay

Use to get ages of oldest (~ 2- 4.5 Gyr) rocks



Many useful radioactive isotopes for age determinations

Several Isotopes Useful in Radioactive Dating

Isotope	Half-Life (years)	Useful Range	Dating Applications
Carbon-14	5730	500 to 50,000 years	Charcoal, organic material
Tritium (^3_1H)	12.3	1 to 100 years	Aged wines
Potassium-40	1.3×10^9	10,000 years to the oldest Earth samples	Rocks, the Earth's crust, the moon's crust
Rhenium-187	4.3×10^{10}	4×10^7 years to oldest samples in the universe	Meteorites
Uranium-238	4.5×10^9	10^7 years to the oldest Earth samples	Rocks, the Earth's crust

TABLE 4.1 *Selected Isotopes Used for Radiometric Dating of Rocks and Fossils*

Some of the isotopes decay in several stages of parent–daughter pairs, and only the final daughter product is shown. (Source: Berkeley Laboratory Isotopes Project)

Parent Isotope	*Daughter Isotope*	*Half-Life*
Rubidium-87	Strontium-87	49.4 billion years
Lutetium-176	Hafnium-176	37.1 billion years
Thorium-232	Lead-208	14.0 billion years
Uranium-238	Lead-206	4.47 billion years
Potassium-40	Argon-40	1.25 billion years
Uranium-235	Lead-207	704 million years
Aluminum-26	Magnesium-26	717,000 years
Carbon-14	Nitrogen-14	5,730 years

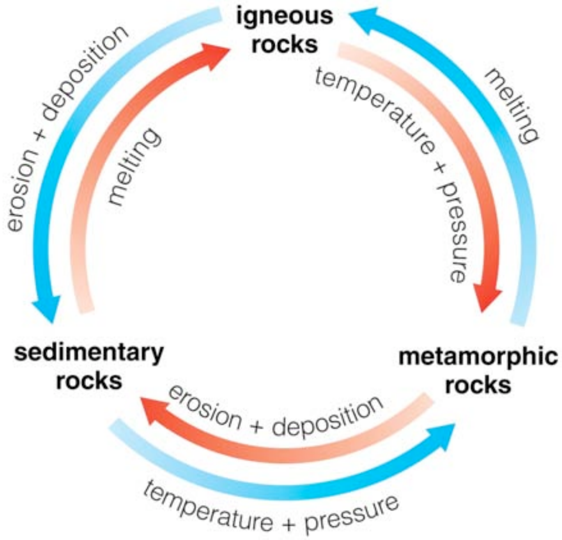
From textbook

Don't *memorize* these.

Establishing biological nature of fossils: stromatolites (below), $^{12}C/^{13}C$ ratio, …

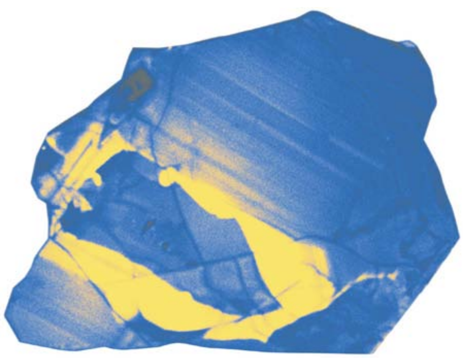
Stromatolites are a classic method for estimating when the Earth's atmosphere became oxygenated, and one will still commonly see statements that the presence of stromatolites at such-and-such an age shows the Earth's atmosphere had already been oxygenated. Now clearer that many mat-building bacteria are not aerobic photosynthesizers.

Oldest rocks, minerals



The rock cycle

Bedrock along the northeast coast of Hudson Bay, Canada, has the oldest rock on Earth.



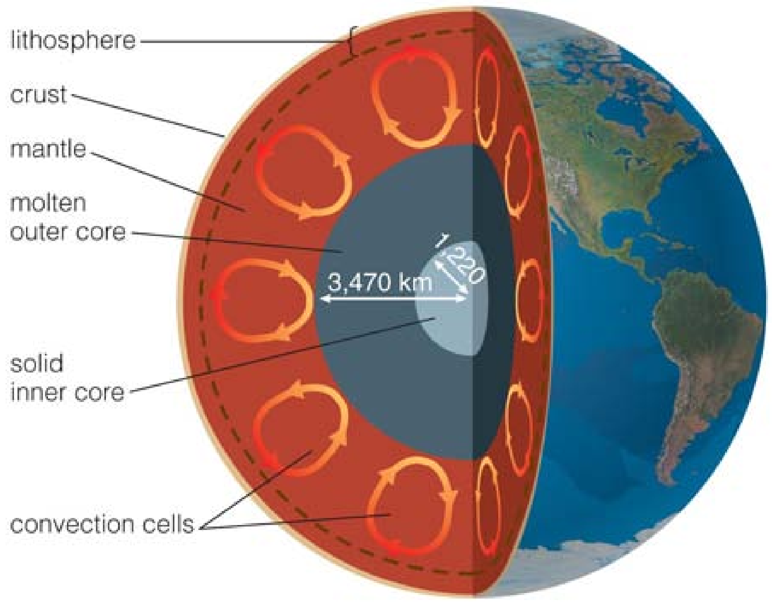
Oldest rocks: Nuvvuagittuq greenstone belt, Northern Quebec: up to 4.28 Gyr (Sept 2008)

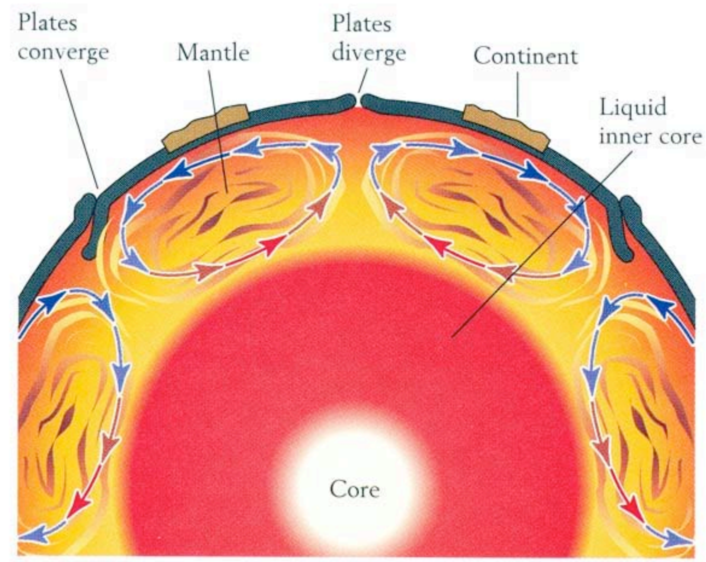
Oldest **zircon** minerals: 4.36 Gyr (Western Australia)
→ Continents and oceans in place!

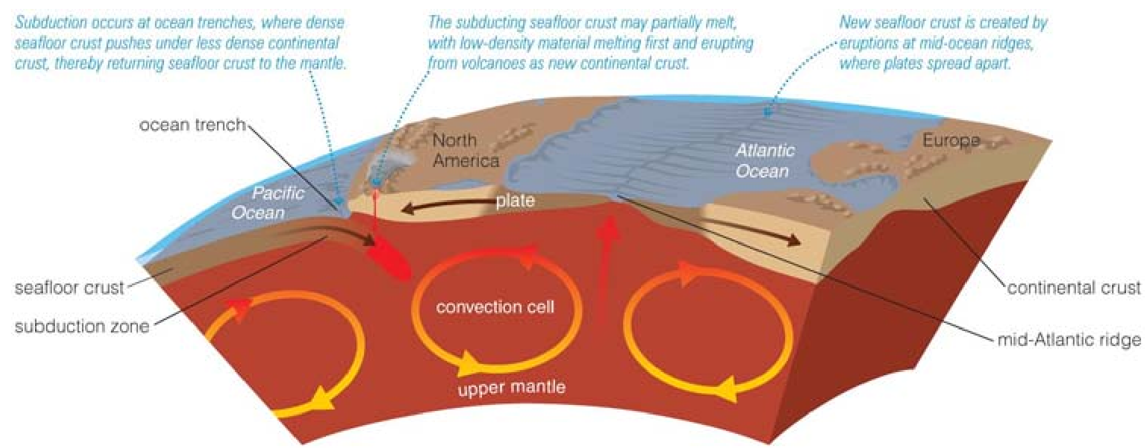
A particularly useful mineral : Zircons. Because crystallized, reveals aqueous environment

Earth's interior

This material should be read on your own, since the textbook has a fairly complete discussion. Notice that the motions in the interior are required for (a) plate tectonics and other geological activity, as well as (b) generation of the Earth's magnetic field (again, read text section). You should be able to answer: Why might plate tectonics or a magnetic field be important for life?

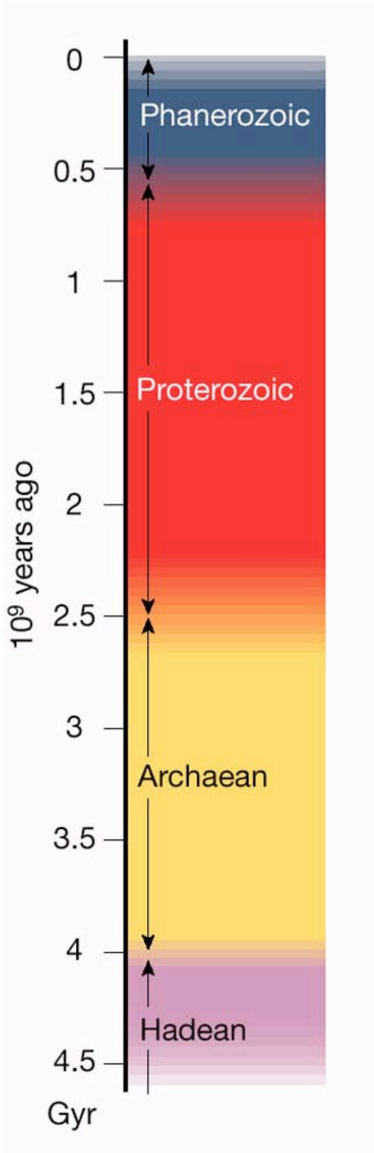






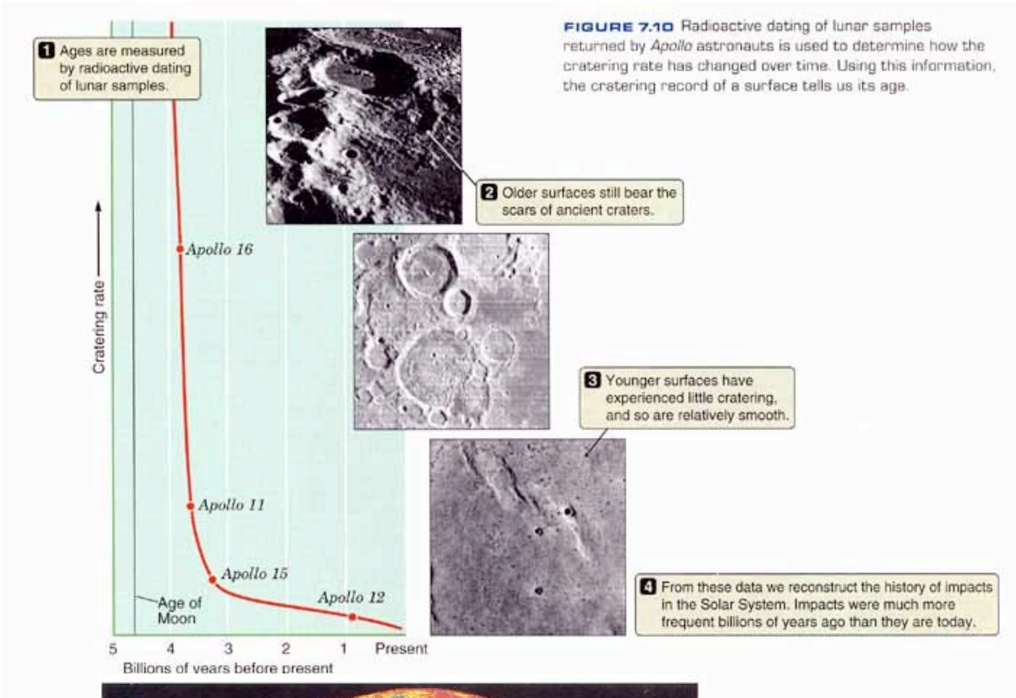
Hadean Eon

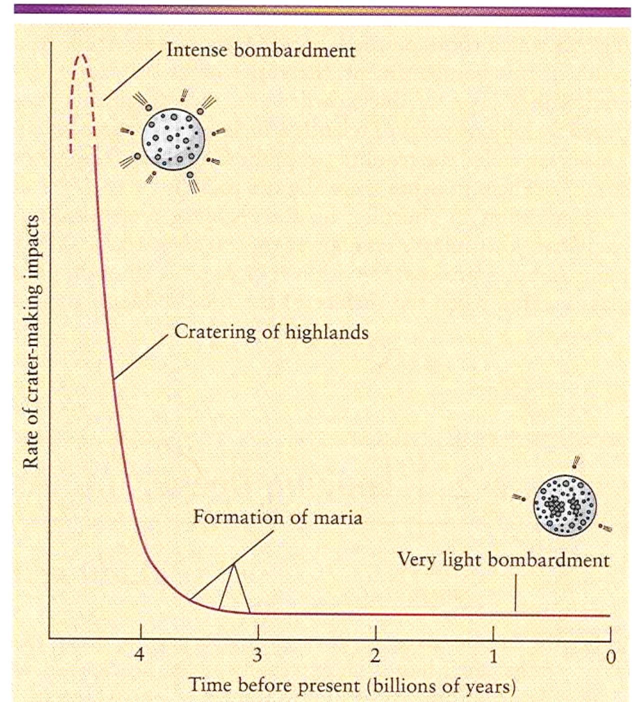
4.5 to 4.0 Gyr ago

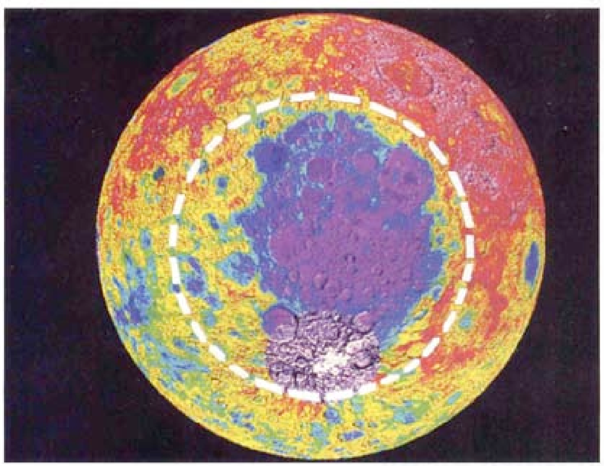


We begin with the time during which the Earth had just formed, and was being pummeled by large impactors, leftovers from the formation of the solar system, a single one of which could vaporize the oceans, or sterilize the planet. This *should* have made the Earth inhospitable for the first ~ 0.5 to 1 billion years…

Heavy bombardment from the lunar cratering record



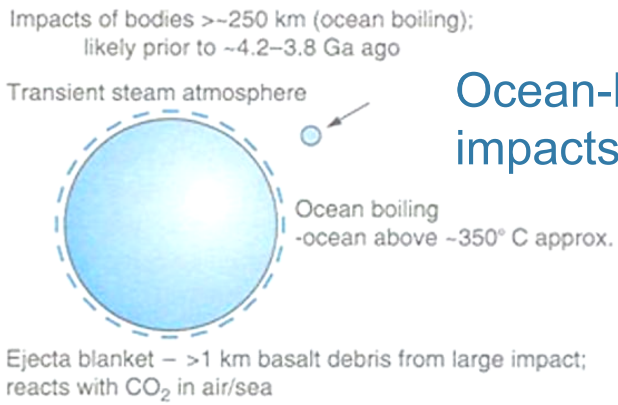




Remember, we know ages of different parts of Moon's surface from Moon rocks returned and analyzed to get radiometric ages. That tells us the age corresponding to various positions over the Moon's surface, where "age" means time since a rock last solidified from the melt. See Ch. 7 if this is not clear.

Giant crater at South Pole of Moon: The Moon took a big one.

How did Earth acquire its atmosphere?

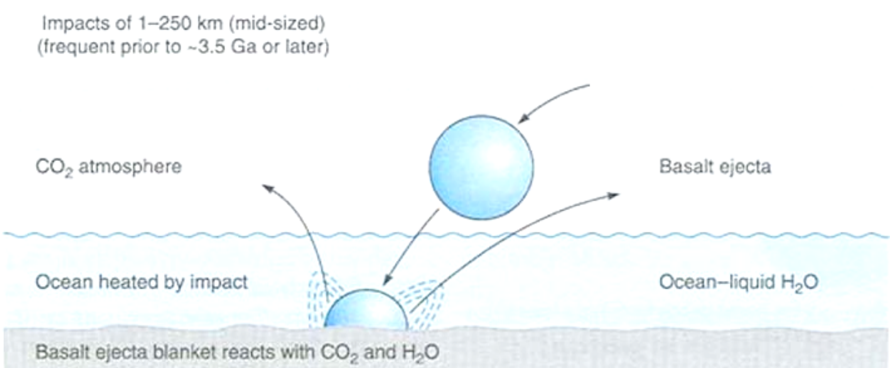


Bombardment by large (ocean-boiling) objects (>~250 km) (not to scale). These would have occurred with declining frequency in the period prior to ~4 Ga ago or later.

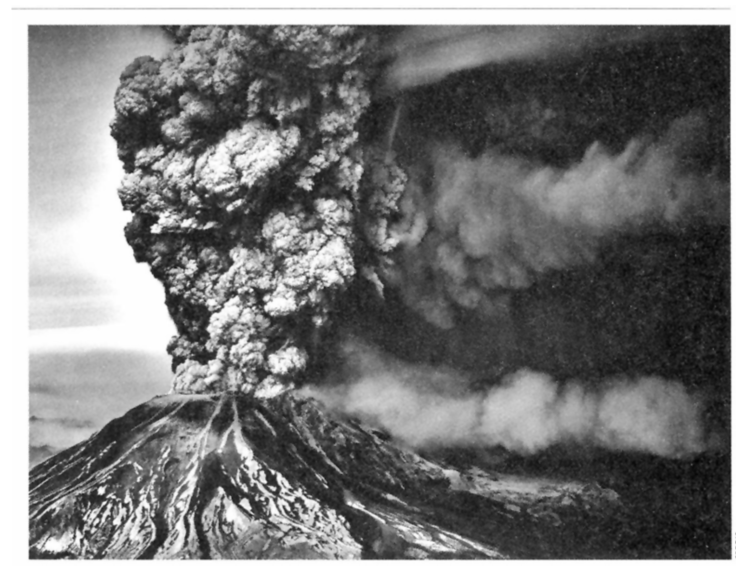
Ocean-boiling impacts

Most was probably outgassed from the Earth's interior

Impact degassing



Bombardment by 1–250 km size objects (ocean warming) (not to scale). These would have been frequent prior to ~3.5 Ga ago.

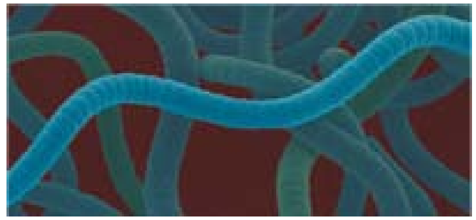


Degassing by vents, volcanism

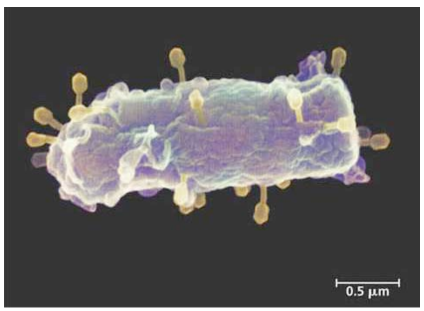
The Hadean/Archean biological world

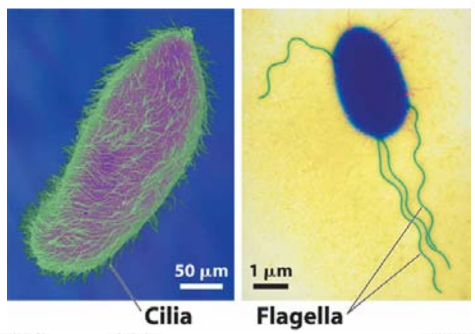
Prokaryotes: Most successful organisms on Earth. The only life for over 2 Gyr, many still with us. Essentially infinite lifetime for colonies. Note the complexity!

→ No organelles (eukaryotic cells only), smaller genome, no sex, but other abilities like extreme adaptation (see "extremophiles"), and *horizontal gene transfer*.

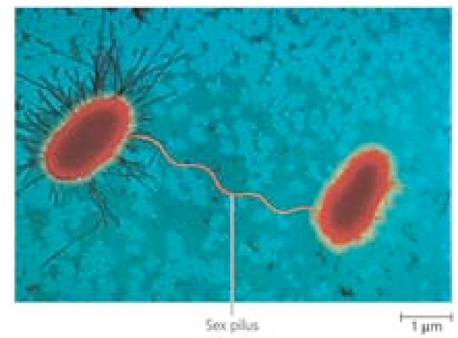


Motors for swimming

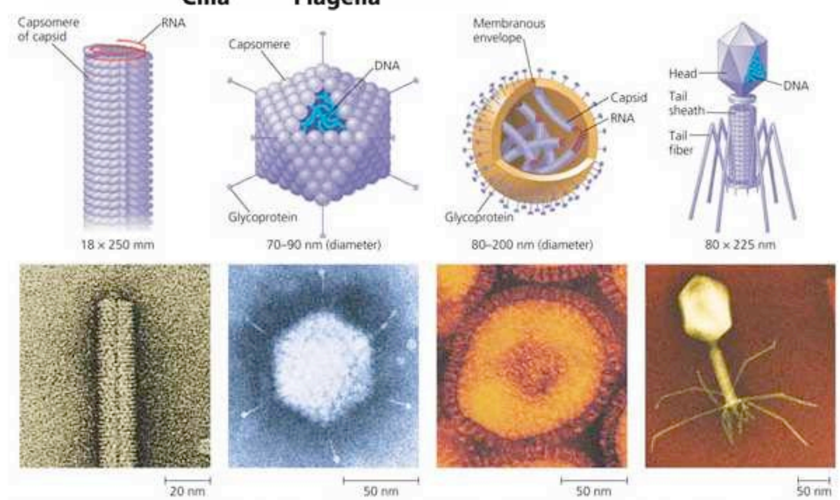




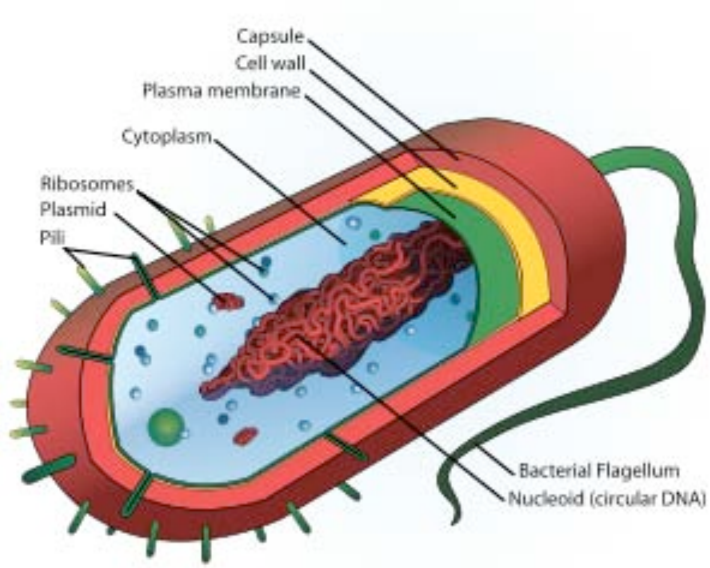
Horizontal (lateral) Transfer of genetic material



(and viruses)



The Hadean/Archaean biological world: Prokaryotes



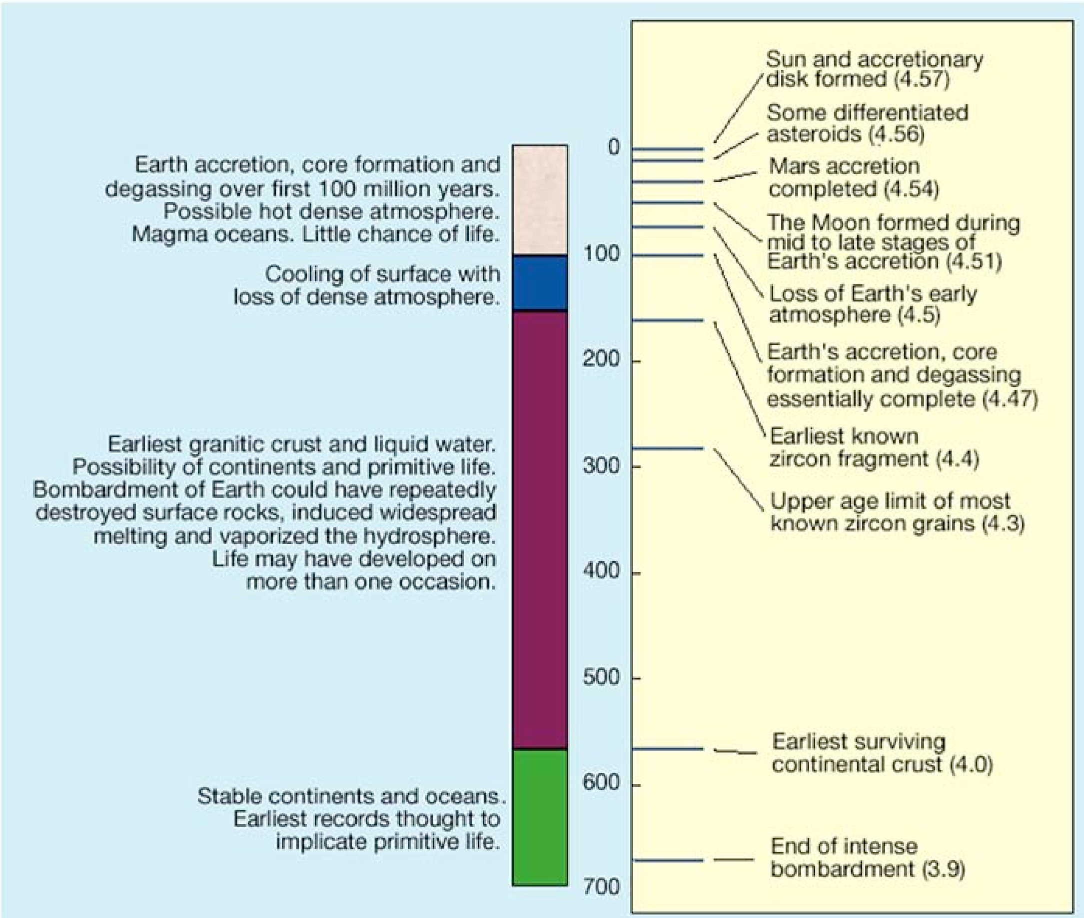
Small size (mostly 1-10 microns) compared to eukaryotes.

Lack cell nucleus or membrane-bound organelles. Nearly all are single-celled.

DNA not membrane-bound in prokaryotes, as it is in eukaryotes (cell nucleus, chromosomes).
Instead, a single loop of DNA is held in *nucleoid* without an envelope.

Two domains: *bacteria* and *archaea*.

The First Billion Years: Hadean Eon

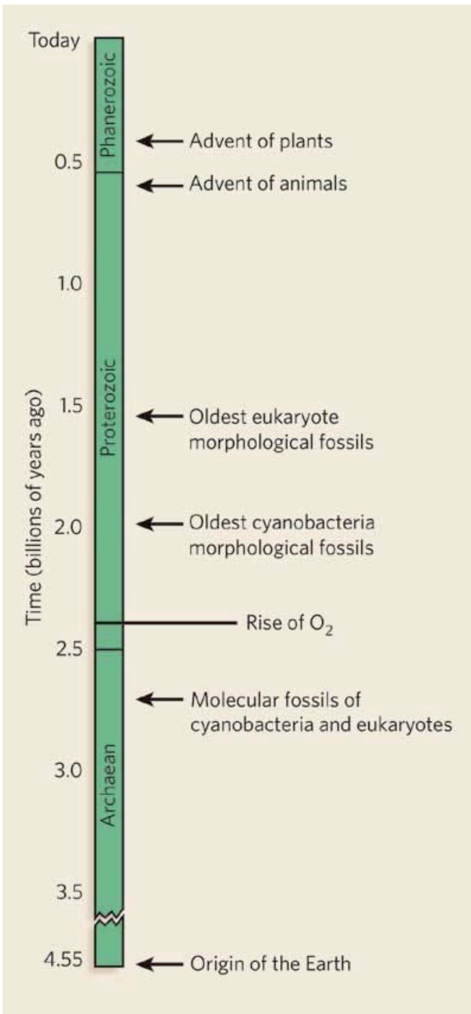


- First 0.1Gyr: Earth finishing accretion, degassing, hot dense atmosphere, magma oceans?
- Moon-forming giant impact **4.5 Gyr**
- Ocean-boiling impacts, several times, 4.5 to 4.4 Gyr
- Impact and volcanic degassing of atmosphere (CO_2, N_2, H_2O, H_2S, …)
- Continents, ocean, atmosphere in place by ~ **4.4 Gyr** (from zircon crystals)
- Smaller, non-sterilizing impacts 4.3-3.9 Gyr (from lunar crater counts vs. age)
- Late heavy bombardment ~ 3.9 Gyr. (Migration of larger leftovers inward?)
- Life? *Former* earliest microfossil ~3.5Gyr now regarded as bogus; $^{12}C/^{13}C$ evidence back to **3.8 Gyr**. *Stromatolites* as early as **3.5 Gyr**: *anaerobic* photosynthesis already operative this early

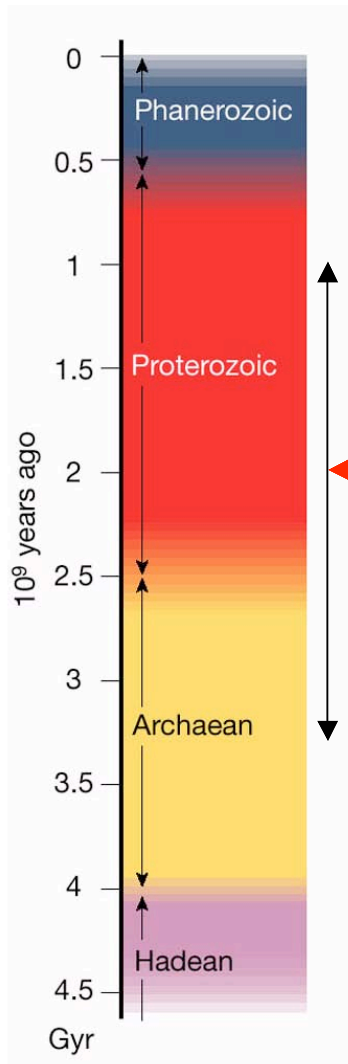
Notice the rapid pace: atmosphere, oceans, continents within the first ~ 0.1 Gyr! Life (possibly) by 3.8 Gyr, photosynthesis by 3.5 Gyr. This level of complexity arose more easily and rapidly than most expected.

Review: Where are we?

New timeline for earliest life and oxygenation of the atmosphere (Oct 2008 Nature)



Geological eons



Four eons

Hadean: oceans, atmosphere; probable origin of life, but punctuated by sterilizing impacts

Archean: age of *anaerobic* prokaryotes.

Proterozoic: aerobic photosynthesis, oxygenation, rise of the eukaryotes, meiosis, SnowballEarth; beginning of “Cambrian explosion.”

Phanerozoic: “Cambrian explosion” then development of all modern eukaryotic body plans, to present