The Evolutionary Timeline

Questions of Time and History

How old is the Universe?
How old are its constituents?
How old is the Earth?

and

When did Life appear on Earth?
What is the evolutionary history of Life on Earth?
(... and what rôle does life play in the Earth's evolution?)

Establishing an Historical Time Line

Step 1: Sequencing Events
Structural trends, stratigraphy, genetic changes ...

Step 2: Establishing a Time Scale
Dating events

Physical Determinations of Earth’s Age

Sedimentation & Erosion Rates

Sediment Thickness/Rate = 150 km/0.3 mm per year = 500 Myr

Erosion Depth/Erosion Rate = 600m/0.06 mm per year = 10 Myr

Salinity of the Seas

John Joly (1899)**: 90 - 100 Myr**

Cooling Times

Comte de Buffon (1779)**: 75,000 yr** (by experiment)

Lord Kelvin (1862)**: 98 Myr; 20 to 400 Myr**

Age of the Sun

Hermann von Helmholtz (1854)**: 21 Myr**

Simon Newcomb (1884)**: 100 Myr**

Biology & Geology

Darwin (c. 1859) **Evolution by Natural Selection requires > 400 Myr (Darwin)**

Charles Lyell (c. 1850) **: 240 MYr based on fossil mollusks.**

Age Dating *via* Radioactive Decay

Radioactivity

Roentgen (1895) - X Rays
Bequerel (1896) - Radioactivity of Uranium
Marie Curie (1898) - Uranium, Polonium, Radium
(“radio-active” and declining radioactivity)
Ernest Rutherford (1911) - Alpha particles and the atomic nucleus

Nomenclature

Atomic Structure

Chemistry and Atomic Physics
Nuclei and Electrons
Charges and Ions

Nuclear Structure

Nucleons = Protons & Neutrons
Atomic Number = Z = Proton Number
Atomic Weight = A = Nucleon Number
Isotopes: Varying A (*i.e.*, neutron number) at fixed Z
(Notation: C^{14}, U^{235}, U^{238}, *etc.*; but sometimes ^{14}C, ^{235}U, ^{238}U,..)

Nuclear Reactions

"Rules" for Nuclear Reactions

- Charge is conserved
- Nucleon number is conserved*
- Mass-energy is conserved

Example: **A Fusion Reaction**

$$H^1 + H^1 \rightarrow H^2 + e^+ + \nu$$

$$(p^+ + p^+ \rightarrow np^+ + e^+ + \nu)$$

Example: **A Fission Reaction**

$$U^{238} \rightarrow Th^{234} + He^4$$

$$(U^{238} \rightarrow Th^{234} + \alpha)$$

Example: **Pair Production and Particle-Antiparticle Annihilation**

$$e^- + e^+ \leftrightarrow \gamma$$

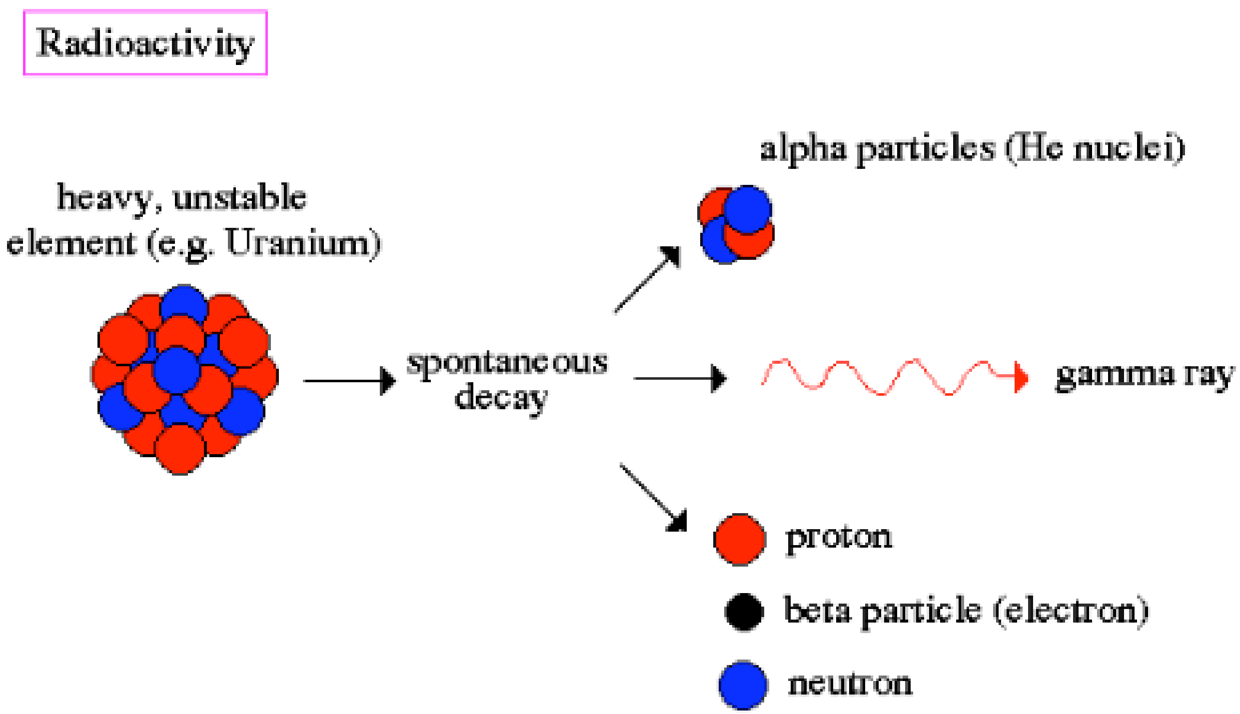
Note: Energy release (or consumption) from ΔMc^2

* excepting (unlikely) pair production or particle-antiparticle annihilation

Natural Radioactive Decay

Principal Decay Mechanisms

Alpha (α) Emission: a helium-4 nucleus (He^{++})
Beta (β) Emission: a positron (e^+) or electron (e^-)
Gamma (γ) Radiation: a high energy photon ("$h\nu$")



Natural Radioactive Decay

- Radioactive nuclei decay into other elements and isotopes.

e.g., $U^{238} \rightarrow Th^{234} + He^4$

- Each decay of a "parent" nucleus produces a "daughter" nucleus (which might itself be radioactive)

e.g., $Th^{234} \rightarrow Pa^{234} + e^-$

- The process ends when a stable non-radioactive nucleus is produced.

e.g., $U^{238} \rightarrow \ldots \rightarrow Pb^{206}$

- The rate of decays (the "radioactivity" of a sample) is proportional to the number of radioactive nuclei present.

.. and independent of other factors such as temperature or chemistry

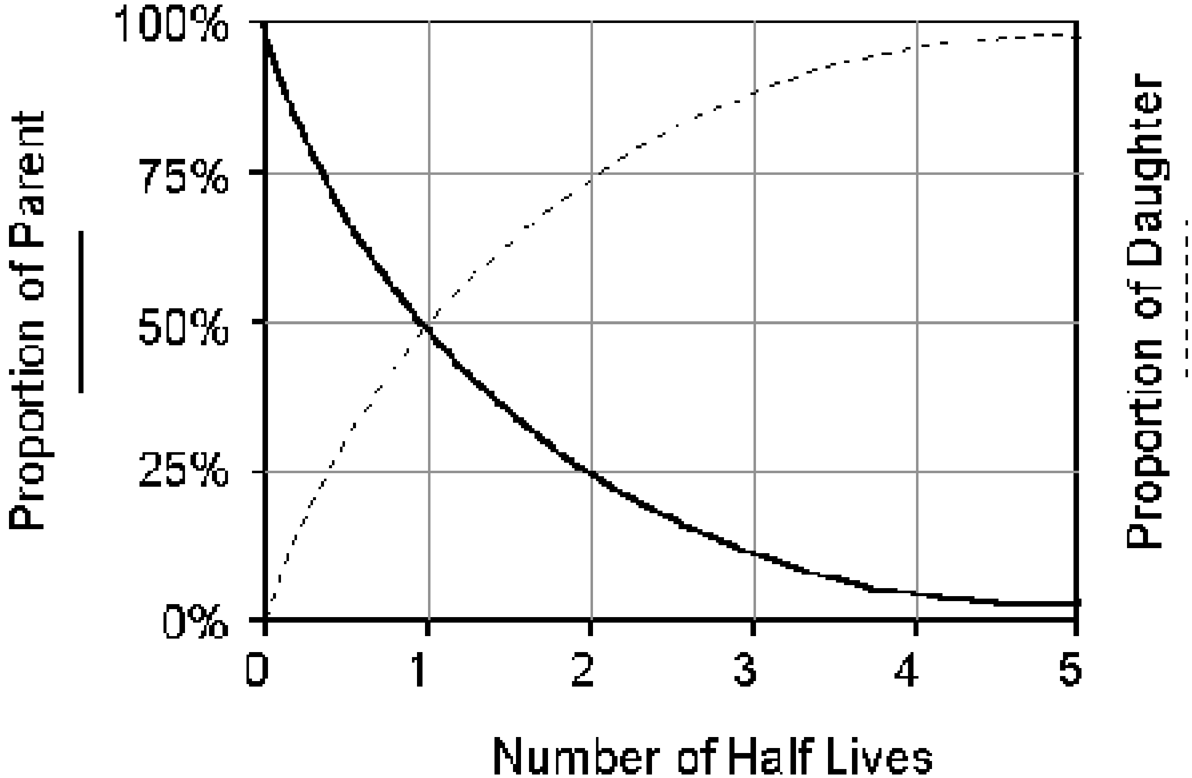
- Each decay step, as well as the full sequence, is characterized by a "half life"

$\tau_{1/2}$ = 24.5 days for $U^{238} \rightarrow Th^{234} + He^4$

$\tau_{1/2}$ = 4.508 Gyr for $U^{238} \rightarrow \ldots \rightarrow Pb^{206}$

- The number of radioactive nuclei is repeatedly halved with the elapse of each additional "half life"

Natural Radioactive Decay



After one half life, half of the parent atoms remain,
After two half lives, one-quarter remain,
After three half-lives, one-eighth remain, *etc.*

The total number of nuclei, radioactive parent plus stable daughter, is a constant.

Radioactive decay proceeds until a stable isotope is reached

URANIUM 238 (U238) RADIOACTIVE DECAY

type of radiation	nuclide	half-life
	uranium—238	4.5×10^{9} years
α	thorium—234	24.5 days
β	protactinium—234	1.14 minutes
β	uranium—234	2.33×10^{5} years
α	thorium—230	8.3×10^{4} years
α	radium—226	1590 years
α	radon—222	3.825 days
α	polonium—218	3.05 minutes
α	lead—214	26.8 minutes
β	bismuth—214	19.7 minutes
β	polonium—214	1.5×10^{-4} seconds
α	lead—210	22 years
β	bismuth—210	5 days
β	polonium—210	140 days
α	lead—206	stable

Natural Radioactive Decay

A Parent/Daughter ratio gives <u>time elapsed</u> since the sample was pure Parent
Important: This is generally the time elapsed since the sample solidified from melt.
(Parent and Daughter elements generally separate upon melting.)

Cross-Checking*: Some Other Radioactive Age Indicators

Decay Path	Half Life	
$Rb^{87} \rightarrow Sr^{87}$	49.82 Gyr	(1 Gyr = 10^9 years)
$Re^{187} \rightarrow Os^{187}$	42.97 Gyr	
$Th^{232} \rightarrow Pb^{208}$	13.89 Gyr	
$U^{238} \rightarrow Pb^{206}$	4.508 Gyr	
$K^{40} \rightarrow Ar^{40}$	1.277 Gyr	
$U^{235} \rightarrow Pb^{207}$	0.713 Gyr	
also of interest:		
$I^{129} \rightarrow Xe^{129}$	15.7 Myr	(1 Myr = 10^6 years)
$Hf^{182} \rightarrow W^{182}$	9.0 Myr	
$Pu^{244} \rightarrow Xe^{136}$	80.8 Myr	
and, particularly:		
$C^{14} \rightarrow N^{14}$	5,370 yr	

***Allows correction for effects of other physical and chemical processes.**

The Age of the Earth

In Search of the oldest rocks:

Zircon ($ZrSiO_4$) Grains (Australia) : 4.404 Gya*

(Melting Point 2200°C *versus* 1710°C for Silica and 1538°C for Iron)

Acasta Gneiss (Canada): 4.04 Gya

Akilia Island Greenstone (Greenland): 3.85 Gya
(Contains the earliest evidence for carbonaceous life)

Isua Supracrustal Rocks (Greenland): 3.75 Gya

•••••• The inferred age of the Earth is 4.567 Gyr •••••

About the same as that of the Moon, Meteorites, Asteroids, Mars, and the Sun

Clarifications:

- **This dates the beginning of the terrestrial accretion process**
- **Accretion was essentially complete by 4.47 Gya**
- **Solidification of the surface begins about 4.4 Gya**
  ....and is more-or-less complete by about 4.0 Gya

***Gya = "Gigayears ago"**

Timeline: The Formation of the Earth

(13.7 Gya ------------ The Origin of the Universe)

4.57 ± 0.07 Gya ----------------- Formation of the Solar System

4.55 Gya --------------- First Solar System Solids (Meteorites)

4.533 Gya ----------------- Formation of the Moon (by collision)

4.53 Gya ---------------- Formation of Martian Crust (ALH84001)

4.527 Gya ------------------- Lunar Regolith (Apollo, Meteorites)

4.49 ± 0.04 Gya ----- Formation of the Sun Complete (ZAMS)

4.404 Gya --------------- First Terrestrial Solids (Zircon Grains)

4.04 Gya --- Oldest surviving rocks (Acasta Gneiss, Canada)

3.9± Gya --------------------- End of “Late Heavy Bombardment”

•

•

(3.85 Gya---- First Indicators of Carbonaceous Life)

Timeline: Life on Earth

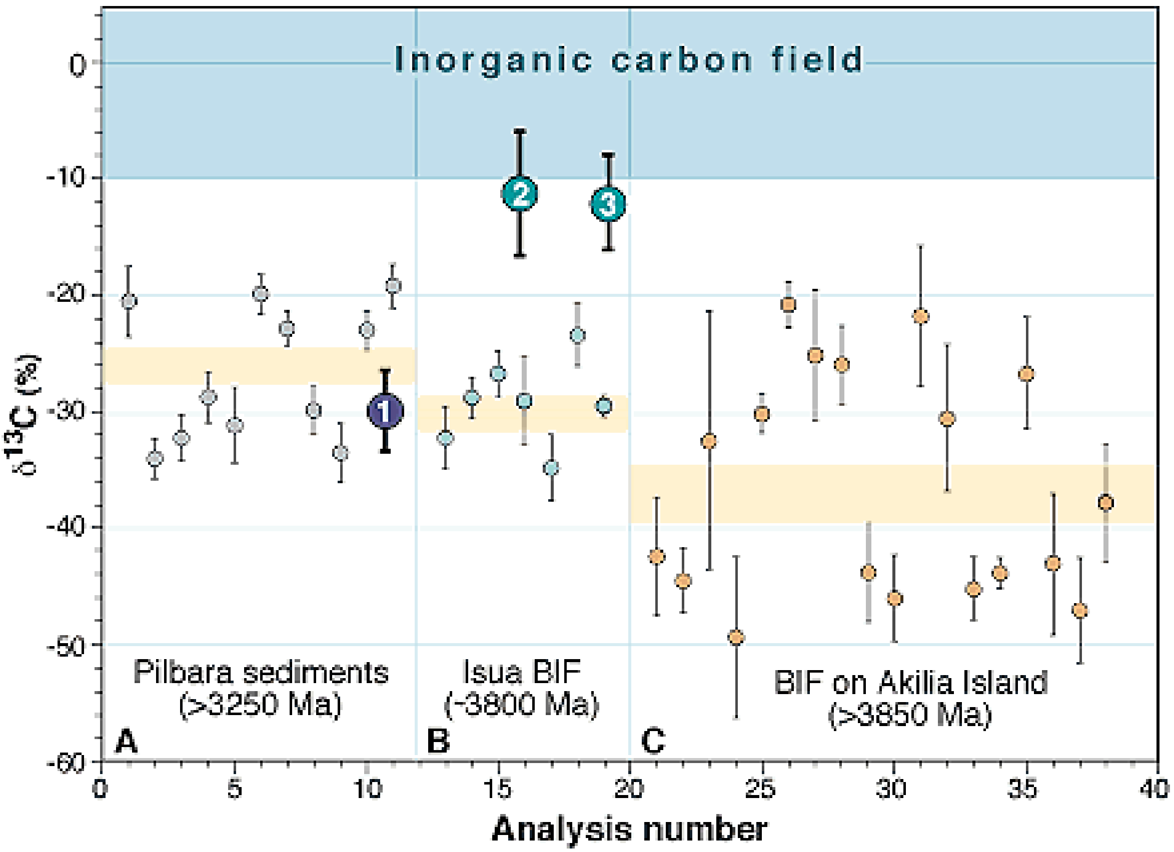
The C^{13}/C^{12} ratio as an indicator of the presence of life

Life prefers "Carbon Light"

Normal C^{13}/C^{12} abundance ratio is $R_o = 0.01120$

$$\delta C^{13} = 1000 \times (R - R_o)/R_o$$

A value of $\delta C^{13} < -10$ is considered a robust indicator of life



Timeline: Life on Earth

Life has been present for 75% to 85 % of the Earth's history

3.85 Gya----------------- First Indicators of Carbonaceous Life (δC^{13})

3.5 Gya ----------- Anaerobic Photosynthesis (O_2 production, LUA?)

3.465 Gya ------------- Oldest Fossils (Microbial Filaments, Australia)

3.4 Gya -------- Banded Iron Formations (Sedimentation, oxidation)

3.375 Gya -------------------------------- Fossil prokaryotes (South Africa)

3.0 Gya ------------ Colonial Cyanobacteria (Stromatolites, Australia)

2.4 Gya ------------ The "Great Oxidation" (To ~O.01 PAL, PAL = 23%)

2.1 Gya ------------------------------- The First Eukaryotes (Algal Ribbons)

1.2 Gya--------------------------------- Cell Division (Sex!), Multicellular Life

600 Mya ------------------------------Simple Multicellular Animals (Sponges)

542 -530 Mya ----- The "Cambrian Explosion" (Body plans and parts)

The Early Fossil History

Microscopic Fossil Prokaryotes (3.375 Gya)
Non-Nucleated Cells: Prokaryotes
(Archaea & Bacteria)
Anaerobic Photosynthesis

- **Fossil Mats (Stromatolites)** (3.0 Gya)
  Colonial Cyanobacteria
  Aerobic Photosynthesis

- **Fossil Algae** (2.1 Gya)
  (Nucleated Cells: Eukaryotes)

- **Multicelluar Fossils (Sponges)** (0.60 Gya)

- **Complex Animals (and tracks on land)** (0.53 Gya)
  "The Cambrian Explosion"

followed eventually by

- **Primates** (0.060 Gya) and ***Homo Erectus*** (0.001 Gya)
  Extinction of the Dinosaurs at 0.065 Gya

Biochemistry and the Earth's Atmosphere

• **First Chemical Indicators: δC^{13}** (3.85 Gya)

Atmospheric Constituents : CO_2, CO, N_2, H_2O, $H_2\uparrow$ (Note: No O_2 or O_3)

Anoxygenic Photosynthesis & Biological Methane Production

• **Slow Oxygenation** (3.85 to 2.33 Gya)

••• **Oxygen increases from 10^{-12} to 10^{-5} PAL** (PAL = 21% Oxygen) •••

Anaerobic Decomposition: $CO_2 + 2H_2O \rightarrow CH_4 + 2O_2$

Oxygenic Photosynthesis (Glucose): $6CO_2 + 6H_2O + h\nu \rightarrow C_6H_{12}O_6 + 6O_2$

(Anoxygenic Photosynthesis uses H_2, H_2S, S, or other molecules in place of H_20)

also

Anoxic Fermentation & Methanogenesis: $2CH_2O \rightarrow CH_3COOH \rightarrow CH_4 + CO_2$

but also

Methane Eaters: $CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$

Iron Oxidation (Basalt): $Fe + H_2O \rightarrow FeO + H_2\uparrow$

and (Magnetite): $3FeO + H_2O \rightarrow Fe_3O_4 + H_2\uparrow$

• **The Great Oxygenation** (2.33 Gya)

••• **Oxygen increases from 10^{-5} to 10^{-2} PAL** •••

Extinction of many species by Oxygen Poisoning

Ozone Formation $3O_2 + h\nu \rightarrow 2O_3$

Evolution: The History of Life On Earth

A Summary

The Earth was formed 4.57 Gya
Life appeared on Earth about 3.85 Gya
Microscopic fossil evidence of life at 3.47 Gya
Eukaryotes (Nucleated cells) appear at 2.1 Gya
Complex animals of diverse types appear at 0.53 Gya

and

The last 0.5 Gyr produced an increasing number and diversity of species

Evolution as a Fact

- Life has been present on the Earth for at least 3.5 Gyr, - and probably for 3.85 Gyr.

- The paleontological fossil record clearly shows temporal evolution - both within species and as speciation.

- The evolutionary trend has been toward greater diversity and complexity with increasing numbers of species.

- Evolutionary sequencing and time scales can be established through radio dating techniques. (*cf . supra)*

- Evolution and Speciation continues to the present day - and is observed to occur in nature and the laboratory

Evolution as Theory

Evolutionary Theory attempts to explain the facts of evolution in terms of natural processes.

- **The strength of any scientific hypothesis lies in its ability to explain the observational evidence in this way.**

- **The success of a scientific theory lies in its predictive ability - and its testability or falsifiability**

Darwin's Theory of Evolution possesses great explanatory and predictive power.
Its precepts and predictions have been extensively tested.
The same cannot be said for the various alternative hypotheses which have been proposed.