Introductions

Rationale

The interactive Earth system: biology in geologic, environmental and climate change throughout Earth history.

Since life began it has continually shaped and re-shaped the atmosphere, hydrosphere, cryosphere and the solid earth.

‘Geobiology’ introduces the concept of 'life as a geological agent' and examines the interaction between biology and the earth system during the roughly 3.5 billion years since life first appeared.
12.007 GEOBIOLOGY
SPRING 2013

Instructors: Roger Summons and Tanja Bosak
Guest Lecturers: Julio Sepulveda
Lectures: Mon and Wed 11-12:30

Course Description:
Parallel evolution of life and the environment. Life processes are influenced by chemical and physical processes in the atmosphere, hydrosphere, cryosphere and the solid earth. In turn, life can influence chemical and physical processes on our planet. This course introduces the concept of life as a geological agent and examines the interaction between biology and the earth system during the roughly 4 billion years since life first appeared.

Grading:
25% Participation in class discussions
15% Problem Sets/Assignments
10% Weekly quizzes
20% Final Blog Piece
15% Midterm Exam
15% Final Exam

Other Recommended Reading
How to Build a Habitable Planet: The Story of Earth from the Big Bang to Humankind (Revised and Expanded Edition)  
CH Langmuir, W Broecker - 2012 - books.google.com

Planet Earth: Cosmology, Geology and the Evolution of Life and Environment, Cesare Emiliani, Cambridge University Press, 1992

Additional readings provided for some lectures.
Week 1

• Lecture Schedule

• 1. Wed 2/6 Overview of course; What is life? Can it be defined? Brief history of paleontology and geobiology; Life as a geological agent. Sedimentary environments and processes; Stratigraphy (William Smith); Isostasy; Plate tectonics; Water and life; Habitable zone; Radiative balance; Greenhouse gases. Faint Young Sun (Summons)

• Stanley, Chap. 1 & 2 Kump 187-195

• 2. Mon 2/11: Time scales of major events in formation of Universe and Solar System; Abundance of elements. Geochronology; Introduction to geological processes, rocks and minerals. Planetary accretion and differentiation. Introduction to the geological timescale and major transitions in Earth history (Summons)

• Stanley pp. 129-151, 177-197

• problem set
Weeks 1&2 Assignment

Essay: What criteria do you think are important for assessing the habitability of a planetary body? Illustrate with reference to current or past missions in our solar system.

OR:

Essay: What is meant by the concept of Galactic Habitable Zone. Illustrate with reference to a current mission that looks outside our solar system.

4 pages incl. figures; due Feb 20th
Voyager 1 Image July 6, 1990
Earth from Space

• 70% of surface covered with liquid water.
• Is this necessary for the formation of life?
• How unusual is the Blue Planet?

Courtesy NASA
Making a Habitable Planet

• The right kind of star and a rocky planet
• A benign cosmological environment
• Matter, temperature where liquid water stable, energy
• And many more...see:

What is life?

**Life**, from wikipedia

“Life is a characteristic that distinguishes objects that have signaling and self-sustaining processes from those that do not,[1][2] either because such functions have ceased (death), or else because they lack such functions and are classified as inanimate.”[3][4]


“Dedicated to Non-Human-Like Life Forms, Wherever They Are.”
Life Qualities

- Terran life uses water as a solvent;
- It is built from cells and exploits a metabolism that focuses on the carbonyl group (C=O);
- It is thermodynamically dissipative, exploiting chemical-energy gradients; and
- It exploits a two-biopolymer architecture that uses nucleic acids to perform most genetic functions and proteins to perform most catalytic functions.

The Committee on the Limits of Organic Life in Planetary Systems uses the term “terran” to denote a particular set of biological and chemical characteristics that are displayed by all life on Earth. Thus “Earth life” has the same meaning as “terran life” when the committee is discussing life on Earth, but if life were discovered on Mars or any other nonterrestrial body, it might be found to be terran or nonterran, depending on its characteristics.
Life Qualities

Many of the definitions of life include the phrase undergoes Darwinian evolution. The implication is that phenotypic changes and adaptation are necessary to exploit unstable environmental conditions, to function optimally in the environment, and to provide a mechanism to increase biological complexity.

The canonical characteristics of life are inherent capacities to adapt to changing environmental conditions and to increase in complexity by multiple mechanisms, particularly by interactions with other living organisms.

The Limits of Organic Life in Planetary Systems
http://www.nap.edu/catalog/11919.html
Rhythm of Life

Guinness “Rhythm of Life – Evolution

http://www.youtube.com/watch?v=9OjkEOdZj3A
## Cosmic Time Scales

**January**
- The Big Bang

**February**
- Milky Way disk forms

**March**
- Solar System and life

**April**
- Photo-synthesis

**May**
- Eukaryotic cells

**June**
- Avg. human life span=0.15 s

**July**
- 4.6 b.y.

**August**
- 2.1 b.y.

**September**
- 65 m.y.

**October**
- 3.5 b.y.

**November**
- 12-15 b.y.

**December**
- 13

**December 1**
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
- 11
- 12
- 13
- 14
- 15
- 16
- 17
- 18
- 19
- 20
- 21
- 22
- 23
- 24
- 25
- 26
- 27
- 28
- 29
- 30
- 31

- 10:15 AM Ape / gibbon divergence
- 8:10 PM Human / chimpanzee divergence
- 10:48 PM Homo erectus evolves
- 11:54 PM Anatomically modern humans evolve
- 11:58 PM Modern humans migrate out of Africa
- 11:59 PM Neanderthals die out, megafauna stressed

- 21 s

---

**The last 60 seconds of the year...**

- 60
- 55
- 50
- 45
- 40
- 35
- 30
- 25
- 20
- 15
- 10
- 5
- 0

- Peak of last glacial period, humans migrate to the Americas
- Agriculture, permanent settlements
- Roman republic, Old Testament, Buddha
- Dynastic China
- First cities in Mesopotamia
- Columbus arrives in America (one second to midnight)
- Christ born
- Mohammed born

---

*Known from telescopes looking back in time, physical models*  
*Written record*

*Known from radiocarbon dating, DNA extraction from remains*  
*Written record*

*Courtesy of Eric Fisk. Used with permission.*
Earth’s Geologic Clock

Original illustration removed due to copyright restriction.


Image by Woudloper.
The standard cosmological model of the formation of the universe:

“The Big Bang”

New NASA Speak: The
theory of The Big Bang

• From: The First Three Minutes, by Steven Weinberg

<table>
<thead>
<tr>
<th>Time T(K)</th>
<th>E</th>
<th>Density</th>
<th>What’s Happening?</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^-3 s</td>
<td>10^11 K</td>
<td>5.0 MeV</td>
<td>4x10^5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The universe is mostly light. Electrons and positrons created from light (pair-production) and destroyed at about equal rates. Protone and neutrons being changed back and forth, so about equal numbers. Only about one neutron or proton for each 10^6 photons.</td>
</tr>
<tr>
<td>1.1 s</td>
<td>3x10^3</td>
<td>2.5 MeV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Free neutrons decaying into protons, so there begins to be an excess of protons over neutrons.</td>
</tr>
<tr>
<td>1.09 s</td>
<td>10^3 K</td>
<td>850 keV</td>
<td>4x10^5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Primordial helium becomes transparent to neutrinos, so they are released. It is still opaque to light and electromagnetic radiation of all wavelengths, so they are still contained. Electron–positron annihilation now proceeding faster than pair–production.</td>
</tr>
<tr>
<td>13.38 s</td>
<td>3x10^3</td>
<td>250 keV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Below pair–production threshold</td>
</tr>
<tr>
<td>3 m</td>
<td>10^3 K</td>
<td>85 keV</td>
<td></td>
</tr>
<tr>
<td>2 s</td>
<td></td>
<td></td>
<td>Electrons and positrons nearly all gone. Photons and neutrinos are major constituents of the universe. Neutron decay leaves 0.6% protons, 14% neutrons but these represent a small fraction of the energy of the universe.</td>
</tr>
<tr>
<td>3 m 45 s</td>
<td>0.9x10^3</td>
<td>78 keV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Deuterium is now stable, so all the neutrons quickly combine to form deuterium and then helium. There is no more neutron decay since they are stable in nuclei. Helium about 26% by weight in universe from this early time. Nothing heavier formed since there is no stable product of mass 5.</td>
</tr>
<tr>
<td>5 mm 40 s</td>
<td>3x10^3</td>
<td>26 keV</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Nuclear processes are stopped, expansion and cooling continues. About 1 in 10^8 electrons left because of a slight excess of electrons over positrons in the primordial fireball.</td>
</tr>
<tr>
<td>7x10^9 y</td>
<td>3000 K</td>
<td>0.26 eV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cool enough for hydrogen and helium nuclei to collect electrons and become stable atoms. Absence of ionized gas makes universe transparent to light for the first time.</td>
</tr>
<tr>
<td>10^10 yrs</td>
<td>3 K</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Living beings begin to analyze this process.</td>
</tr>
</tbody>
</table>

© Rod Nave. All rights reserved. This content is excluded from our Creative Commons license. For more information, see [http://ocw.mit.edu/help/faq-fair-use/](http://ocw.mit.edu/help/faq-fair-use/).
Evidence for the Big Bang #1: An Expanding Universe

- The galaxies we see in all directions are moving away from the Earth, as evidenced by their red shifts (Hubble).
- The fact that we see all stars moving away from us does not imply that we are the center of the universe!
- All stars will see all other stars moving away from them in an expanding universe.
- A rising loaf of raisin bread is a good visual model: each raisin will see all other raisins moving away from it as the loaf expands.
Evidence for the Big Bang #2: The 3K Cosmic Microwave Background

• Uniform background radiation in the microwave region of the spectrum is observed in all directions in the sky.
• Has the wavelength dependence of a Blackbody radiator at ~3K.
• Considered to be the remnant of the radiation emitted at the time the expanding universe became transparent (to radiation) at ~3000 K. (Above that T matter exists as a plasma (ionized atoms) & is opaque to most radiation.)
Science Magazine: Breakthrough of the Year 2003

• Wilkinson Microwave Anisotropy Probe (WMAP) produced data to indicate the abundances and sizes of hot and cold spots in the CMB.
• Universe is very strange
• Universe not just expanding but accelerating
• Universe is 4% ordinary matter, 23% ‘exotic matter = dark matter’ and 73% dark energy
• Age is 13.7 ± .2 b.y. and expanding
• It’s flat

Courtesy NASA
Evidence for the Big Bang #3: H-He Abundance

**In the hot, early universe, protons and neutrons were equally numerous since the energy was high enough to exchange them freely back and forth.**

- Hydrogen (73%) and He (25%) account for nearly all the nuclear matter in the universe, with all other elements constituting < 2%.
- High % of He argues strongly for the big bang model, since other models gave very low %.
- Since no known process significantly changes this H/He ratio, it is taken to be the ratio which existed at the time when the deuteron became stable in the expansion of the universe.

Image by MIT OpenCourseWare.
Nucleosynthesis

## Nucleosynthesis I: Fusion Reactions in Stars

<table>
<thead>
<tr>
<th>Fusion Process</th>
<th>Reaction</th>
<th>Ignition T (10^6 K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Burning</td>
<td>H→He, Li, Be, B</td>
<td>50-100</td>
</tr>
<tr>
<td>Helium Burning</td>
<td>He→C, O</td>
<td>200-300</td>
</tr>
<tr>
<td>Carbon Burning</td>
<td>C→O, Ne, Na, Mg</td>
<td>800-1000</td>
</tr>
<tr>
<td>Neon, Oxygen Burning</td>
<td>Ne, O→Mg-S</td>
<td>2000</td>
</tr>
<tr>
<td>Silicon Burning</td>
<td>Si→Fe</td>
<td>3000</td>
</tr>
</tbody>
</table>

Produced in early universe
3He=C, 4He=O

Fe is the end of the line for E-producing fusion reactions...
Hydrogen to Iron

- Elements above iron in the periodic table cannot be formed in the normal nuclear fusion processes in stars.
- Up to iron, fusion yields energy and thus can proceed.
- But since the "iron group" is at the peak of the binding energy curve, fusion of elements above iron dramatically absorbs energy.

Image by MIT OpenCourseWare.
Nuclear Binding Energy

• Nuclei are made up of protons and neutrons, but the mass of a nucleus is always less than the sum of the individual masses of the protons and neutrons which constitute it.

• The difference is a measure of the nuclear binding energy which holds the nucleus together.

• This energy is released during fusion.

BE can be calculated from the relationship: \( BE = \Delta m c^2 \)

For \( \alpha \) particle, \( \Delta m = 0.0304 \text{ u} \), yielding \( BE = 28.3 \text{ MeV} \)

**The mass of nuclei heavier than Fe is greater than the mass of the nuclei merged to form it.**
Elements Heavier than Iron

- To produce elements heavier than Fe, enormous amounts of energy are needed which is thought to derive solely from the cataclysmic explosions of supernovae.

- In the supernova explosion, a large flux of energetic neutrons is produced and nuclei bombarded by these neutrons build up mass one unit at a time (neutron capture) producing heavy nuclei.

- The layers containing the heavy elements can then be blown off be the explosion to provide the raw material of heavy elements in distant hydrogen clouds where new stars form.

Courtesy NASA
Neutron Capture & Radioactive Decay

- Neutron capture in supernova explosions produces some unstable nuclei.
- These nuclei radioactively decay until a stable isotope is reached.

Nucleosynthesis by Neutron Capture

Construction of elements beyond iron involves the capture of a neutron to produce isophotes. Unstable isotopes decay into new elements.

Atomic mass = Number of protons + Neutrons

Atomic number = Numbers of protons

Element name

<table>
<thead>
<tr>
<th>Neutron capture</th>
<th>Stable isotope</th>
<th>Unstable isotope</th>
<th>Radioactive decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{110}\text{Cd}_{48} + ^1\text{n}<em>0 \rightarrow ^{111}\text{Cd}</em>{48}$</td>
<td>$^{111}\text{Cd}_{48} + ^1\text{n}<em>0 \rightarrow ^{112}\text{Cd}</em>{48}$</td>
<td>$^{113}\text{Cd}_{48} + ^1\text{n}<em>0 \rightarrow ^{114}\text{Cd}</em>{48}$</td>
<td>$^{115}\text{Cd}<em>{48} \rightarrow ^{115}\text{In}</em>{49} + e^- + \nu$</td>
</tr>
</tbody>
</table>

Image by MIT OpenCourseWare.
Cosmic Abundance of the Elements

- H (73%) & He (25%) account for 98% of all nuclear matter in the universe.
- Low abundances of Li, Be, B due to high combustibility in stars.
- High abundance of nuclei w/ mass divisible by $^4$He: C, O, Ne, Mg, Si, S, Ar, Ca
- High Fe abundance due to max binding energy.
- Even heavy nuclides favored over odd due to lower “neutron-capture cross-section” (smaller target = higher abundance).
- All nuclei with >209 particles ($^{209}$Bi) are radioactive.

Note that this is the inverse of the binding energy curve.

No stable isotopes of: Technetium (43) or Prometheum (59)

The "cosmic" abundance of the elements is derived from spectroscopic studies of the sun supplemented by chemical analyses of chondritic meteorites.

Magic neutron #’s 82 & 126 are unusually stable

Planet-building elements: O, Mg, Si, Fe

Image by MIT OpenCourseWare.
Basics of Geology
Lithosphere & Asthenosphere

Mantle and Crust
Lithosphere/Asthenosphere
   Outer 660 km divided into two layers based on mechanical properties
     Lithosphere
        Rigid outer layer including crust and upper mantle
        Averages 100 km thick; thicker under continents
     Asthenosphere
        Weak, ductile layer under lithosphere
        Lower boundary about 660 km (entirely within mantle)

The Core
   Outer Core
      ~2300 km thick
      Liquid Fe with Ni, S, O, and/or Si
      Magnetic field is evidence of flow
      Density ~ 11 g/cm³
   Inner Core
      ~1200 km thick
      Solid Fe with Ni, S, O, and/or Si
      Density ~13.5 g/cm³

Earth’s Interior: How do we know its structure?
   Avg density of Earth (5.5 g/cm³)
   Denser than crust & mantle
   Composition of meteorites
   Seismic wave velocities
   Laboratory experiments
   Chemical stability
   Earth’s magnetic field
Earth’s Surface

Principle Features of Earth’s Surface

Continent
  Shield--Nucleus of continent composed of Precambrian rocks
Continent-Ocean Transition
  Continental shelf--extension of continent
  Continental slope--transition to ocean basin

Ocean basin--underlain by ocean crust
  Why do oceans overlie basaltic crust?
Mid-ocean ridge
  Mountain belt encircling globe
  Ex: Mid-Atlantic Ridge, East Pacific Rise
Deep-ocean trenches
  Elongate trough
  Ex: Peru-Chile trench
3° Crust = Formed from slow, continuous distillation by volcanism on a geologically active planet (i.e., plate tectonics).
• Results in highly differentiated magma distinct from basalt--the low-density, light-colored granite.
• Earth may be the only planet where this type of crust exists.
• Unlike 1° & 2° crusts, which form in < 200 M.y., 3° crusts evolve over billions of years.

Crustal Growth has proceeded in episodic fashion for billions of years. An important growth spurt lasted from about 3.0 to 2.5 billion years ago, the transition between the Archean and Proterozoic eons. Widespread melting at this time formed the granite bodies that now constitute much of the upper layer of the continental crust.

Igneous Rocks

Basalt
(2° Crust; Oceanic crust)

Granite
(1° Crust; Continental Crust)

Photograph of basalt courtesy United States Geological Survey.
Photograph of rhyolite courtesy James St. John.
Photograph of gabbro courtesy Mark A. Wilson.
Photograph of granite courtesy James Bowe.
### The Crust

**Ocean Crust**
- 3-15 km thick
- Basaltic rock
- Young (<180 Ma)
- Density ~ 3.0 g/cm³

**Continental Crust**
- 35 km average thickness
- Granitic rock
- Old (up to 3.8 Ga)
- Density ~ 2.7 g/cm³

Crust "floating" on "weak" mantle

### The Mantle

- ~2900 km thick
- Comprises >82% of Earth’s volume
- Mg-Fe silicates (rock)
- Two main subdivisions:
  - Upper mantle (upper 660 km)
  - Lower mantle (660 to ~2900 km; "Mesosphere")
Structure of Earth

[Diagram of Earth's structure with labels for different layers such as crust, mantle, core, and lithosphere.]

Figure courtesy United States Geologic Society.

Why is Continental Crust “Elevated Relative to Oceanic Crust?"

- High-density Basalt sinks into mantle more than low-density Granite.
- Volcanism continually produces highly differentiated continental crust on Earth.
- Venus surface appears to be all basalt.
- Plate tectonics & volcanism do not appear to be happening on Venus (or Mars, Moon).
- So Earth may be unique in Solar System. And plate tectonics & volcanism likely critical in determining habitability.


Lithospheric Plates

- 8 large plates (+ add’l. small ones)
- Average speed: 5 cm/yr
- 3 types of motion result in 3 types of boundaries: sliding toward (subduction zones), sliding away (ridge axes), skiding along (transform faults)
Convection Drives Plate Movements

Courtesy NASA
Magma rises along fractures

Asthenosphere source of basaltic magma

Subduction zone with volcanism

Magma from remelting lithosphere rises through felsic crust to feed volcanic chain

Felsic continental crust

Basaltic oceanic crust

Basaltic lava rises into Mid-Atlantic Ridge

Image by MIT OpenCourseWare.
Rock Basics

Igneous + metamorphic
= Crystalline Rocks

Image by MIT OpenCourseWare.
The Rock Cycle

Igneous rock

Inactive volcanoes

Volcano

Intrusion

Sedimentary rock

Erosion

Metamorphic rock

Sediments

Image by MIT OpenCourseWare.
- **Felsic**: Si-, Al-rich. Light-colored, low-density. Feldspar (pink) & quartz (SiO₂)-rich. Most continental crust. Granite most abundant.
- **Mafic**: Mg-, Fe-rich. Dark-colored, high-density. Most oceanic crust. Ultramafic rock (more dense) forms mantle below crust.
- **Extrusive**: cools rapidly; small crystals
- **Intrusive**: cools slowly; large crystals

---

**Basalt**

(2° Crust; Oceanic crust)

• Slab of lithosphere is subducted, melted & incorporated into asthenosphere
• Convection carries molten material upward where it emerges along a spreading zone as new lithosphere.

- Subducted sediment melts at a shallower depth where it contributes to magma emitted from an island arc volcano and a mountain chain volcano
- Erosion of volcanic rock provides sediment to complete cycle

Figure courtesy Jose F. Virgil, United States Geological Survey.
Sedimentary Rocks Represent Homogenous Mixture of Continental Crust

RARE-EARTH ELEMENT abundance patterns provide characteristic chemical markers for the types of rock that have formed the earth’s crust. Although igneous rocks (those that solidify from magma) can have highly variable rare-earth element signatures (dotted lines), the pattern for most sedimentary rocks falls within a narrow range (gray band). This uniformity of composition can record the average composition of the upper continental crust.
A major difference between geologists and most other scientists is their attitude about time.

A "long" time may not be important unless it is > 1 million years.

Source: www.SnowballEarth.org
Absolute Calibration: Geochronology

- Add numbers to the stratigraphic column based on fossils.
- Based on the regular radioactive decay of some chemical elements.
Radioactive Decay of Rubidium to Strontium

Rubidium-87 (nucleus) is a parent with 37 protons and 50 neutrons. It decays into Strontium-87 (nucleus) with 38 protons and 49 neutrons, emitting an electron and a neutrino in the process.

Image by MIT OpenCourseWare.
Proportion of Parent Atoms Remaining as a Function of Time

Image by MIT OpenCourseWare.
Isotopic dating

- Radioactive elements (parents) decay to nonradioactive (stable) elements (daughters).
- The rate at which this decay occurs is constant and knowable.
- Therefore, if we know the rate of decay and the amount present of parent and daughter, we can calculate how long this reaction has been proceeding.
### Major Radioactive Elements Used in Isotopic Dating

<table>
<thead>
<tr>
<th>ISOTOPES</th>
<th>PARENT</th>
<th>DAUGHTER</th>
<th>HALF-LIFE OF PARENT (YEARS)</th>
<th>EFFECTIVE DATING RANGE (YEARS)</th>
<th>MINERALS AND OTHER MATERIALS THAT CAN BE DATED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium-238</td>
<td>Lead-206</td>
<td>4.5 billion</td>
<td>10 million - 4.6 billion</td>
<td>Zircon</td>
<td>Uraninite</td>
</tr>
<tr>
<td>Potassium-40</td>
<td>Argon-40</td>
<td>1.3 billion</td>
<td>50,000 - 4.6 billion</td>
<td>Muscovite</td>
<td>Biotite</td>
</tr>
<tr>
<td>Rubidium-87</td>
<td>Strontium-87</td>
<td>47 billion</td>
<td>10 million - 4.6 billion</td>
<td>Muscovite</td>
<td>Biotite</td>
</tr>
<tr>
<td>Carbon-14</td>
<td>Nitrogen-14</td>
<td>5730</td>
<td>100 - 70,000</td>
<td>Wood, charcoal, peat</td>
<td>Bone and tissue</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Shell and other calcium carbonate</td>
<td>Groundwater, ocean water, and glacier ice containing dissolved carbon dioxide</td>
</tr>
</tbody>
</table>

Image by MIT OpenCourseWare.
Geologically Useful Decay Schemes

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Decay Product</th>
<th>Half-life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}\text{U}$</td>
<td>$^{207}\text{Pb}$</td>
<td>$0.71 \times 10^9$</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>$^{206}\text{Pb}$</td>
<td>$4.5 \times 10^9$</td>
</tr>
<tr>
<td>$^{40}\text{K}$</td>
<td>$^{40}\text{Ar}$</td>
<td>$1.25 \times 10^9$</td>
</tr>
<tr>
<td>$^{87}\text{Rb}$</td>
<td>$^{87}\text{Sr}$</td>
<td>$47 \times 10^9$</td>
</tr>
<tr>
<td>$^{14}\text{C}$</td>
<td>$^{14}\text{N}$</td>
<td>5730</td>
</tr>
</tbody>
</table>
From dendrochronology to geochronology

• Tree rings can be dated with $^{14}$C to calibrate them

• Radiocarbon can only be used to date organic material (plant or animal) younger than ~ 60,000 yrs

• For rocks and older material, we need other methods: e.g. uranium/lead

Photograph courtesy of Henri D. Grissino-Mayer. Used with permission.
Two ways to date geologic events

1) relative dating (fossils, structure)
2) absolute dating (isotopic, tree rings, etc.)
Amount of Time Required for Some Geologic Processes and Events

<table>
<thead>
<tr>
<th>Time in years</th>
<th>Process or Event</th>
<th>Timekeeping Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>One billion years</td>
<td>Age of the earth</td>
<td>Radioactive decay</td>
</tr>
<tr>
<td></td>
<td>Time for mountain range to be uplifted 3000m at 0.2mm/year</td>
<td>Only micro organism fossils</td>
</tr>
<tr>
<td>One million years</td>
<td>Time for the Atlantic ocean to widen 1 km at 4cm/year</td>
<td>Historical records</td>
</tr>
<tr>
<td>One thousand years</td>
<td>Human Lifetime</td>
<td>Calendars</td>
</tr>
<tr>
<td>One year</td>
<td>Measurable erosion of rivers and shorelines</td>
<td>Clocks</td>
</tr>
<tr>
<td>One month</td>
<td>Floods</td>
<td></td>
</tr>
<tr>
<td>One day</td>
<td></td>
<td></td>
</tr>
<tr>
<td>One hour</td>
<td></td>
<td></td>
</tr>
<tr>
<td>One minute</td>
<td>Earthquake waves go through and around earth</td>
<td></td>
</tr>
<tr>
<td>One second</td>
<td></td>
<td></td>
</tr>
<tr>
<td>One thousand of a second</td>
<td>Time for one sound wave detectable by human ears</td>
<td>Nuclear Processes</td>
</tr>
</tbody>
</table>

Image by MIT OpenCourseWare.
Some geologic processes can be documented using historical records

The present pattern of erosion is shown on the map on the right. Red shows shoreline undergoing wave erosion; green shows shoreline undergoing deposition.

About 6,000 years ago, before extensive wave erosion of the glacial deposits had occurred, glacial Cape Cod probably resembled the green area as shown on the left map.

Ammonite Fossils

Photographs courtesy Smabs Sputzer and Candie_N

Petrified Wood
Steno's Laws

Nicolaus Steno (1669)

- Principle of Superposition
- Principle of Original Horizontality
- Principle of Lateral Continuity

Laws apply to both sedimentary & volcanic rocks.
Principle of Superposition

In a sequence of undisturbed layered rocks, the oldest rocks are on the bottom.
Principle of Superposition

Photograph courtesy Mark A. Wilson
Principle of Original Horizontality

Layered strata are deposited horizontal or nearly horizontal or nearly parallel to the Earth’s surface.
Principles of original horizontality and superposition

Sedimentation in lake or sea

Older

Younger

Image by MIT OpenCourseWare.
Principle of Lateral Continuity

Layered rocks are deposited in continuous contact.
Using Fossils to Correlate Rocks

Outcrops may be separated by a long distance.
William (Strata) Smith

- The Principle of Faunal Succession, first geological map ever (UK)
Disconformity and Unconformity

A buried surface of erosion
Formation of a Disconformity

Sedimentation of beds A-D beneath the sea

Continual erosion strips D away completely and exposes C to erosion

Uplift above sea level and exposure of D to erosion

Subsidence below the sea and sedimentation of E over C; erosion surface of C preserved as an unconformity

Image by MIT OpenCourseWare.
Rocks Exposed in the Grand Canyon

Photography courtesy Grand Canyon National Park.
Generalized Stratigraphic Section of Rocks Exposed in the Grand Canyon

Figure courtesy National Park Service.
Some of the Geologic Units Exposed in the Grand Canyon

Photograph of the Grand Canyon removed due to copyright restriction.

Annotated photograph of the Grand Canyon with labeled rock formations.
South Rim of the Grand Canyon

Photography courtesy [Grand Canyon National Park](https://www.nps.gov/).
South rim of the Grand Canyon

The nonconformity of the Grand Canyon is outlined.
The Great Unconformity of the Grand Canyon

Photograph courtesy Chris M. Morris
Angular Unconformity at Siccar Point

Photograph courtesy Lysippos.
Sedimentation of Beds A-D Beneath the Sea

Image by MIT OpenCourseWare
Deformation and Erosion During Mountain Building
Uniformitarianism

— James Hutton


His theories of geology and geologic time, also called deep time came to be included in theories which were called plutonism and uniformitarianism.

He is also credited as the first scientist to publicly express the Earth was alive and should be considered a superorganism.

Hutton reasoned that there must have been innumerable cycles, each involving deposition on the seabed, uplift with tilting and erosion then undersea again for further layers to be deposited. On the belief that this was due to the same geological forces operating in the past as the very slow geological forces seen operating at the present day, the thicknesses of exposed rock layers implied to him enormous stretches of time.
Many methods have been used to determine the age of the Earth

1) Bible: In 1664, Archbishop Usher of Dublin used chronology of the Book of Genesis to calculate that the world began on Oct. 26, 4004 B.C.

2) Salt in the Ocean: (ca. 1899) Assuming the oceans began as fresh water, the rate at which rivers are transporting salts to the oceans would lead to present salinity in ~100 m.y.
Many methods have been used to determine the age of the Earth

3) Sediment Thickness: Assuming the rate of deposition is the same today as in the past, the thickest sedimentary sequences (e.g., Grand Canyon) would have been deposited in \( \sim 100 \text{ m.y.} \)

4) Kelvin’s Calculation: (1870): Lord Kelvin calculated that the present geothermal gradient of \( \sim 30^\circ \text{C/km} \) would result in an initially molten earth cooled for \( 30 - 100 \text{ m.y.} \)
Oldest rocks on Earth

Slave Province, Northern Canada

- Zircons in a metamorphosed granite dated at 4.03 Ga by the U-Pb method

Yilgarn block, Western Australia

- Detrital zircons in a sandstone dated at 4.4 Ga by U-Pb method.

Several other regions dated at 3.8 Ga by various methods including Minnesota, Wyoming, Greenland, South Africa, and Antarctica.
The geologic timescale and absolute ages

Isotopic dating of intebedded volcanic rocks allows assignment of an absolute age for fossil transitions
The big assumption

The half-lives of radioactive isotopes are the same as they were billions of years ago.
Test of the assumption

Meteorites and Moon rocks (that are thought to have had a very simple history since they formed), have been dated by up to 10 independent isotopic systems all of which have given the same answer. However, scientists continue to critically evaluate this data.
Frequently used decay schemes have half-lives which vary by a factor of > 100

<table>
<thead>
<tr>
<th>Element</th>
<th>Half-life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U}$</td>
<td>4.5 x $10^9$</td>
</tr>
<tr>
<td>$^{235}\text{U}$</td>
<td>0.71 x $10^9$</td>
</tr>
<tr>
<td>$^{40}\text{K}$</td>
<td>1.25 x $10^9$</td>
</tr>
<tr>
<td>$^{87}\text{Rb}$</td>
<td>47 x $10^9$</td>
</tr>
<tr>
<td>$^{147}\text{Sm}$</td>
<td>106 x $10^9$</td>
</tr>
</tbody>
</table>
Minerals with no initial daughter

- $^{40}$K decays to $^{40}$Ar (a gas)
- Zircon: $\text{ZrSiO}_4$

<table>
<thead>
<tr>
<th>ion</th>
<th>radius (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zr$^{4+}$</td>
<td>0.92</td>
</tr>
<tr>
<td>U$^{4+}$</td>
<td>1.08</td>
</tr>
<tr>
<td>Pb$^{2+}$</td>
<td>1.37</td>
</tr>
</tbody>
</table>
World’s Oldest Rock: Acasta Gneiss

Photograph courtesy Ellenm1.
Acasta Zircon (Ages in My)

Photograph of Acasta Zircon removed due to copyright restriction.

~300 μm zircon crystal, SAB94-134, Grain 1, with ages of 4036, 4029, 3846, 2998, 4014, 3971, 4028, 3984 (ages in millions of years).
Figure of North American craton removed due to copyright restriction.

Image courtesy R. Clucas.
Zircons: Nature’s Time Capsules

Microscope photograph of zircons removed due to copyright restrictions.
The Geologic time scale

Figure courtesy Geological Society of America. Used with permission.
The Eras of the Phanerozoic

Figure 1 Genus diversity. a, The green plot shows the number of known marine animal genera versus time from Sepkoski’s compendium1, converted to the 2004 Geologic Time Scale5. b, The black plot shows the same data, with single occurrences and poorly dated genera removed. The trend line (blue) is a third-order polynomial fitted to the data. c, As b, with the trend subtracted and a 62-Myr sine wave superimposed. d, The detrended data after subtraction of the 62-Myr cycle and with a 145-Myr sine wave superimposed. Dashed vertical lines indicate the times of the five major extinctions2. e, Fourier spectrum of c. Curves W (in blue) and R (in red) are estimates of spectral background. Conventional symbols for major stratigraphic periods are shown at the bottom.

Also see: Phillips, John. Life on the earth: its origin and succession. 1860.
A Revised Geological Time-Scale

Photograph in the public domain.

Image by MIT OpenCourseWare.
Figure courtesy Sam Bowring.
Paleontology

The study of life in the past based on fossilized plants and animals.

: Evidence of past life

Fossils preserved in sedimentary rocks are used to determine:
1) Relative age
2) Environment of deposition
Photograph courtesy Kevin Walsh.
Photograph courtesy Black Country Museums.
Fossil Sycamore-like Leaf (Eocene)

Photograph courtesy Daderot.
• Tree rings can be counted and dated with $^{14}$C to calibrate them
• Radiocarbon can only be used to date organic material (plant or animal) younger than ~ 60,000 yrs
• For rocks and older material, we need other methods: e.g. uranium/lead

Photograph courtesy of [Henri D. Grissino-Mayer.](#) Used with permission.

### Isotopic Dating

• Radioactive elements (parents) decay to nonradioactive (stable) elements (daughters).
• The rate at which this decay occurs is constant and knowable.
• Therefore, if we know the rate of decay and the amount present of parent and daughter, we can calculate how long this reaction has been proceeding.