Geobiology 2013

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

Textbook: The Earth System, Lee R. Kump, James F. Kasting & Robert G. Crane. Earth System History, Steven M. Stanley. The following books will also be on reserve in Hayden Library:. Brock Biology of Microorganisms, Madigan, Martinko and Parker, F. M. M. Morel and J. Hering, Principles and Applications of Aquatic Chemistry

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

The Spark of Life, Christopher Wills & Jeffrey Bada (Perseus, Cambridge, MA, 2000).
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:

Langmuir, Charles Herbert, and Wallace Smith Broecker. *How to build a habitable planet*. Princeton University Press, 2012.

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]

Committee on the Limits of Organic Life in Planetary Systems. *The Limits of Organic Life in Planetary Systems*. National Academies Press, 2007.

“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.

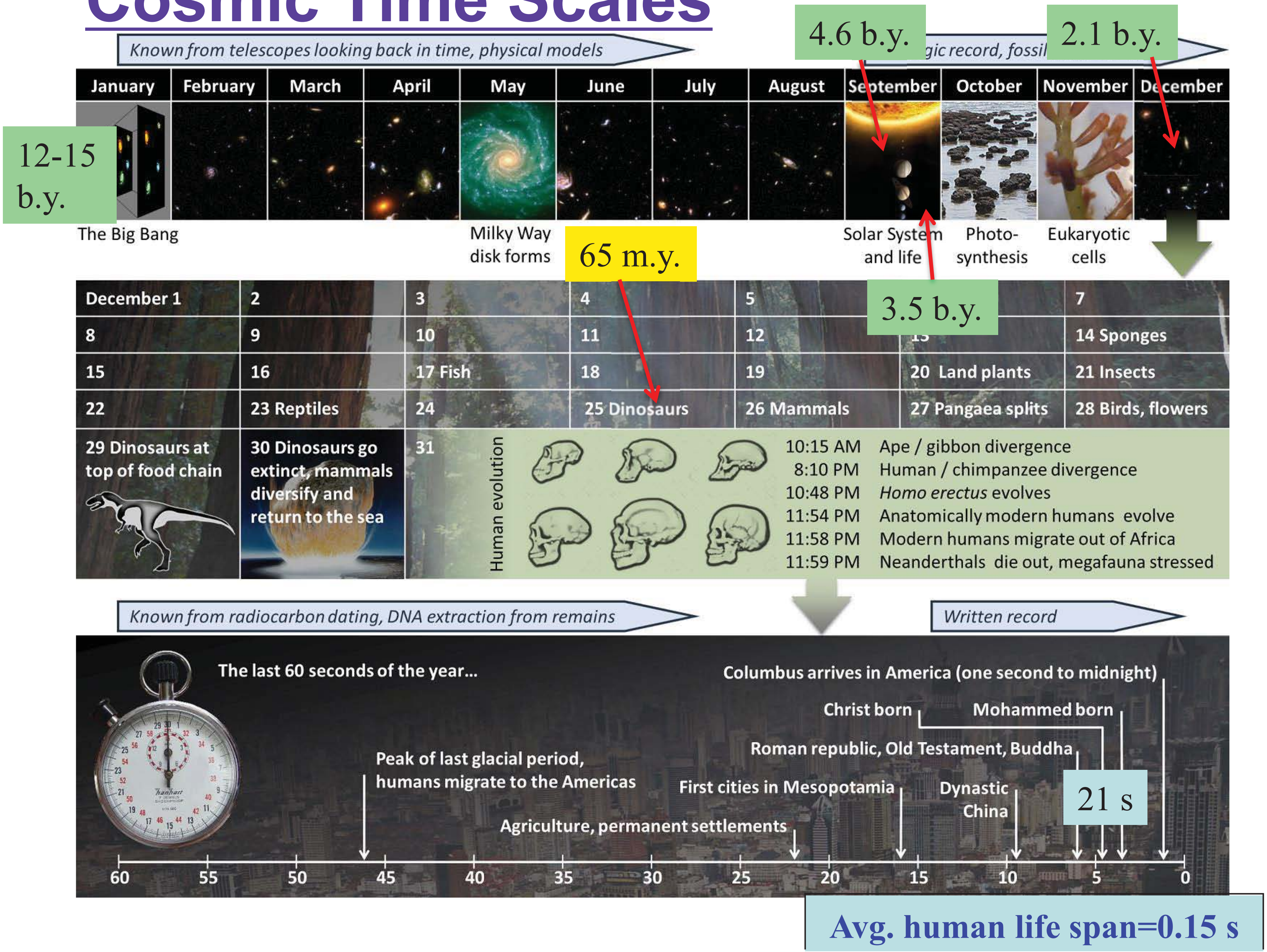
The canonical characteristics of life are inherent capacities to adapt to changing environmental conditions and to increase in complexity by multiple mechanisms, particularly by interactions with other living organisms.

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



Courtesy of Eric Fisk. Used with permission.

Earth's Geologic Clock

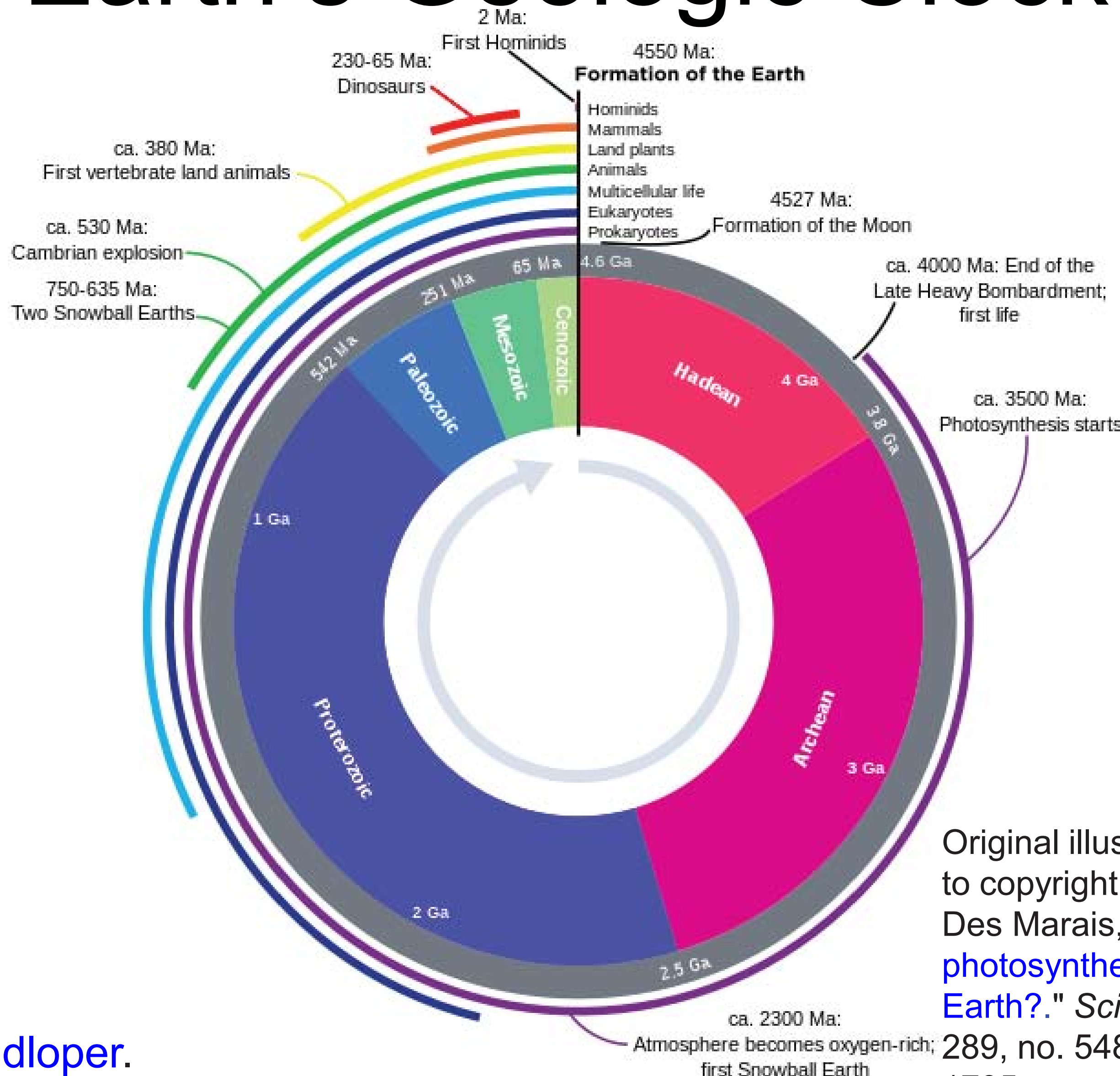


Image by Woudloper.

Original illustration removed due to copyright restriction.
Des Marais, David J. "When did photosynthesis emerge on Earth?." *Science (Washington)* 289, no. 5485 (2000): 1703-1705.

The standard cosmological model of the formation of the universe:

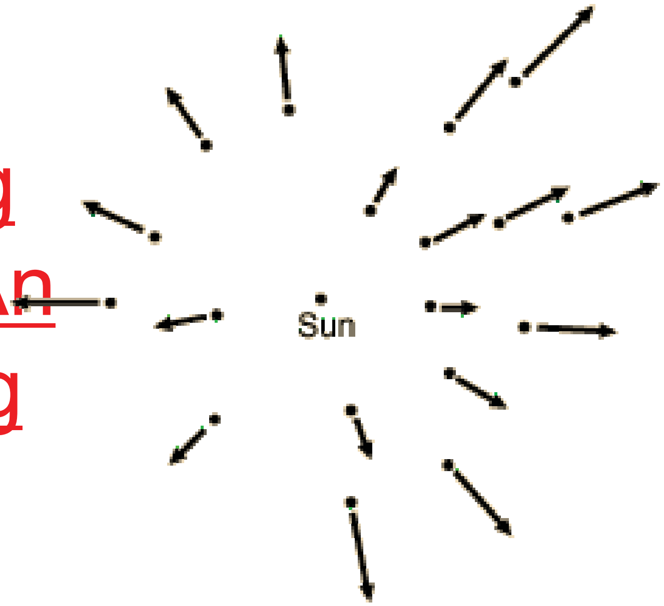
"The Big Bang"

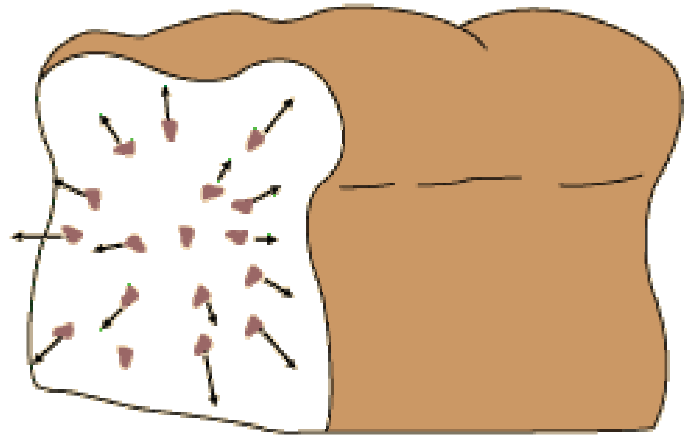
New NASA Speak: The *theory of* The Big Bang

- From: *The First Three Minutes*, by Steven Weinberg

Time	T(K)	E	Density	What's Happening?
.02 s	10^{11} K	6.6 MeV	4×10^{9}	The universe is mostly light. Electrons and positrons created from light (pair-production) and destroyed at about equal rates. Protons and neutrons being changed back and forth, so about equal numbers. Only about one neutron or proton for each 10^9 photons.
.11 s	3×10^{10}	2.6 MeV		Free neutrons decaying into protons, so there begins to be an excess of protons over neutrons.
1.09 s	10^{10} K	860 KeV	4×10^{5}	Primeval fireball 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.
13.8s	3×10^{9}	260 KeV		Below pair-production threshold
3 m 2 s	10^{9} K	86 KeV		Electrons and positrons nearly all gone. Photons and neutrinos are main constituents of the universe. Neutron decay leaves 86% protons, 14% neutrons but these represent a small fraction of the energy of the universe.
3 m 46s	0.9×10^{9} K	78 KeV		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.
34m 40 s	3×10^{8}	26 KeV	10	Nuclear processes are stopped, expansion and cooling continues. About 1 in 10^9 electrons left because of a slight excess of electrons over positrons in the primeval fireball.
7×10^{5} yrs	3000 K	0.26 eV		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.
10^{10} yrs	3K			Living beings begin to analyze this process.

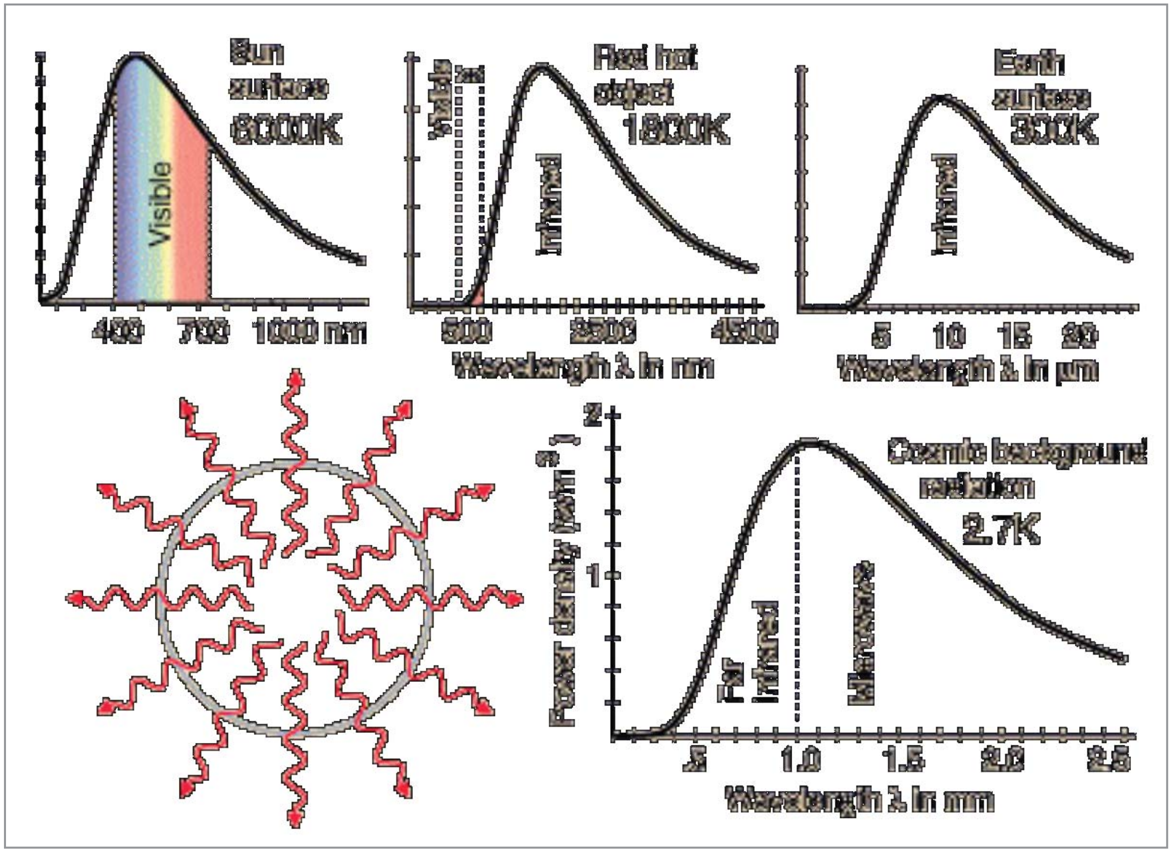
Evidence for the Big Bang #1: An Expanding Universe





- 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

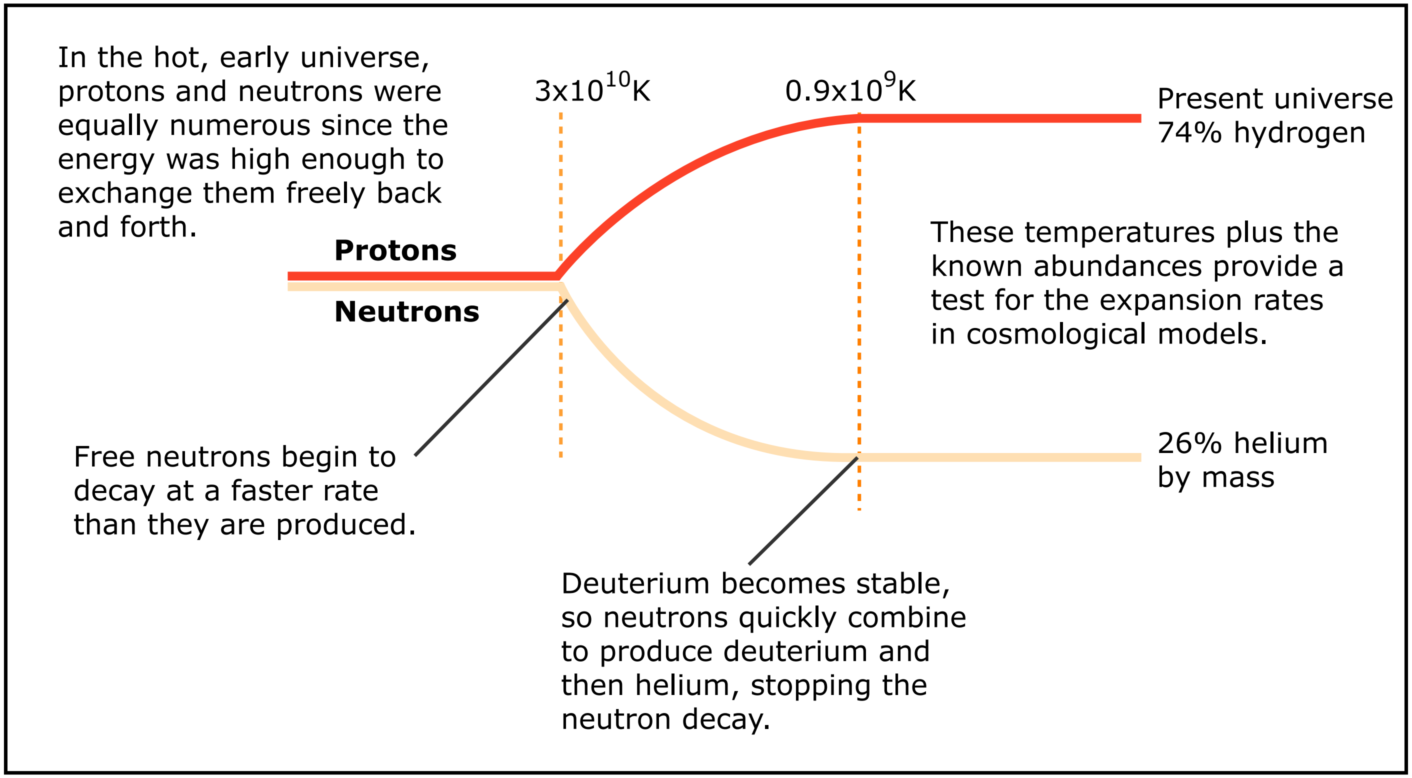


Image by MIT OpenCourseWare.

- 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.

Nucleosynthesis

Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo

Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Source: wikimedia user Cepheus. Image in the public domain.

Nucleosynthesis I: Fusion Reactions in Stars

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

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.

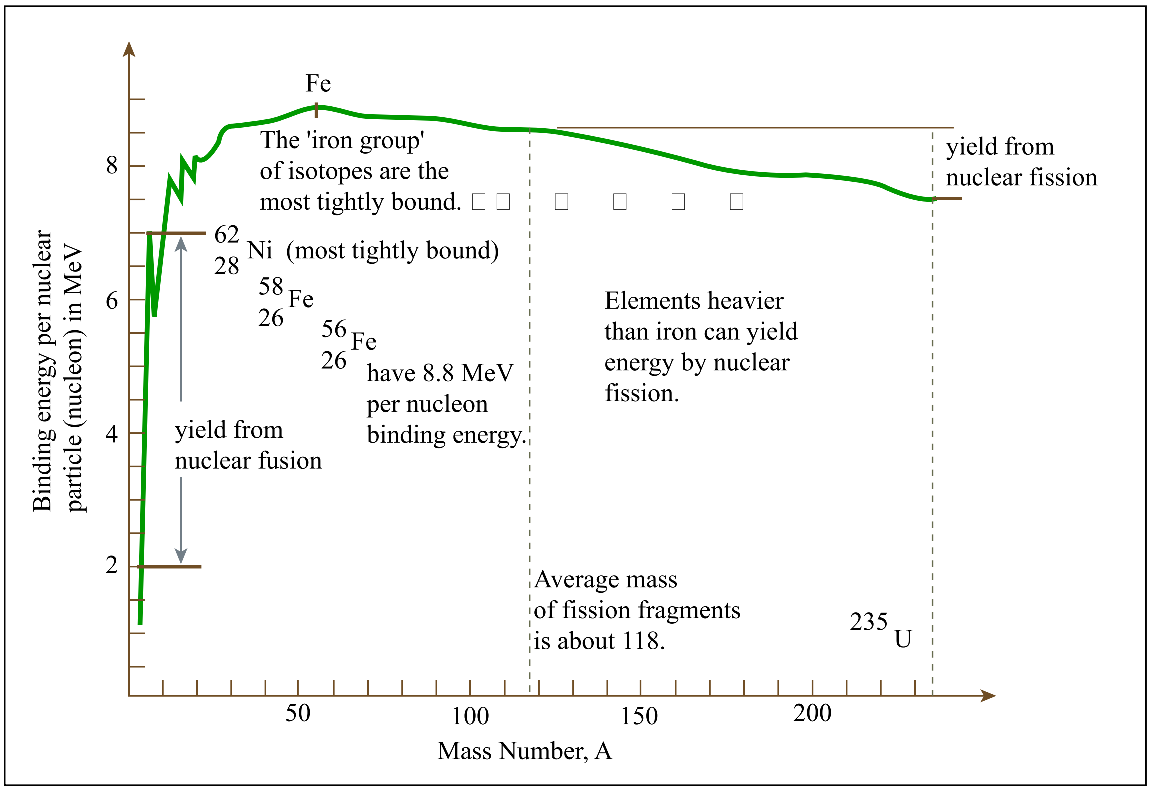


Image by MIT OpenCourseWare.

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.

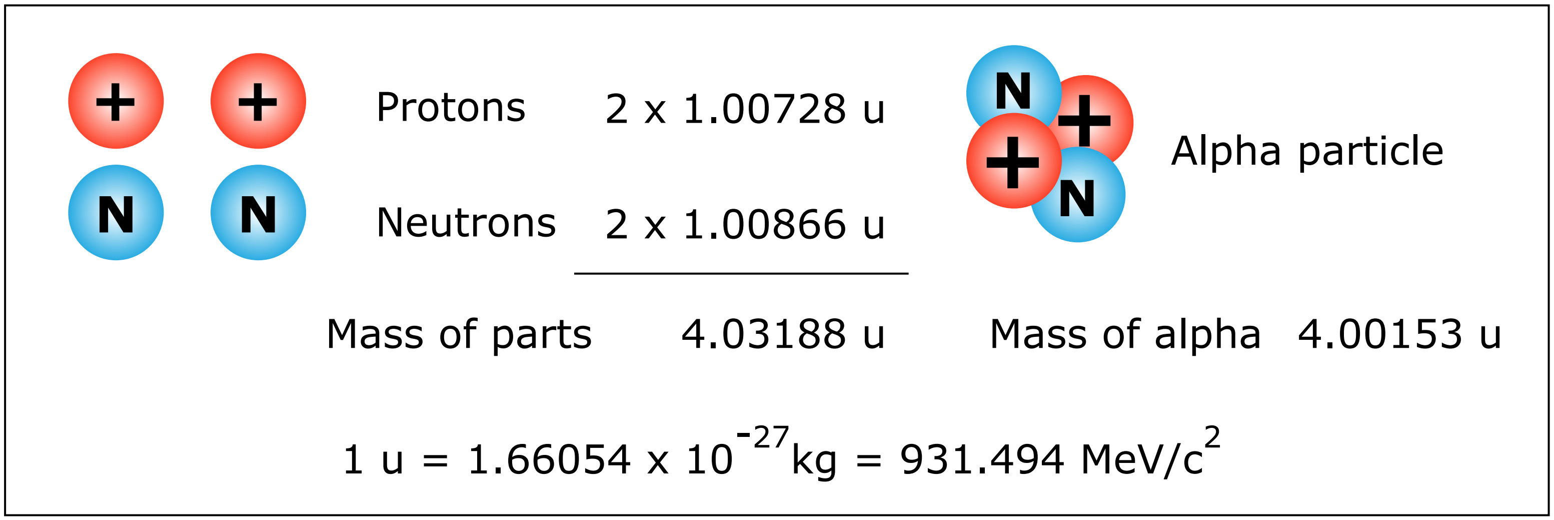


Image by MIT OpenCourseWare.

•BE can be calculated from the relationship: BE = Δmc^2

•For α particle, Δm= 0.0304 u, yielding BE=28.3 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

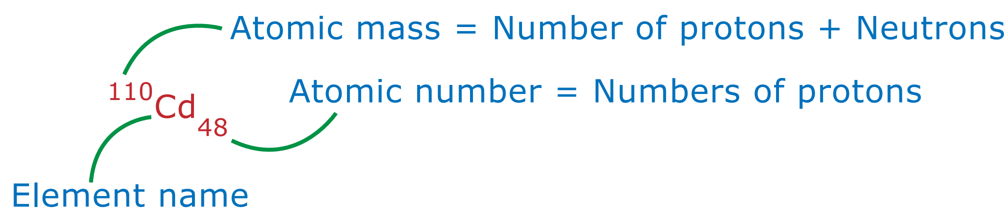
Neutron Capture & Radioactive Decay

- 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



$^{110}Cd_{48} + {}^{1}n_{0} \longrightarrow {}^{111}Cd_{48}$	Neutron capture
$^{111}Cd_{48} + {}^{1}n_{0} \longrightarrow {}^{112}Cd_{48}$	Stable isotope
$^{112}Cd_{48} + {}^{1}n_{0} \longrightarrow {}^{113}Cd_{48}$	Stable isotope
$^{113}Cd_{48} + {}^{1}n_{0} \longrightarrow {}^{114}Cd_{48}$	Stable isotope
$^{114}Cd_{48} + {}^{1}n_{0} \longrightarrow {}^{115}Cd_{48}$	Unstable isotope
$^{115}Cd_{48} \longrightarrow {}^{115}In_{49} + e^{-} + \nu$	Radioactive decay

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.

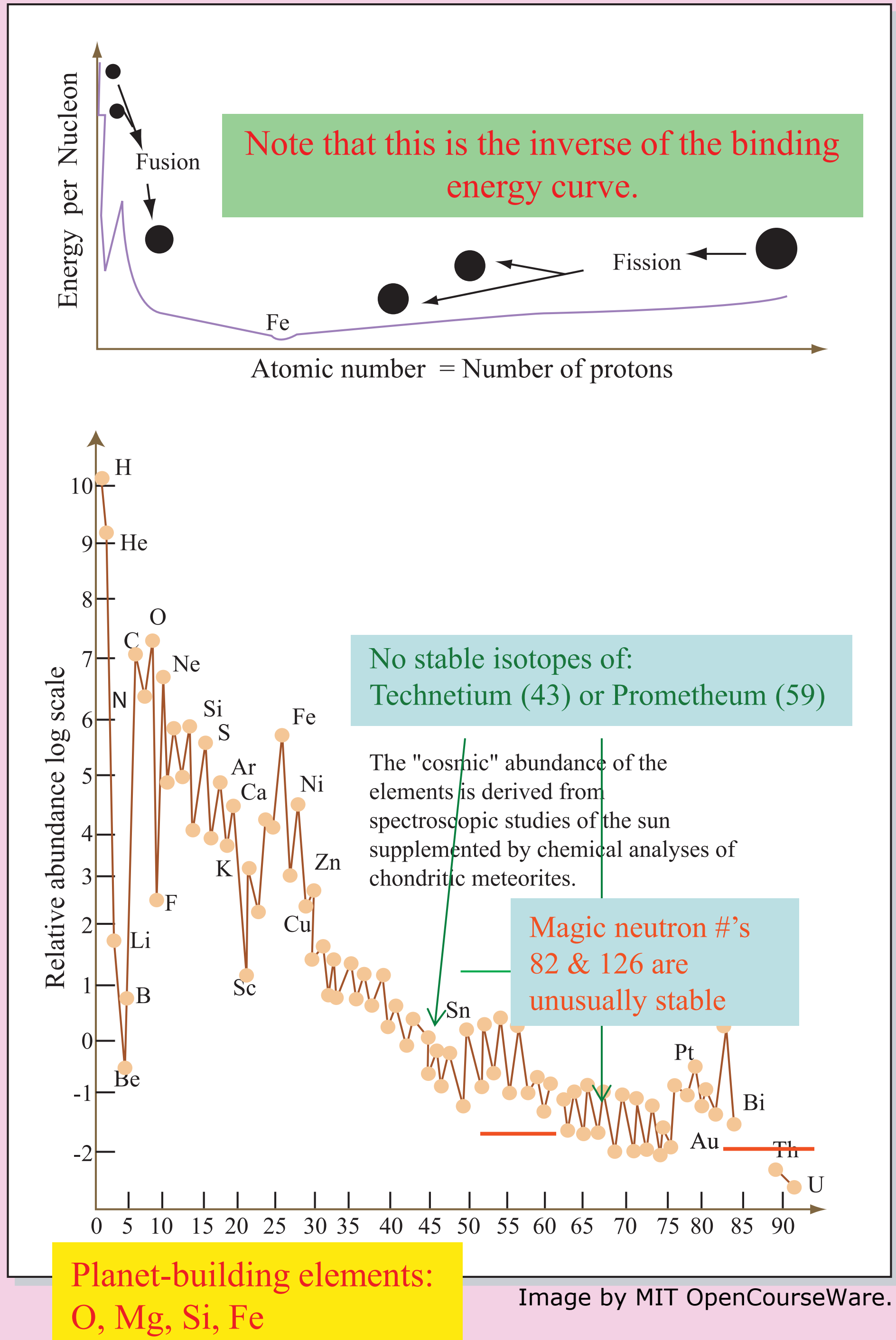


Image by MIT OpenCourseWare.

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/cm^3)
- 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

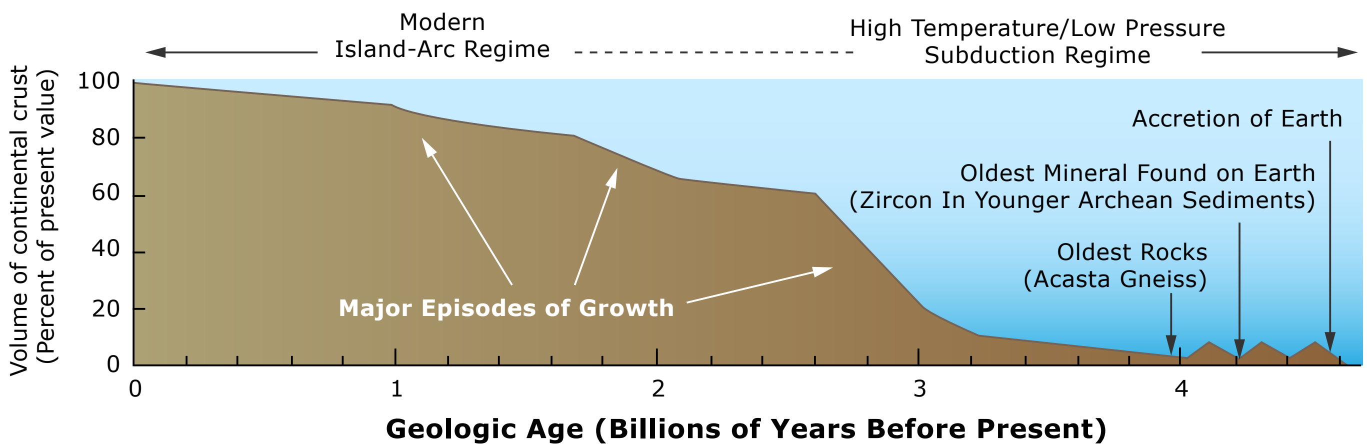
Earth's Crustal Evolution: 2

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.

Image by MIT OpenCourseWare. After Taylor, S. Ross, and Scott M. McLennan. "The Evolution of Continental Crust." *Scientific American* 274 (1996): 76-81.

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 & Mantle

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

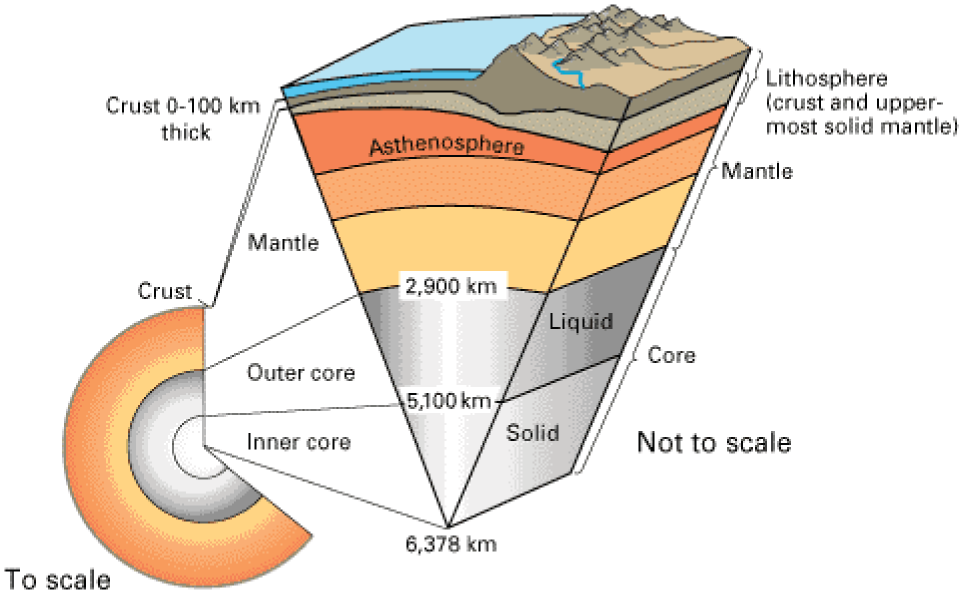


Figure courtesy United States Geologic Society.

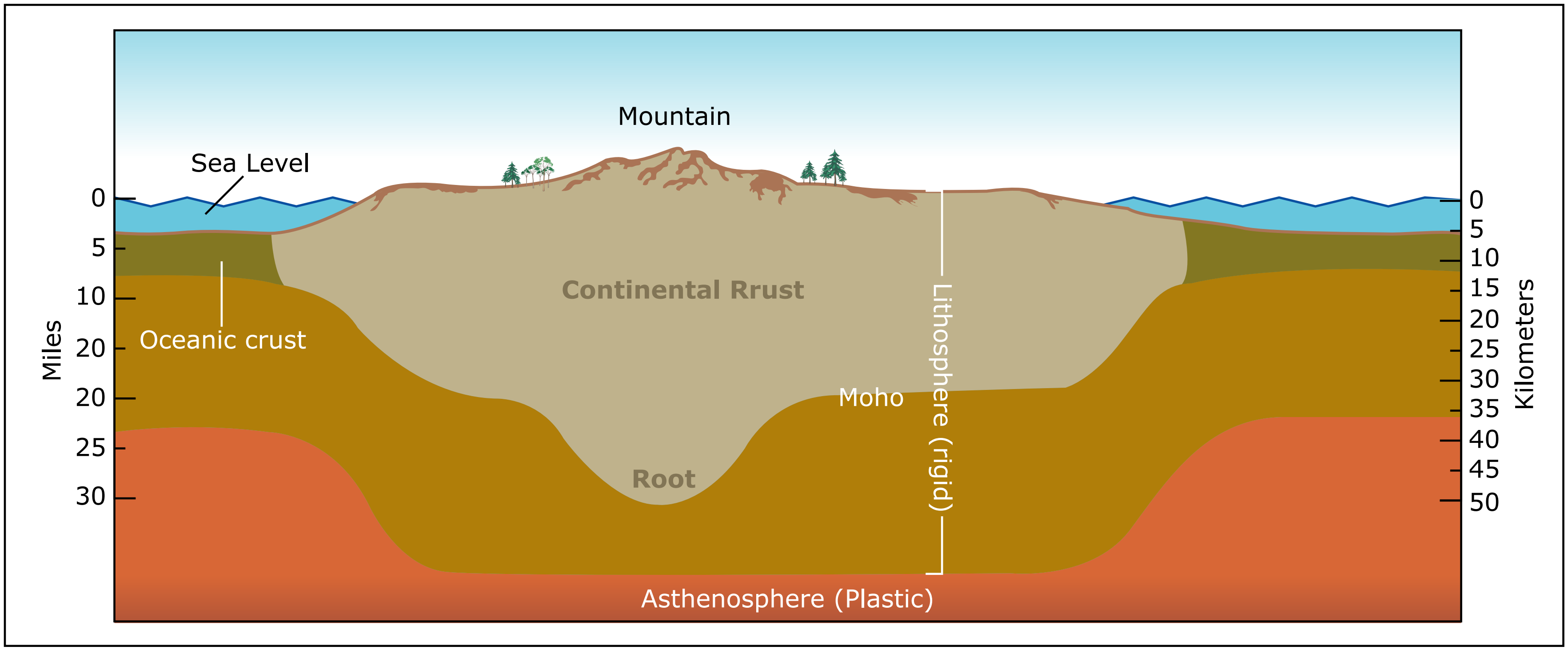
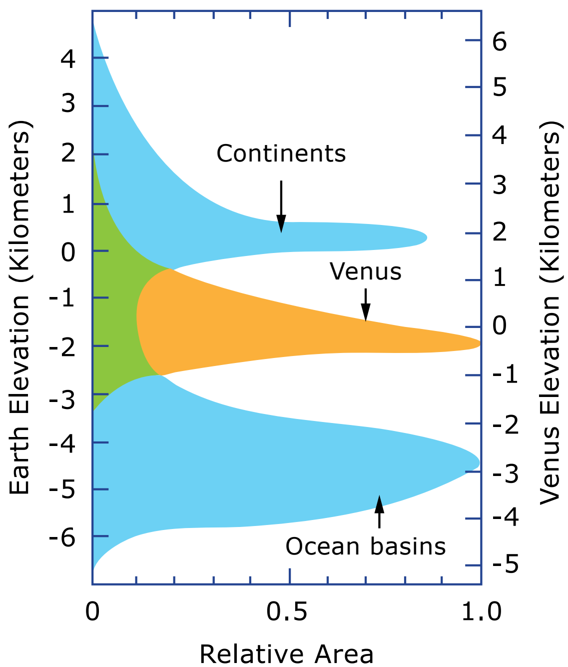


Image by MIT OpenCourseWare. After Stanley, Steven M. Earth system history. W.H. Freeman and Company, 2005.

Why is Continental Crust "Elevated Relative to Oceanic Crust?



SURFACE ELEVATIONS are distributed quite differently on the earth (blue) and on Venus (gold). Most places on the earth stand near one of two prevailing levels. In contrast, a single height characterizes most of the surface of Venus, (Elevation on Venus is given with respect to the planet's mean radius.)

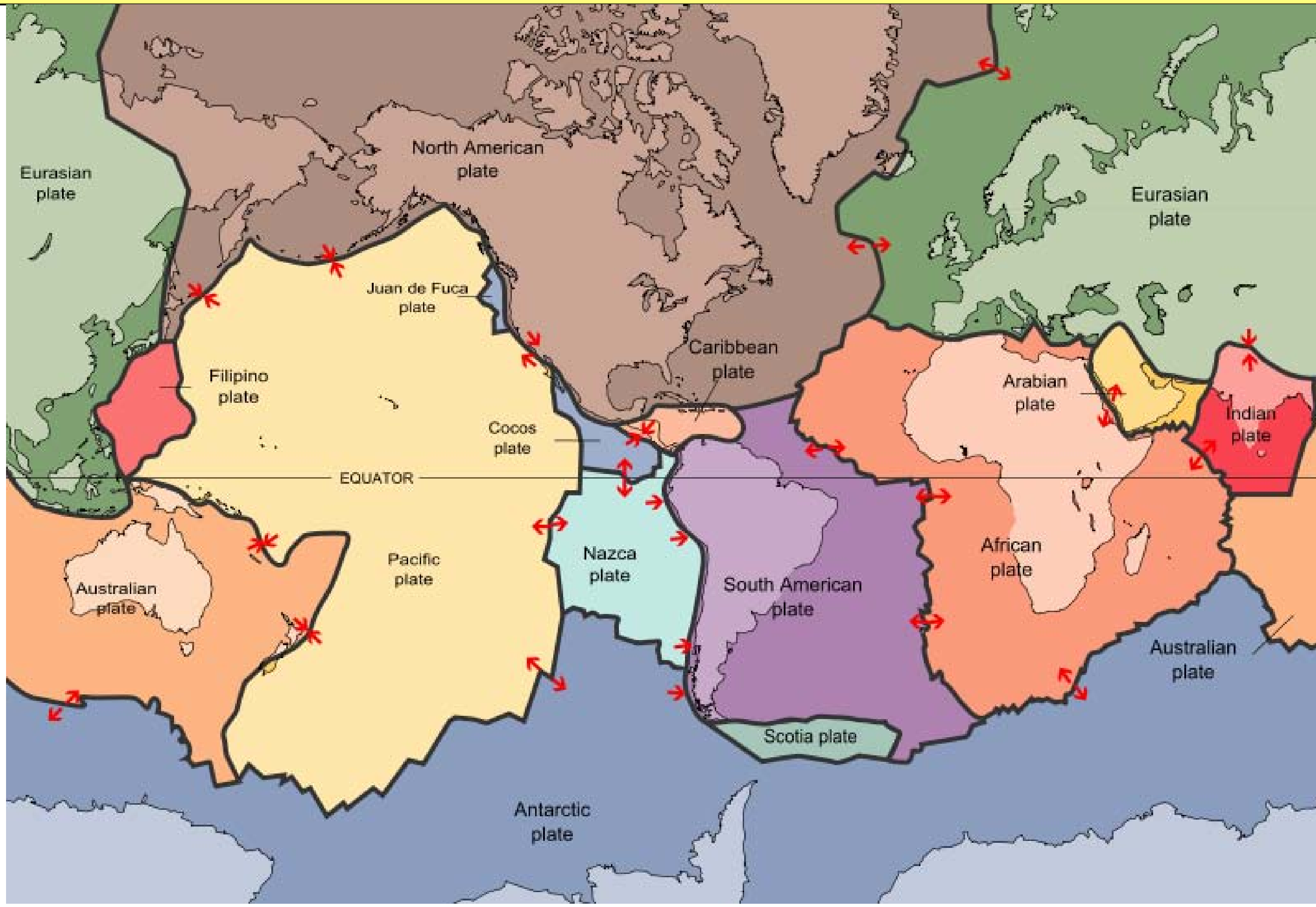
Image by MIT OpenCourseWare. After Taylor, S. Ross, and Scott M. McLennan. "The evolution of continental crust." Scientific American 274 (1996): 76-81.

- 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.

Taylor & McLennan *Sci. Am.* (1996)

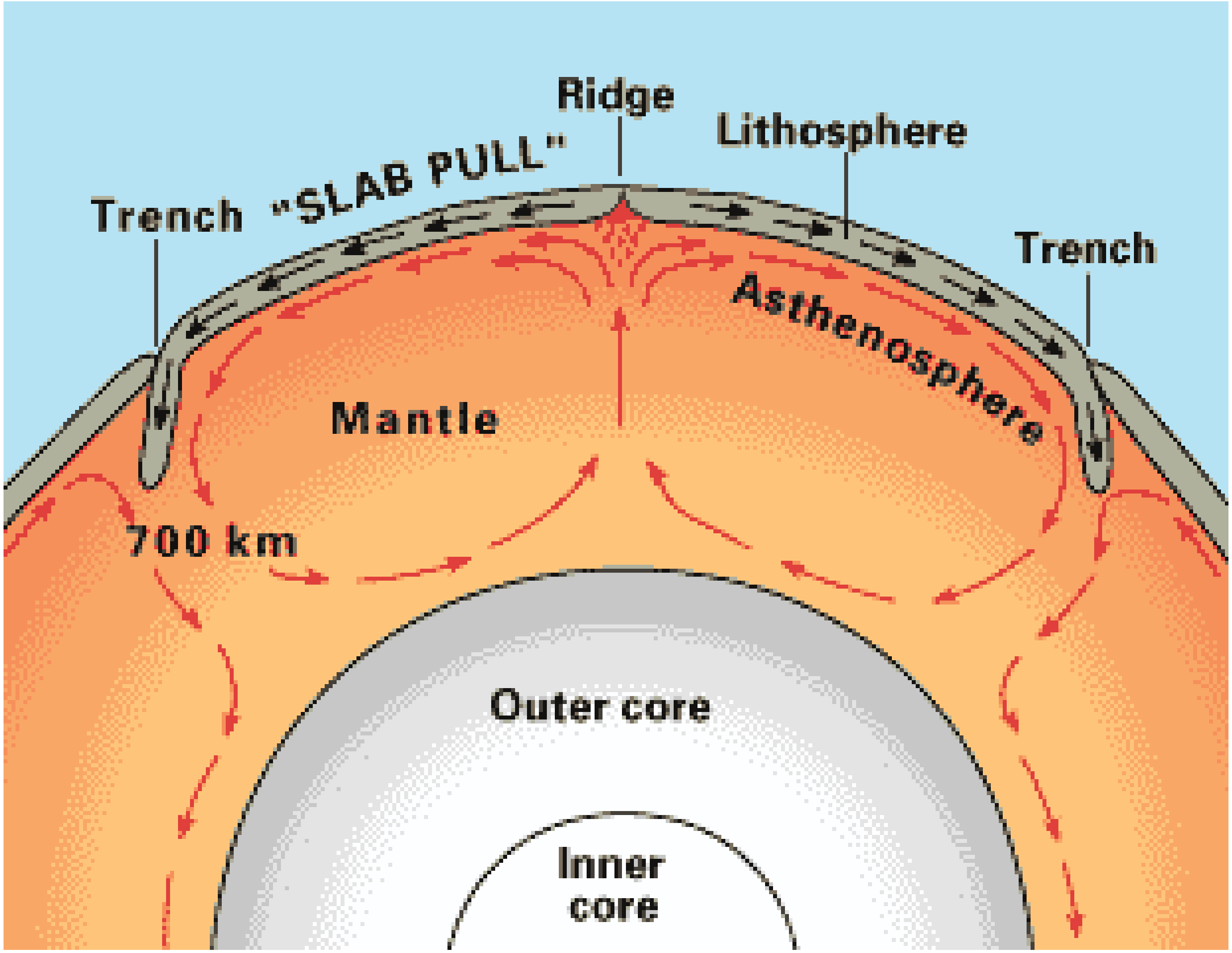
Lithospheric Plates

- 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)



Courtesy US Geological Survey

Convection Drives Plate Movements



Courtesy NASA

Tectonic Activity in the South Atlantic

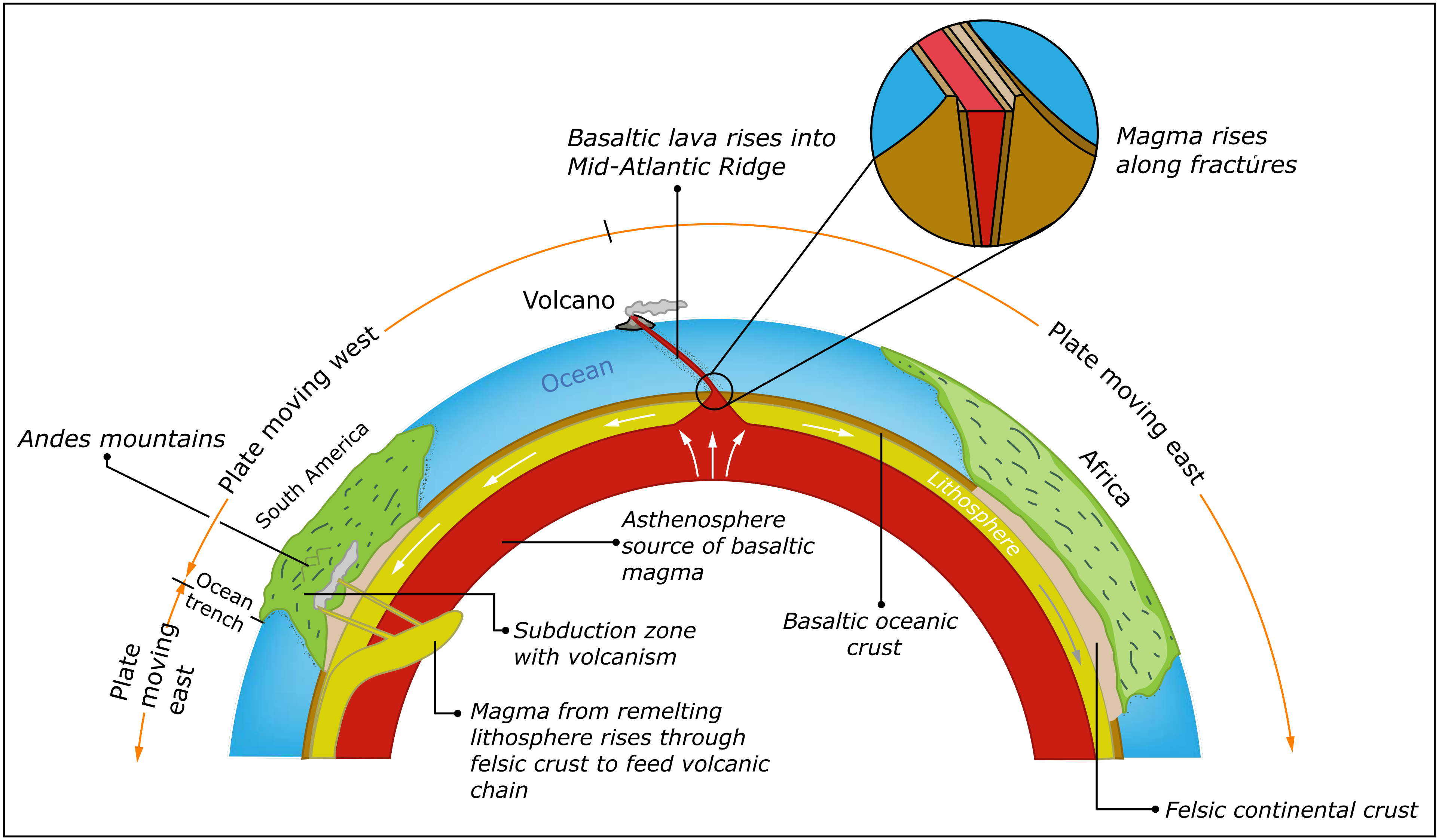
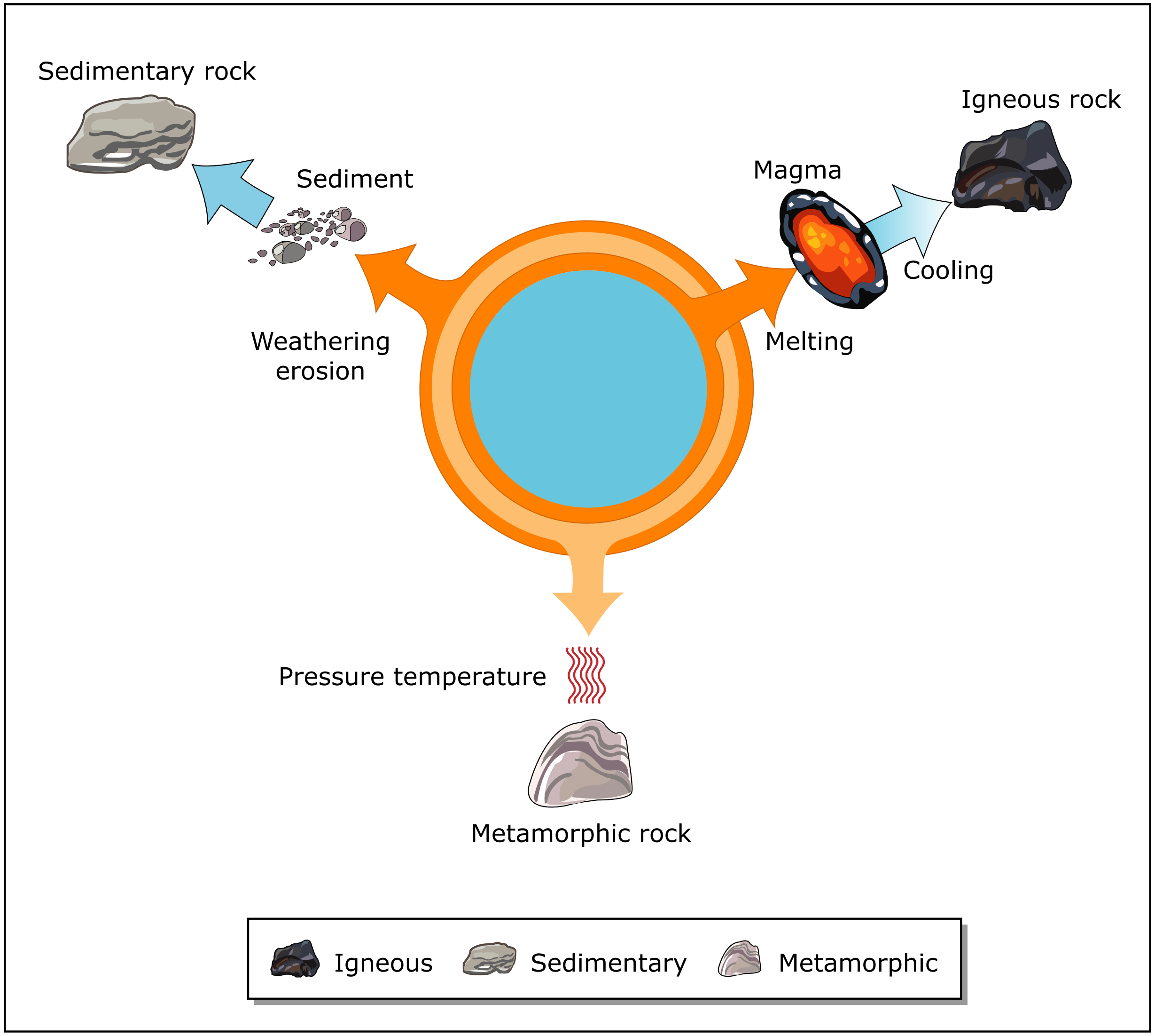


Image by MIT OpenCourseWare.



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Rock Basics

Igneous + metamorphic = Crystalline Rocks

The Rock Cycle

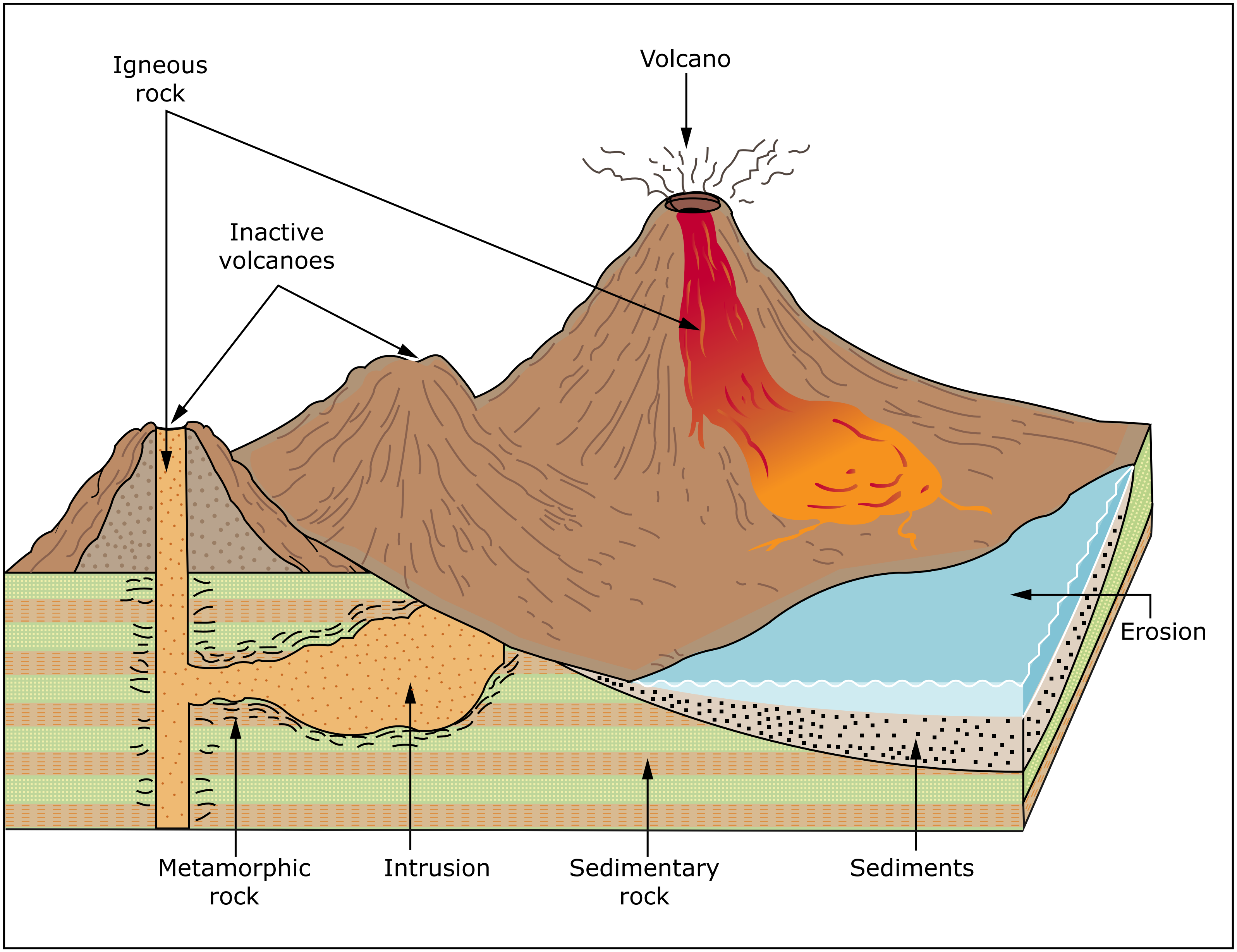


Image by MIT OpenCourseWare.

Igneous Rocks 101

•Felsic: Si-,Al-rich. Light-colored, low-density. Feldspar (pink) & quartz (SiO_2)-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

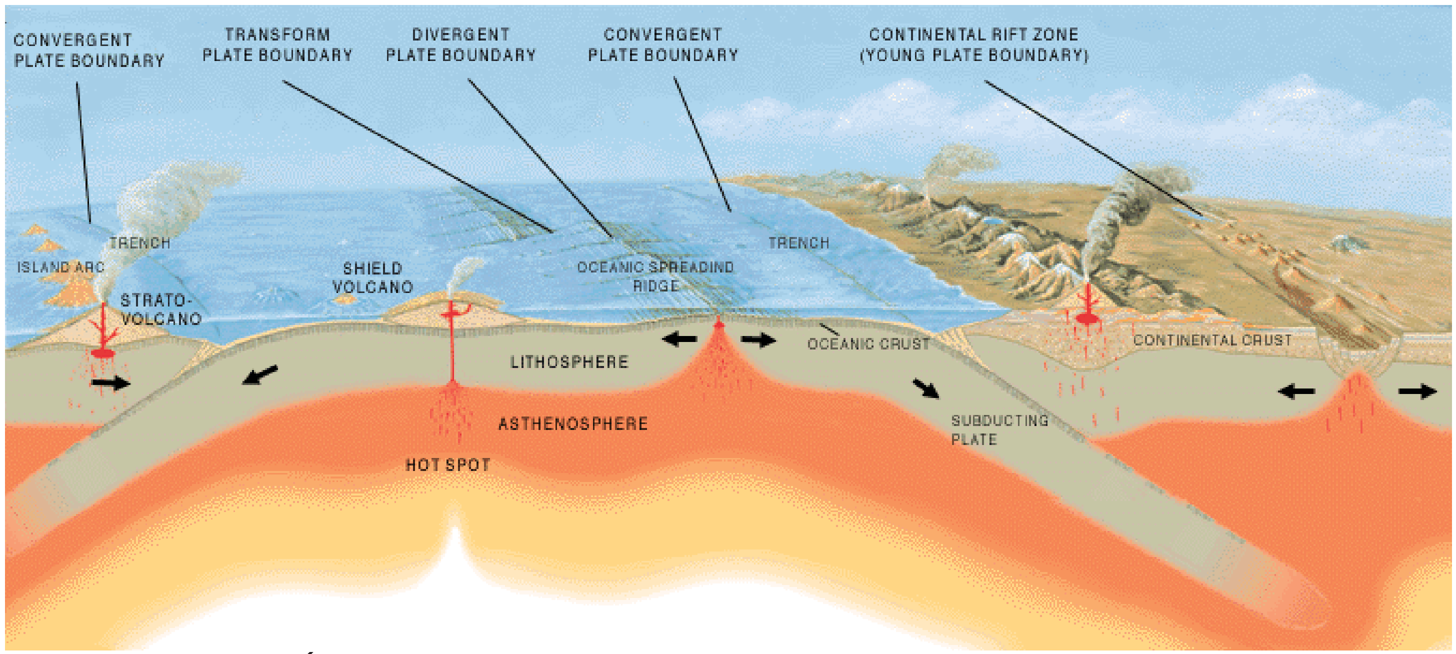
Basalt
(2° Crust; Oceanic crust)

Granite
(1° Crust; Continental Crust)

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

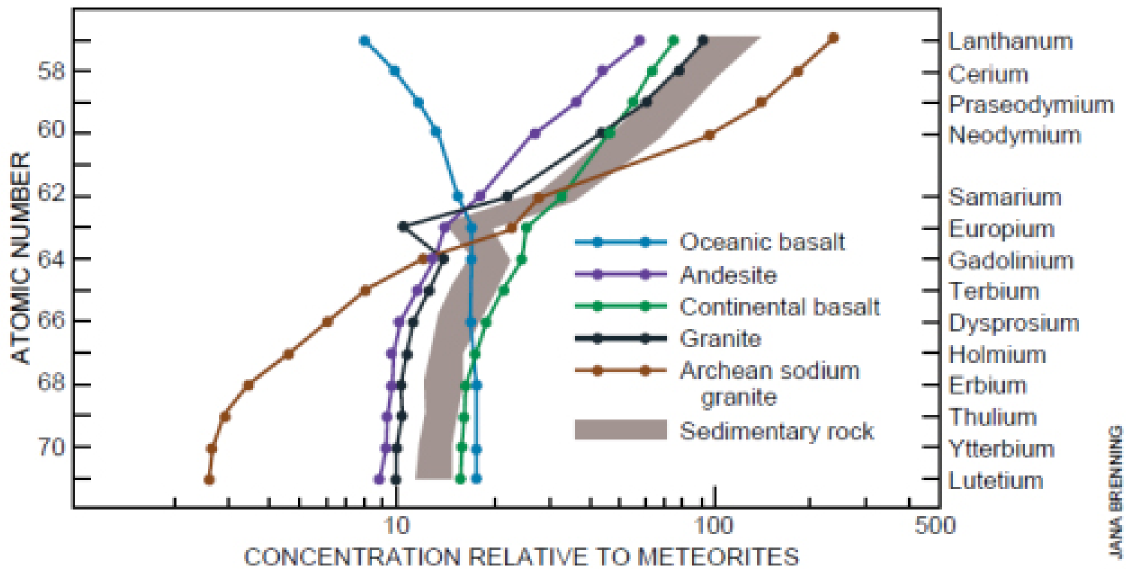
- Slab of lithosphere is subducted, melted & incorporated into asthenosphere
- Convection carries molten material upward where it emerges along a spreading zone as new lithosphere.

Plate Tectonics & the Rock Cycle



- 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.



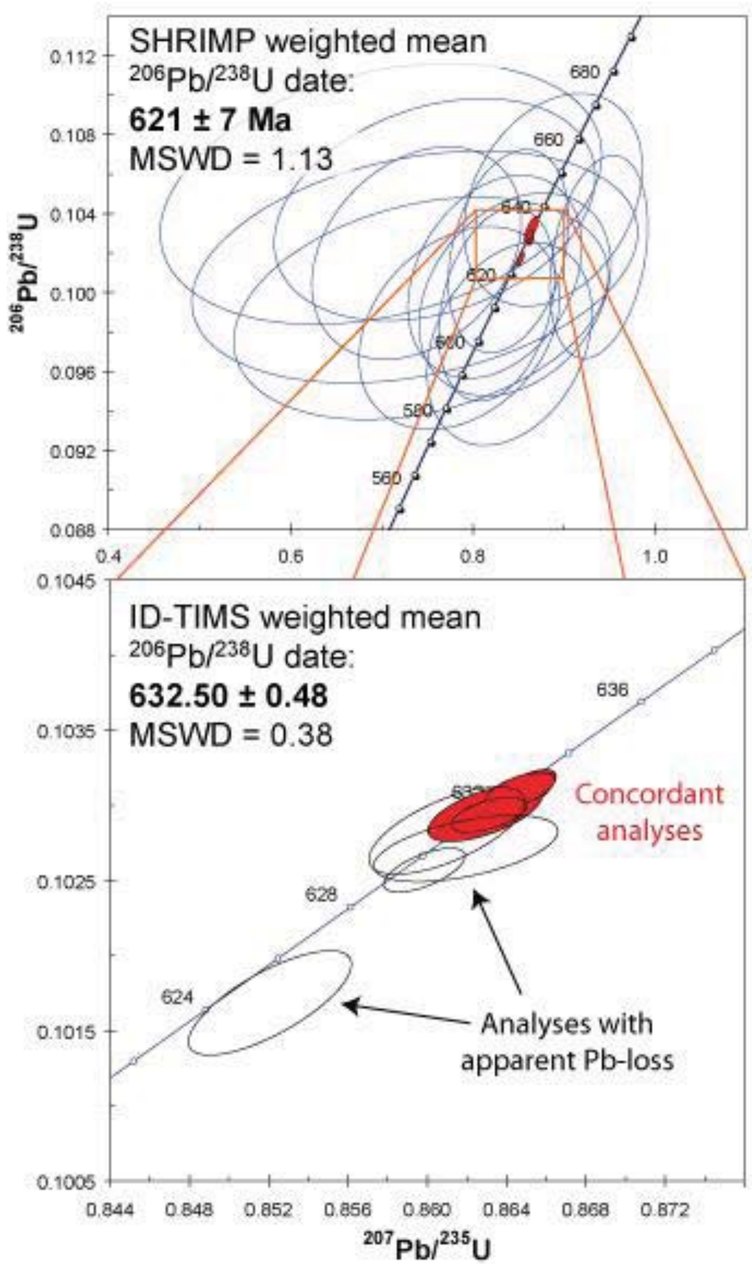
RARE-EARTH ELEMENT abundance patterns provide characteristic chemical markers for the types of rock that have formed the earth's crust. Although igneous rocks (those that solidify from magma) can have highly variable rare-earth element signatures (*dotted lines*), the pattern for most sedimentary rocks falls within a narrow range (*gray band*). That uniformity arises because sediments effectively record the average composition of the upper continental crust.

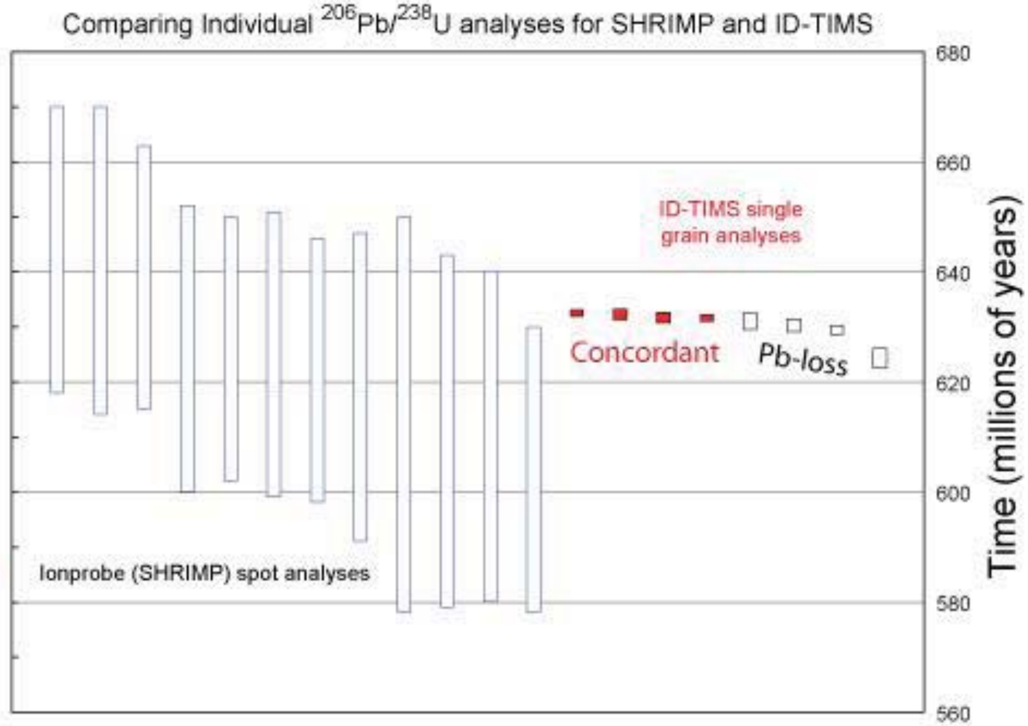
Sedimentary Rocks Represent Homogenous Mixture of Continental Crust

Geologic Time

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.





Precise analyses on single grains permits evaluation of scatter in data prior to calculating weighted mean dates from *n* analyses.

This example from the Neoproterozoic Doushantuo Formation illustrates how the inability of the Ionprobe to detect subtle amounts of Pb-loss (resulting in slightly younger $^{206}Pb/^{238}U$ dates), and reliance upon calculating weighted means from imprecise high-*n* datasets, can result in inaccurate $^{206}Pb/^{238}U$ dates which are younger than the true age.

The advent of pre-treatment techniques (such as CA-TIMS) permits increased concordance for ID-TIMS datasets which combined with the higher precision results in precise *and* accurate dates.

Source: www.SnowballEarth.org

Bowring, S. A., and D. Condon. "Sequencing the Neoproterozoic: the importance of high-precision geochronology." In Snowball Earth 2006 Conference, July, pp. 16-21. 2006.

Absolute Calibration: Geochronology

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

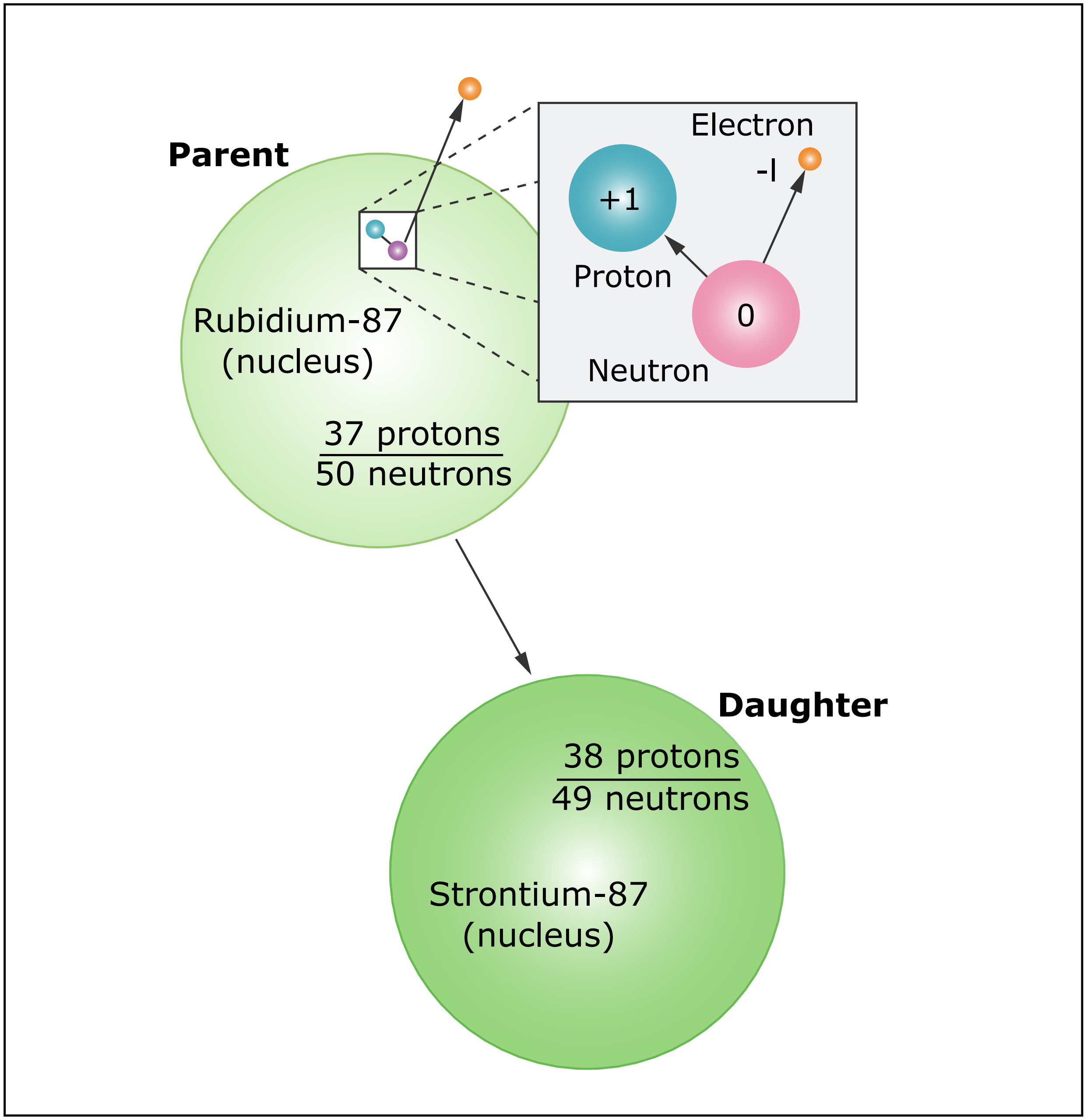


Image by MIT OpenCourseWare.

Radioactive Decay of Rubidium to Strontium

Proportion of Parent Atoms Remaining as a Function of Time

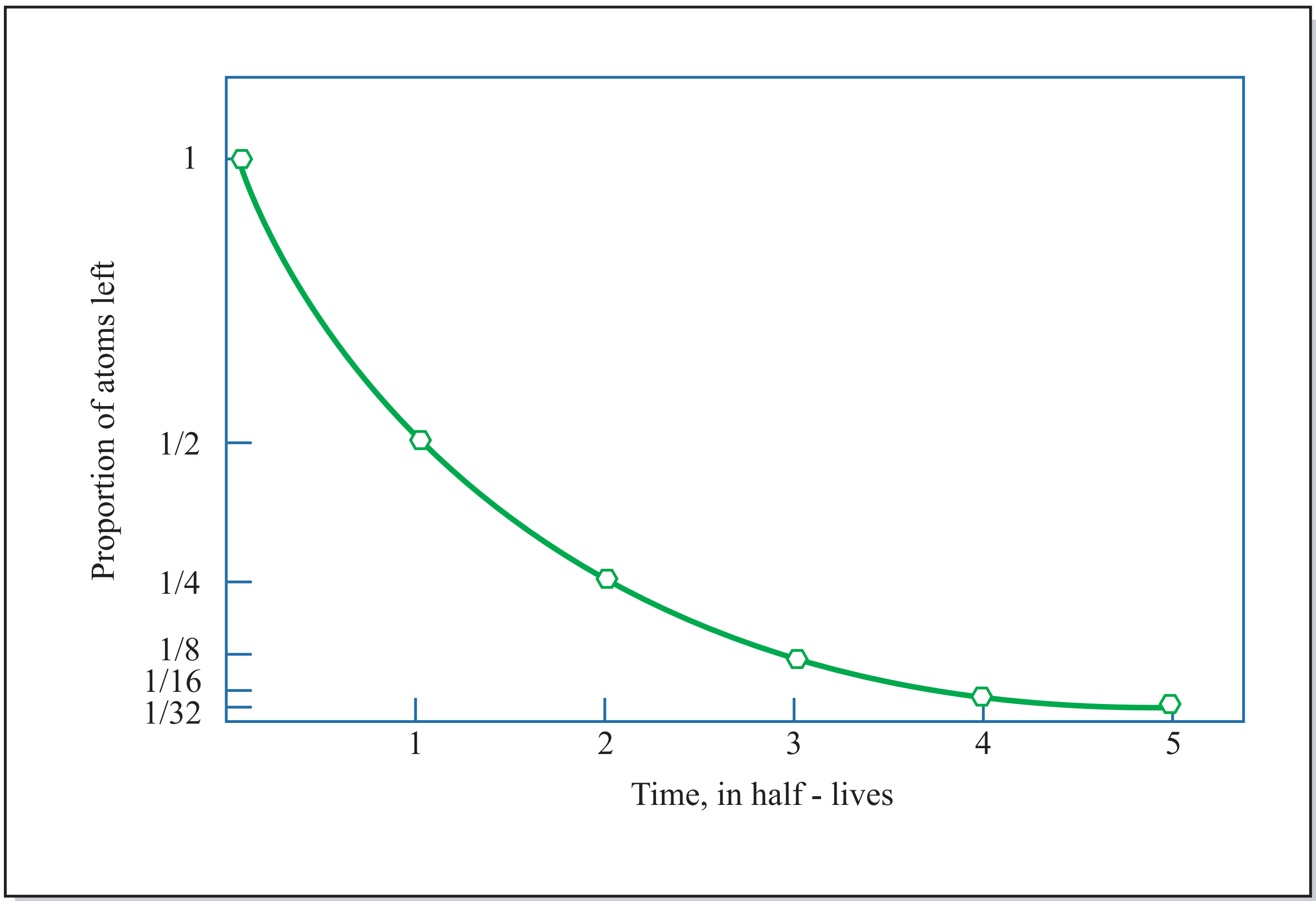


Image by MIT OpenCourseWare.

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

ISOTOPES		HALF-LI FE OF PARENT (YEARS)	EFFECTIVE DATING RANGE (YEARS)	MINERALS AND OTHER MATERIALS THAT CAN BE DATED
PARENT	DAUGHTER			
Uranium-238	Lead-206	4.5 billion	10 million- 4.6 billion	Zircon Uraninite
Potassium-40	Argon-40	1.3 billion	50,000 - 4.6 billion	Muscovite Biotite Hornblende Whole volcanic rock
Rubidium-87	Strontium-87	47 billion	10 million - 4.6 billion	Muscovite Biotite Potassium feldspar Whole metamorphic or igneous rock
Carbon-14	Nitrogen-14	5730	100 -70,000	Wood, charcoal, peat Bone and tissue Shell and other calcium carbonate Groundwater, ocean water, and glacier ice containing dissolved carbon dioxide

Image by MIT OpenCourseWare.

Geologically Useful Decay Schemes

^{235}U	^{207}Pb	0.71×10^9
^{238}U	^{206}Pb	4.5×10^9
^{40}K	^{40}Ar	1.25×10^9
^{87}Rb	^{87}Sr	47×10^9
^{14}C	^{14}N	5730

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

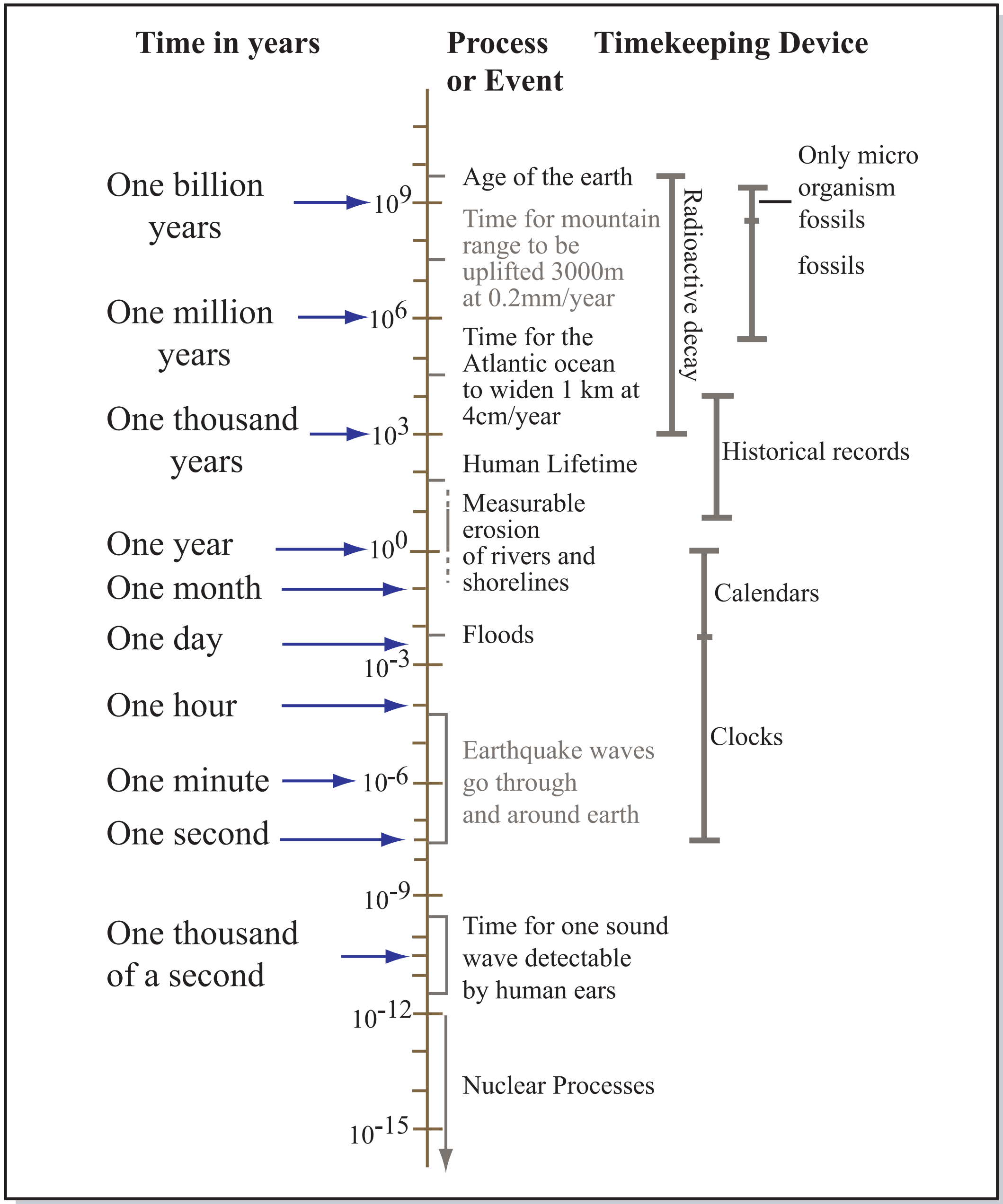
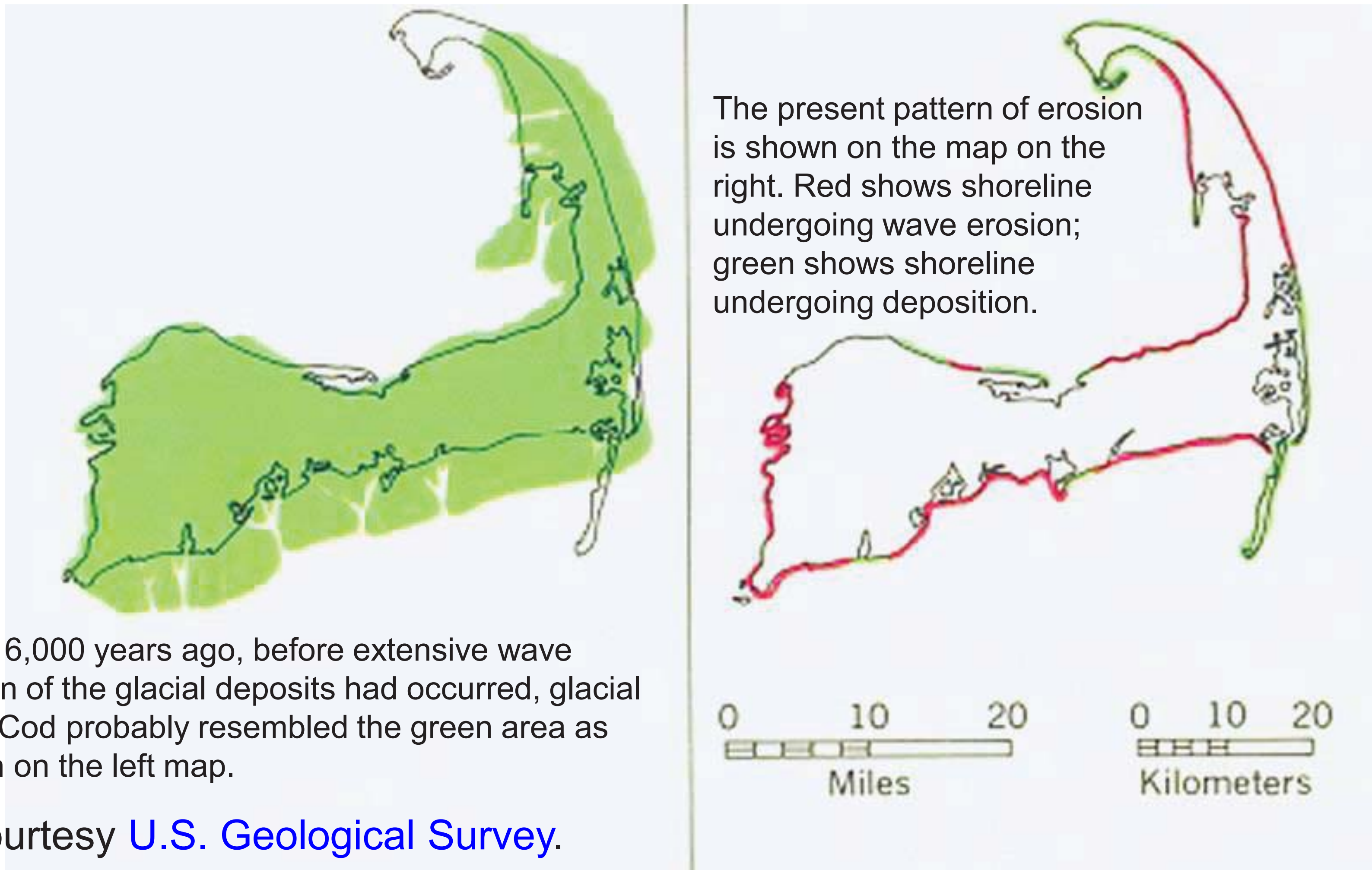


Image by MIT OpenCourseWare.

Some geologic processes can be documented using historical records



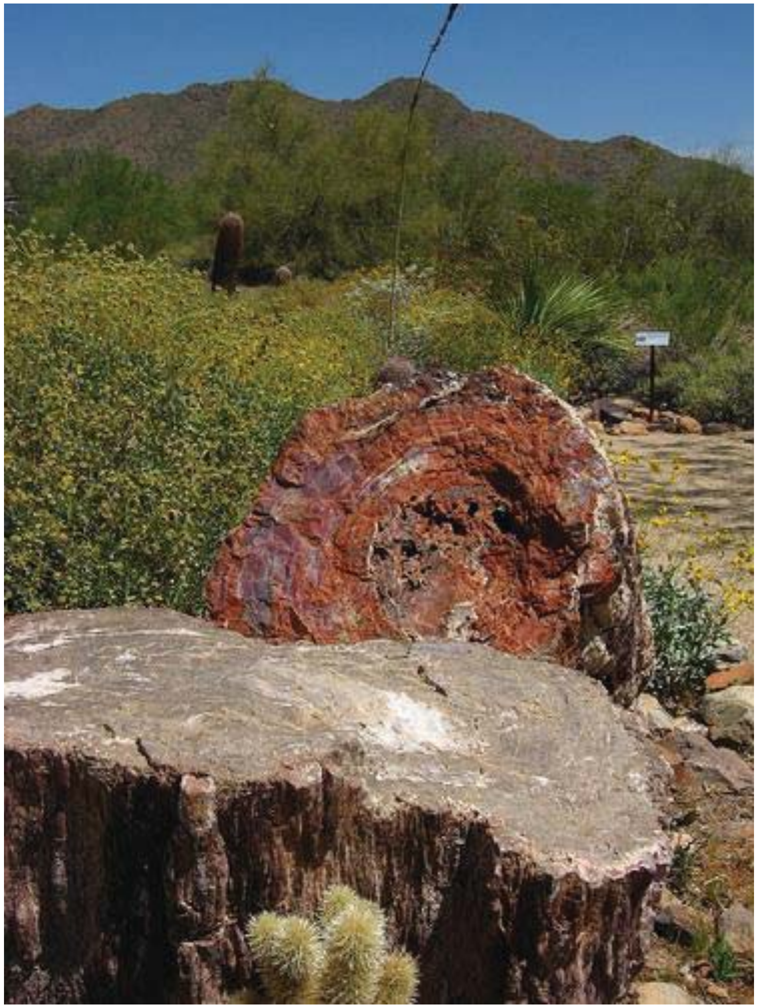
The present pattern of erosion is shown on the map on the right. Red shows shoreline undergoing wave erosion; green shows shoreline undergoing deposition.

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.

Maps courtesy U.S. Geological Survey.

Ammonite Fossils

Petrified Wood



Photographs courtesy Smabs Sputzer and Candie_N

Steno's Laws

Nicolaus Steno (1669)

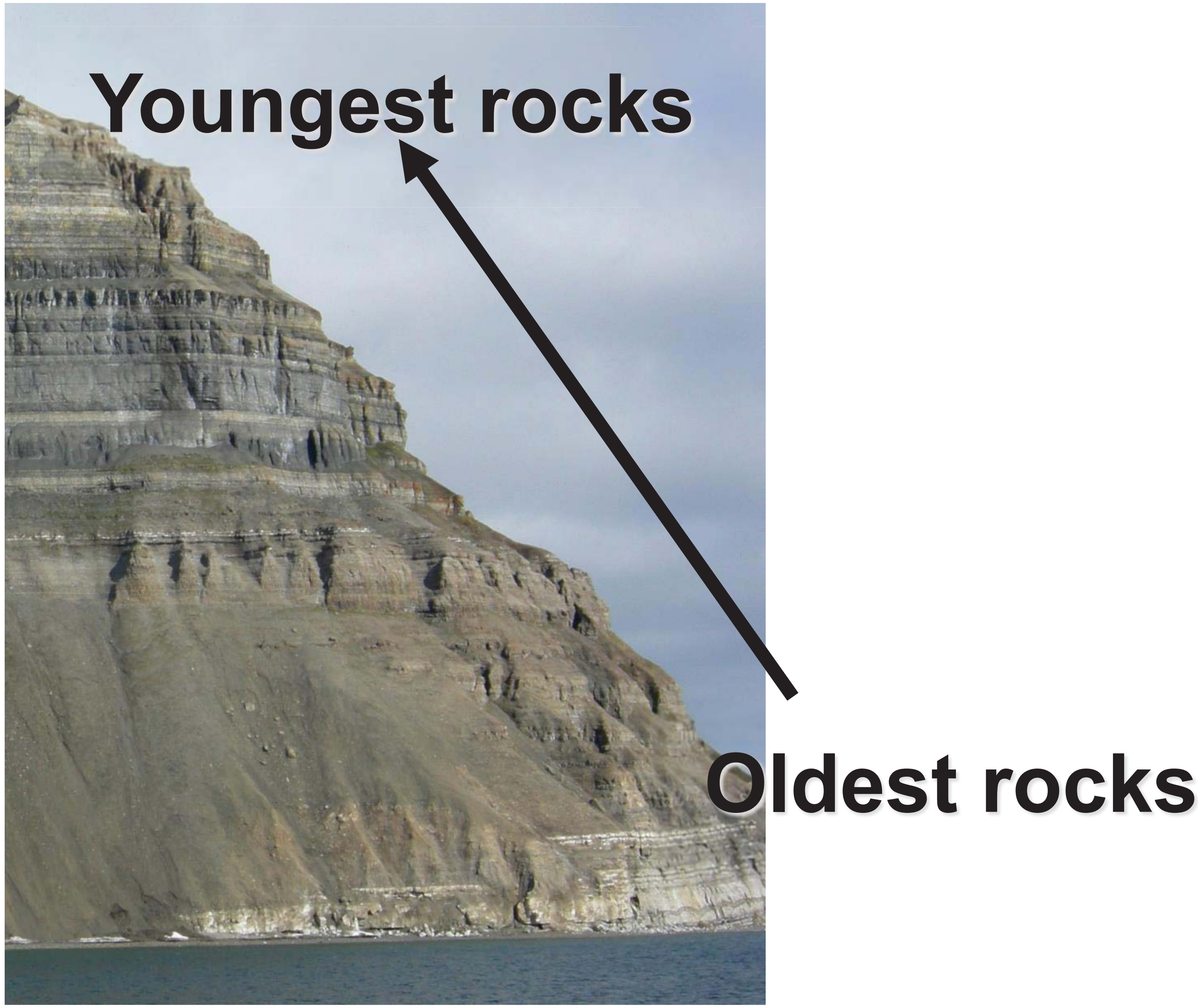
- Principle of Superposition
- Principle of Original Horizontality
- Principle of Lateral Continuity

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

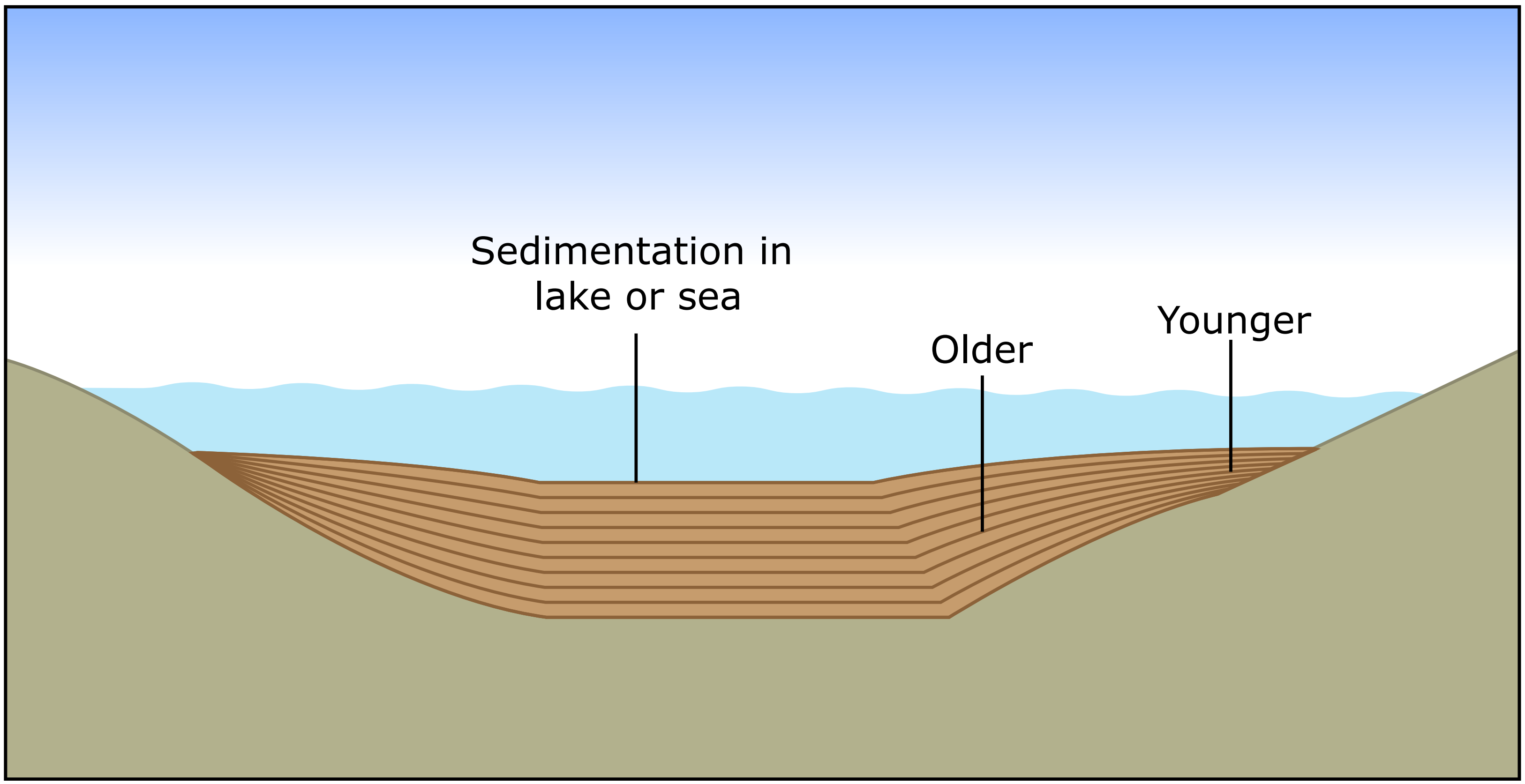
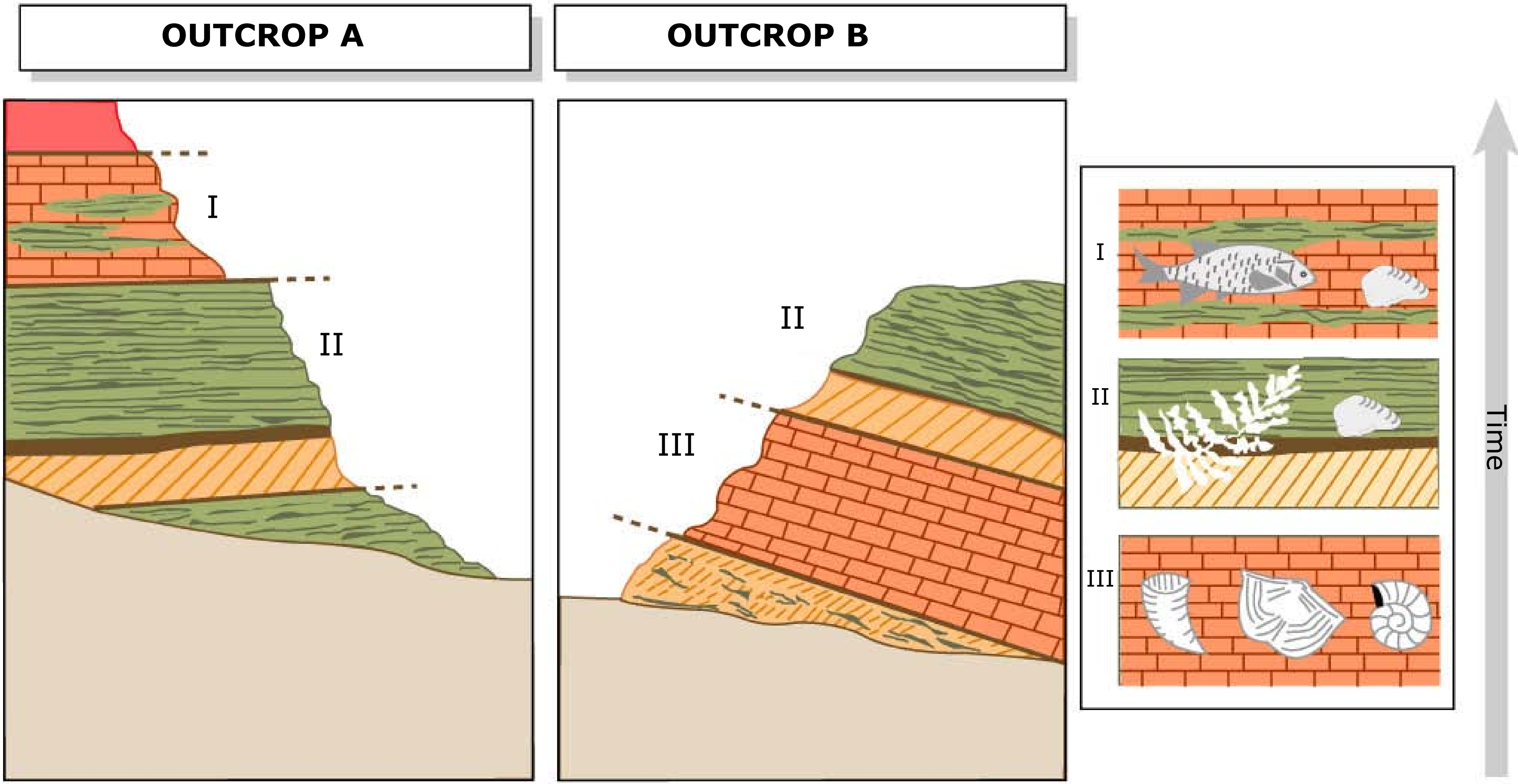


Image by MIT OpenCourseWare.

Principle of Lateral Continuity

Layered rocks are deposited in continuous contact.

Using Fossils to Correlate Rocks



Outcrops may be separated by a long distance.

Image by MIT OpenCourseWare.

William (Strata) Smith

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

Portrait of William Smith by Hugues Fourau

Disconformity and Unconformity

A buried surface of erosion

Formation of a Disconformity

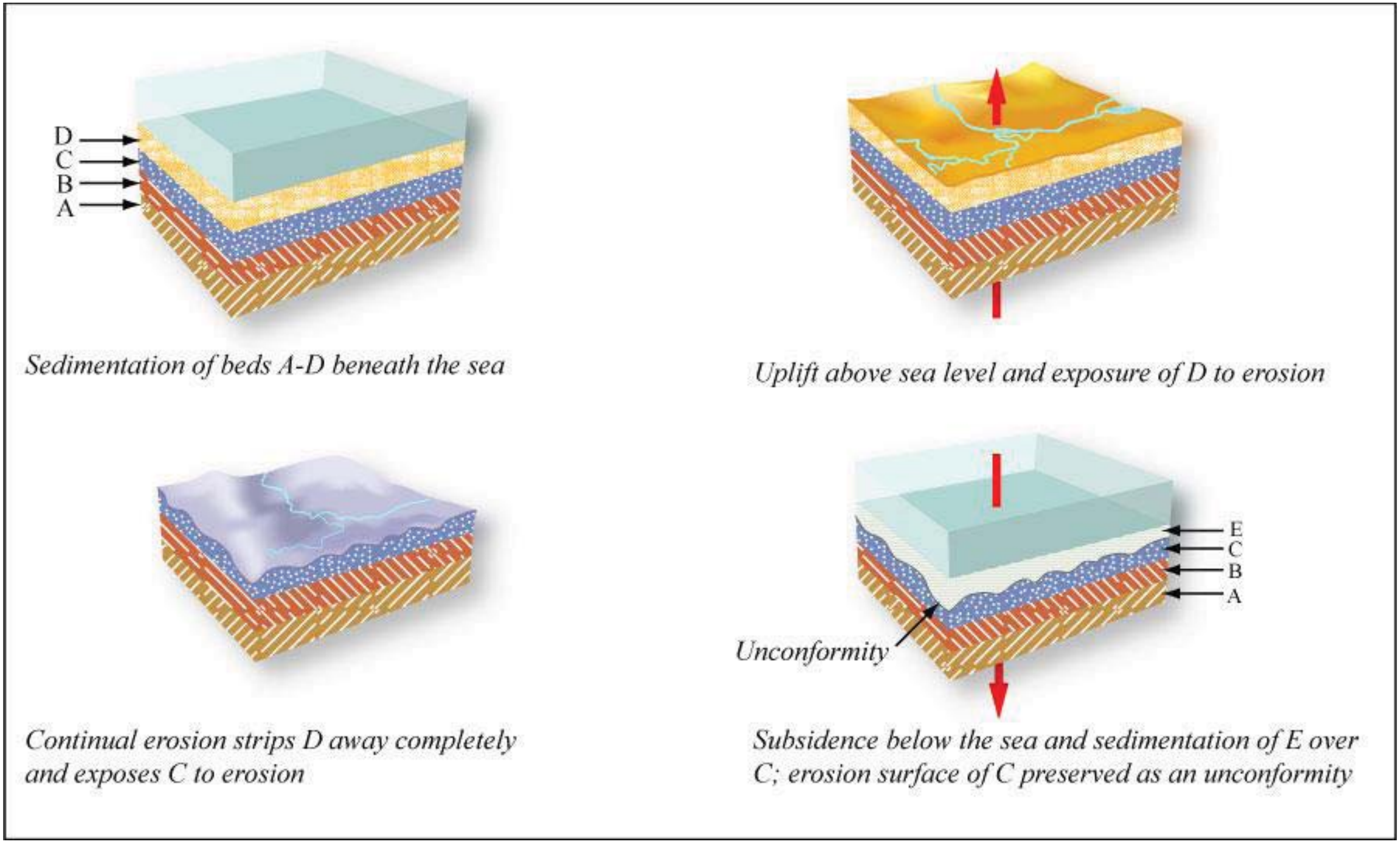


Image by MIT OpenCourseWare.

Rocks Exposed in the Grand Canyon

Photography courtesy Grand Canyon National Park.

Generalized Stratigraphic Section of Rocks Exposed in the Grand Canyon

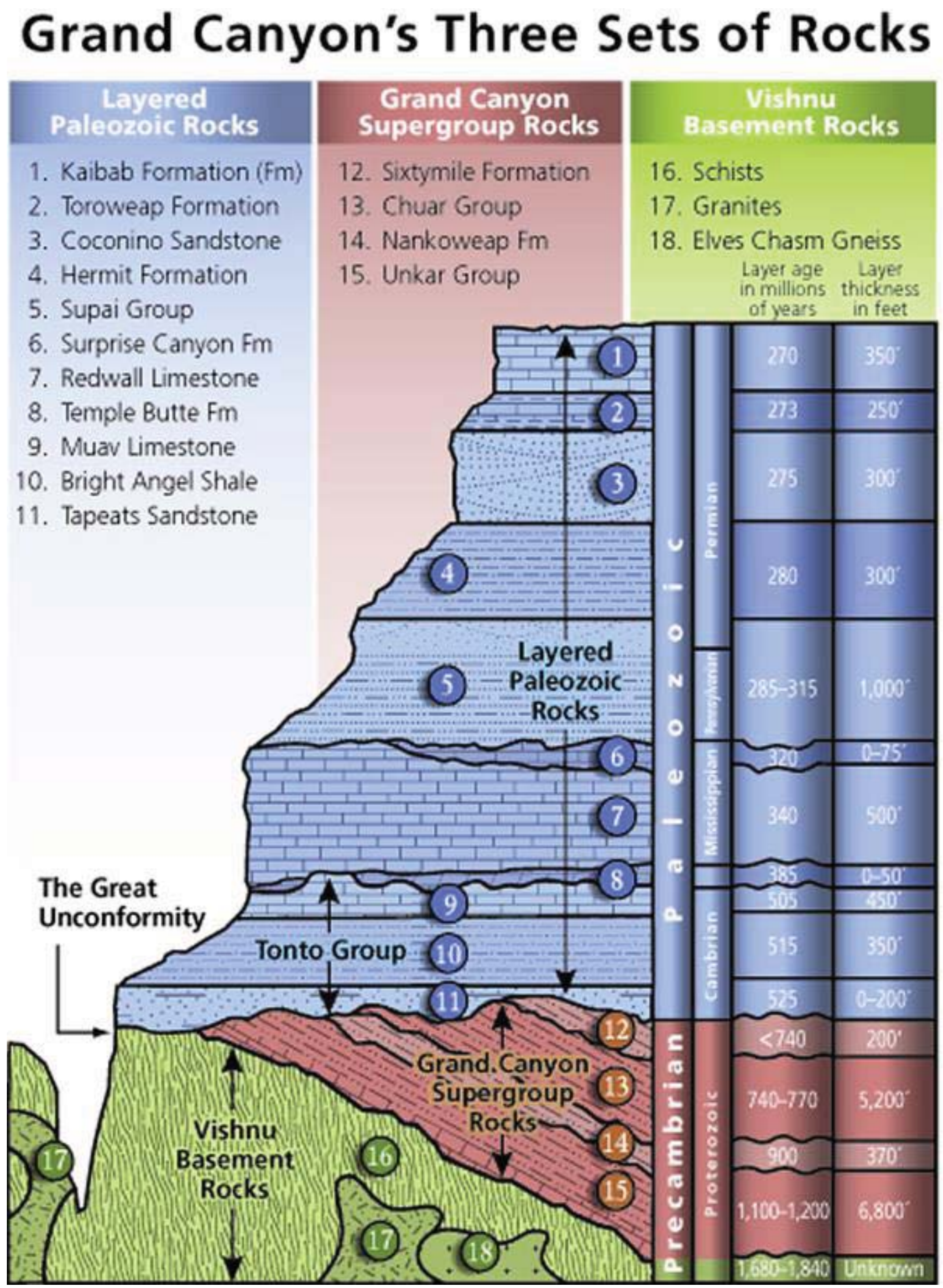


Figure courtesy National Park Service.

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.

South rim of the Grand Canyon

Photograph of the Grand Canyon removed due to copyright restriction.

The nonconformity of the Grand Canyon is outlined.

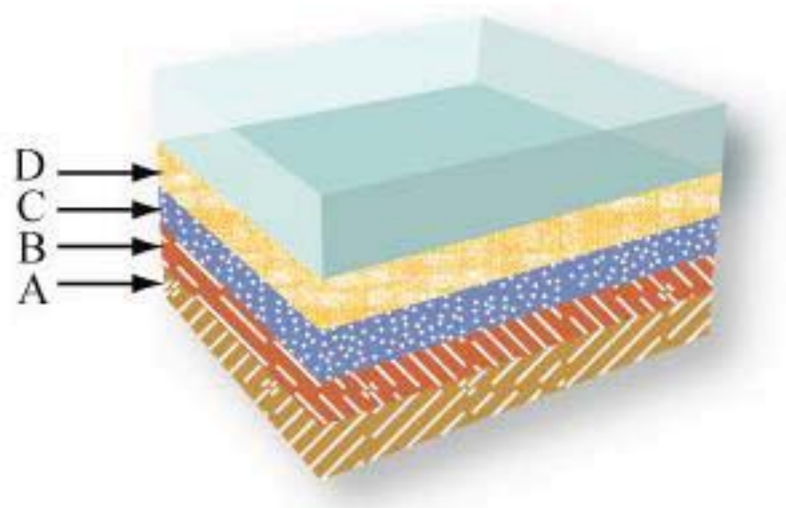
The Great Unconformity of the Grand Canyon

Photograph courtesy Chris M. Morris

Angular Unconformity at Siccar Point

Photograph courtesy Lysippos.

Sedimentation of Beds A-D Beneath the Sea



Sedimentation of beds A-D beneath the sea

Image by MIT OpenCourseWare

Deformation and Erosion During Mountain Building

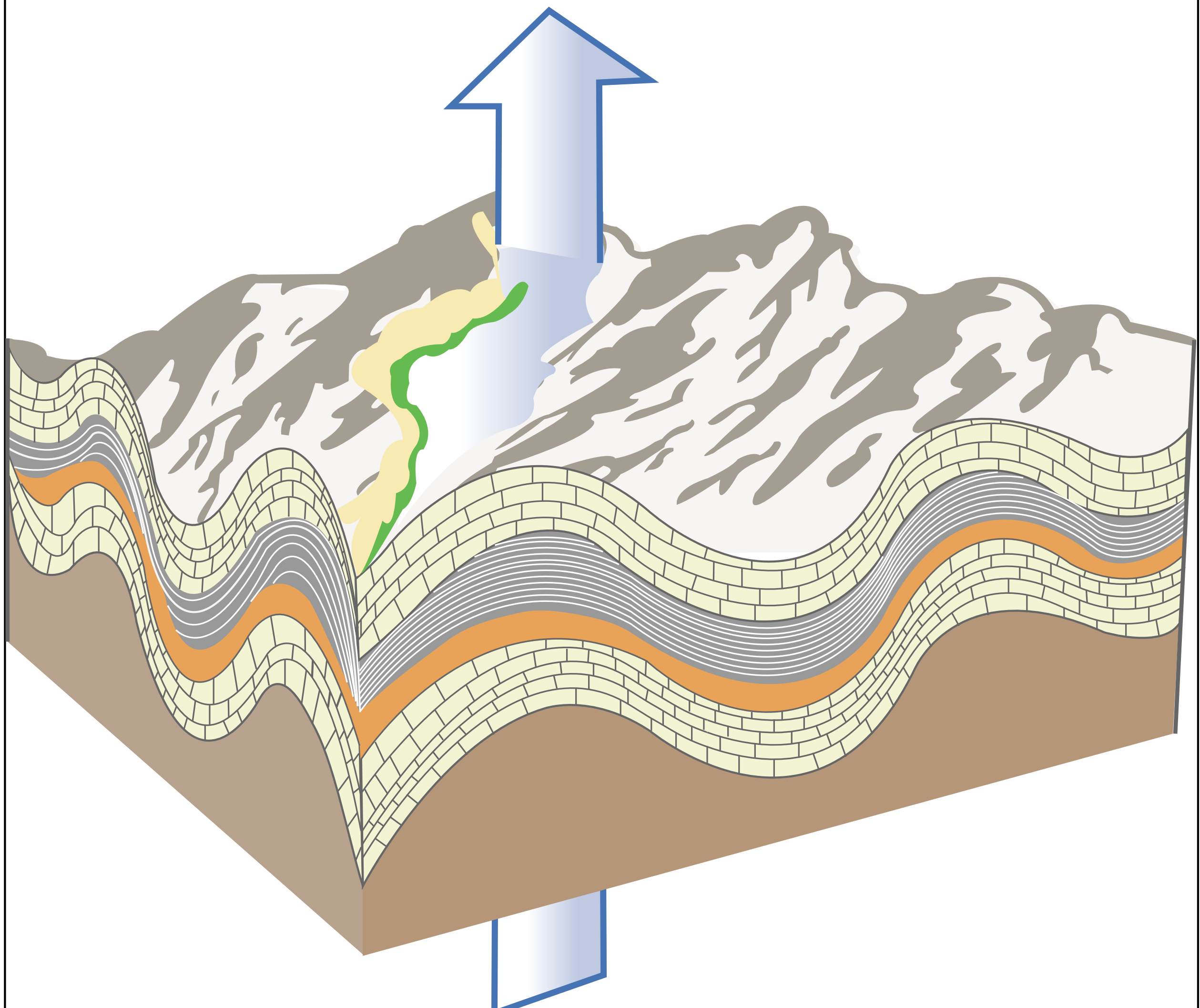


Image by MIT OpenCourseWare.

Uniformitarianism

— James Hutton

http://en.wikipedia.org/wiki/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 ~ 100 m.y.

4) Kelvin's Calculation: (1870): Lord Kelvin calculated that the present geothermal gradient of ~30° C/km would result in an initially molten earth cooled for 30 – 100 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

^{238}U	^{206}Pb	4.5×10^9
^{235}U	^{207}Pb	0.71×10^9
^{40}K	^{40}Ar	1.25×10^9
^{87}Rb	^{87}Sr	47×10^9
^{147}Sm	^{144}Nd	106×10^9

Minerals with no initial daughter

- ^{40}K decays to ^{40}Ar (a gas)
- Zircon: $ZrSiO_4$

ion	radius (Å)
Zr^{4+}	0.92
U^{4+}	1.08
Pb^{2+}	1.37

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).

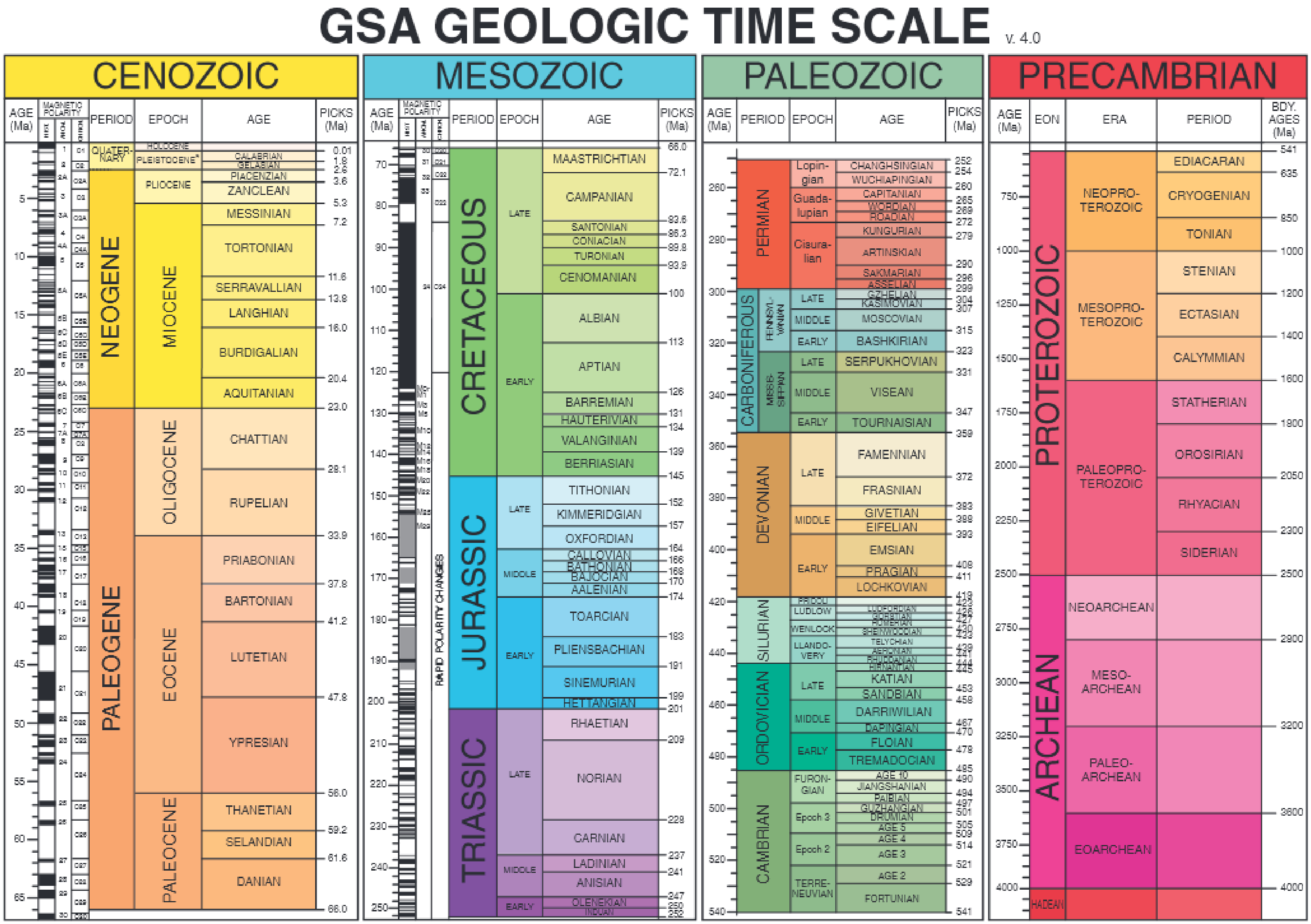
Figure of North American craton removed due to copyright restriction.

See Figure 1 in Hoffman, Paul. "United plates of America, the birth of a craton: Early Proterozoic Assembly and Growth of Laurentia." *Annual Reviews of Earth and Planetary Sciences* 16, 1998.

Image courtesy R. Clucas.

Zircons: Nature's Time Capsules

Microscope photograph of zircons removed due to copyright restrictions.



THE GEOLOGICAL SOCIETY OF AMERICA®

*The Pleistocene is divided into four ages, but only two are shown here. What is shown as Calabrian is actually three ages—Calabrian from 1.8 to 0.78 Ma, Middle from 0.78 to 0.13 Ma, and Late from 0.13 to 0.01 Ma.

Walker, J.D., Geissman, J.W., Bowring, S.A., and Babcock, L.E., compilers, 2012, Geologic Time Scale v. 4.0: Geological Society of America, doi: 10.1130/2012.CTS004R3C. ©2012 The Geological Society of America.

The Cenozoic, Mesozoic, and Paleozoic are the Eras of the Phanerozoic Eon. Names of units and age boundaries follow the Gradstein et al. (2012) and Cohen et al. (2012) compilations. Age estimates and picks of boundaries are rounded to the nearest whole number (1 Ma) for the pre-Cenomanian, and rounded to one decimal place (100 ka) for the Cenomanian to Pleistocene interval. The numbered epochs and ages of the Cambrian are provisional.

REFERENCES CITED Cohen, K.M., Finney, S., and Gibbard, P.L., 2012, International Chronostratigraphic Chart: International Commission on Stratigraphy, www.stratigraphy.org (last accessed May 2012). (Chart reproduced for the 34th International Geological Congress, Brisbane, Australia, 5–10 August 2012.)

Gradstein, F.M, Ogg, J.G., Schmitz, M.D., et al., 2012, The Geologic Time Scale 2012: Boston, USA, Elsevier, DOI: 10.1016/B978-0-444-59425-9.00004-4.

Figure courtesy Geological Society of America. Used with permission.

The Eras of the Phanerozoic

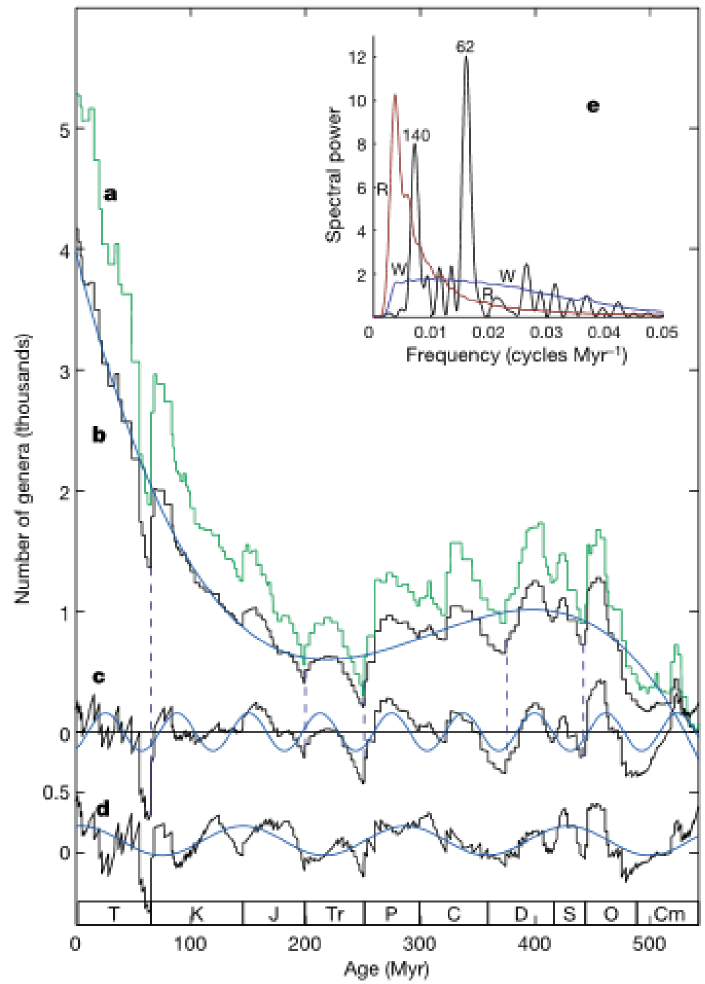
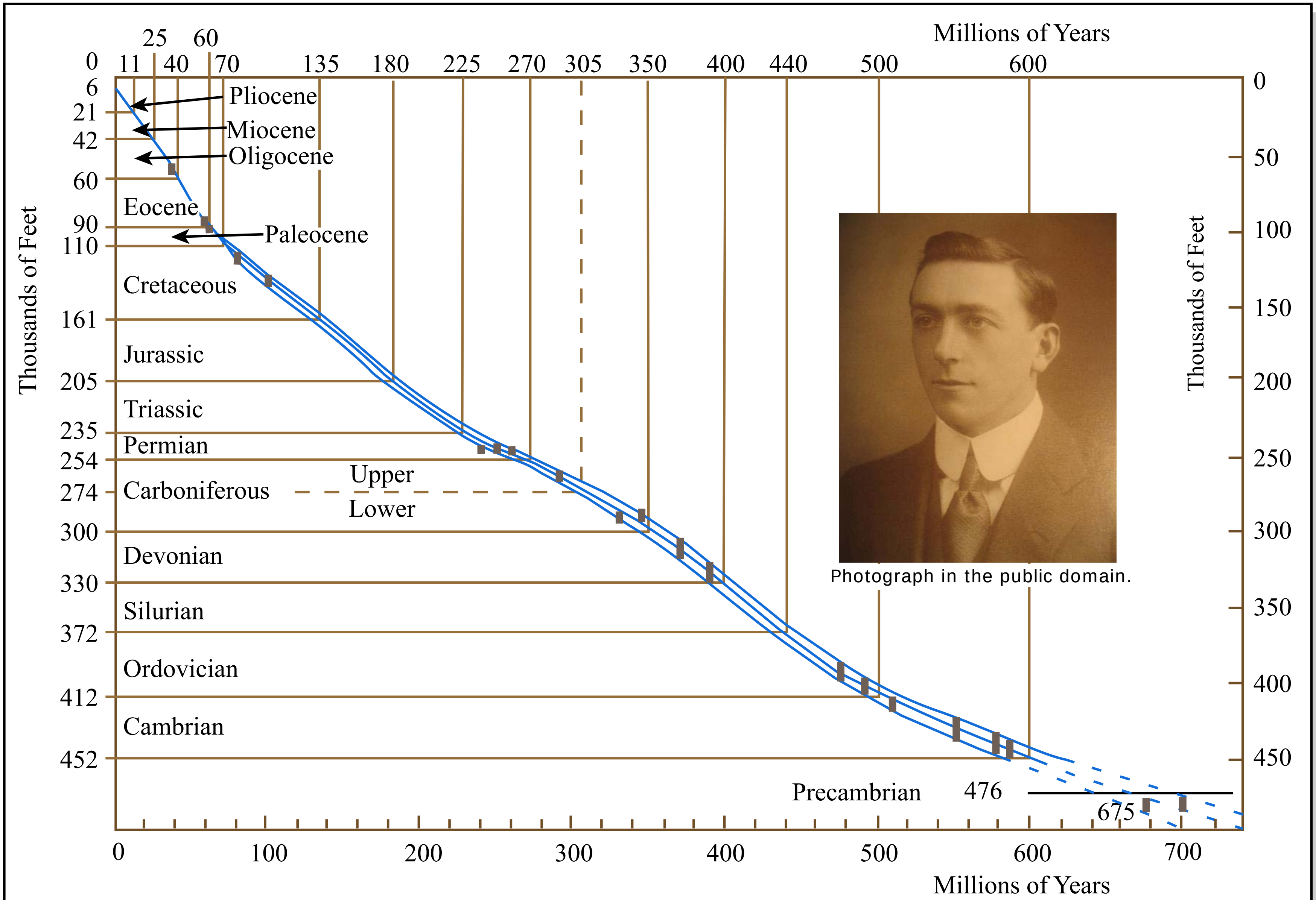


Figure 1 Genus diversity. **a**, The green plot shows the number of known marine animal genera versus time from Sepkoski's compendium[1], converted to the 2004 Geologic Time Scale[5]. **b**, The black plot shows the same data, with single occurrence and poorly dated genera removed. The trend line (blue) 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 140-Myr sine wave superimposed. Dashed vertical lines indicate the times of the five major extinctions[2]. **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

Image by MIT OpenCourseWare.

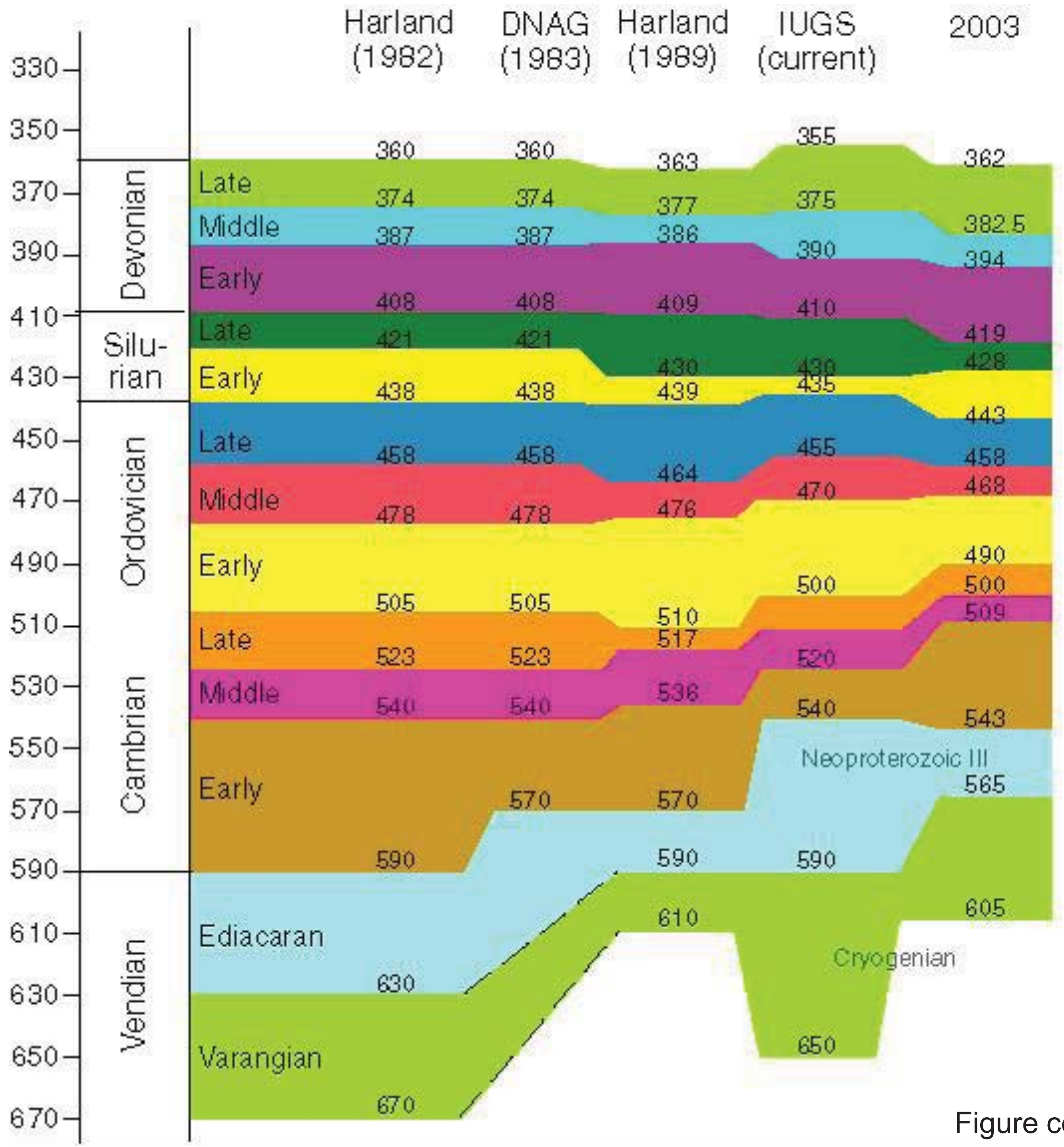


Figure courtesy Sam Bowring.

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).
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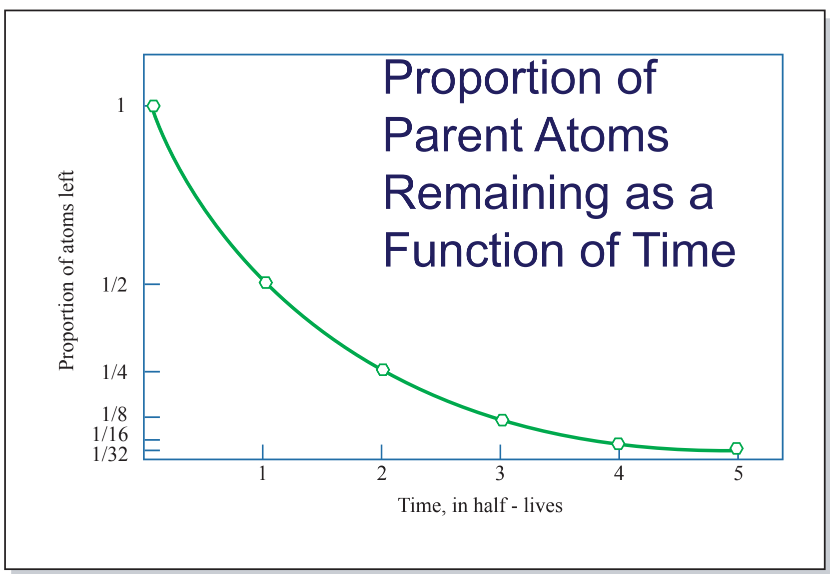

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