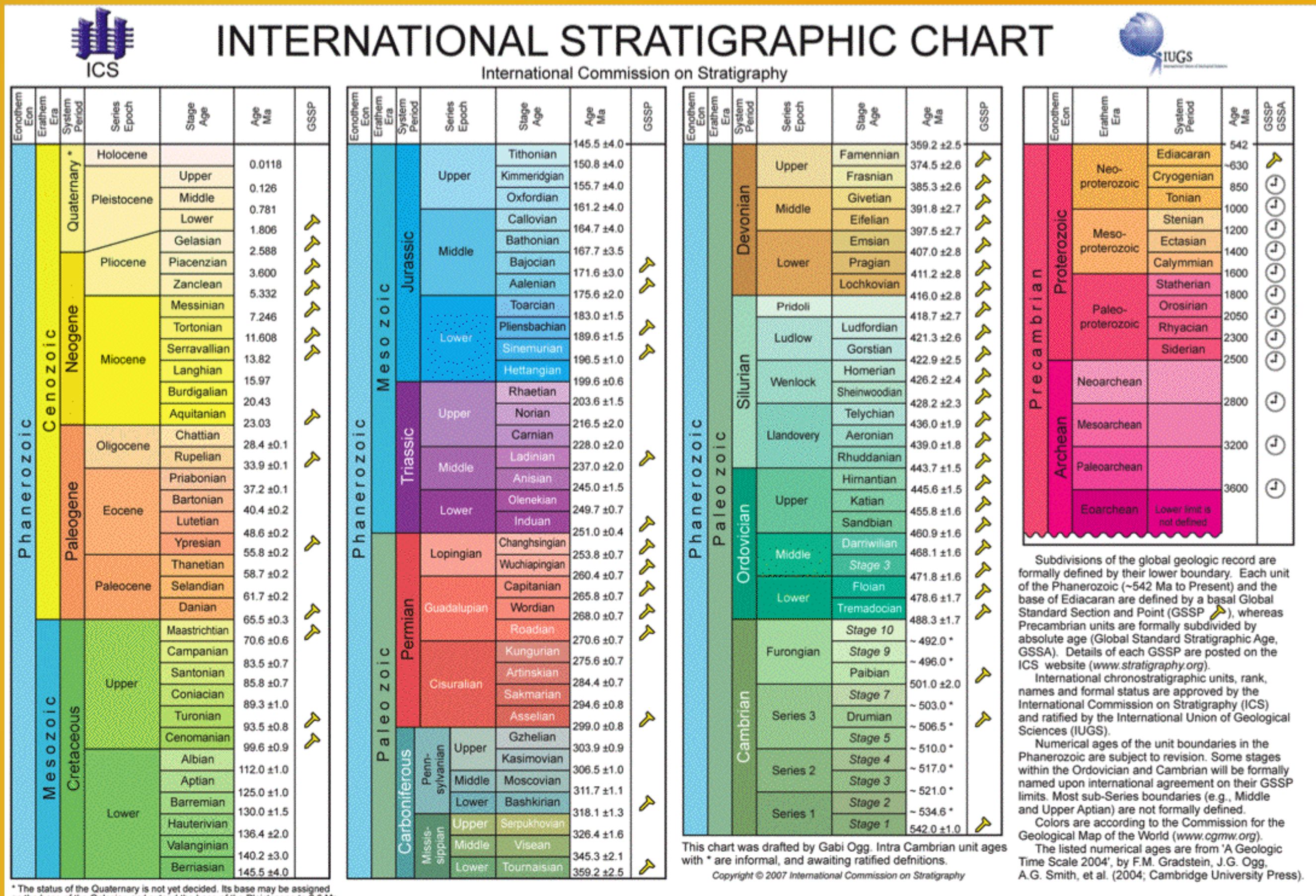
INTEGRATED STRATIGRAPHY

Amalia Spina

Time in stratigraphy

"Time Stratigraphy"



Isochronous:
of equal duration (have synchronous boundaries)

Synchronous:
sychronous (at the same time or over the same period of time)

Diachronous:
time transgressive (non-synchronous)

Geologic time" refers to the interval of time since the formation of the Earth. It is the time frame geologists use to describe the ages of geologic features (rocks, structures, or landforms). In common language, it now has the implication of long expanses of time (e.g., time measured in millions or billions of years).

Absolute Time and Dating

Geochronology

Early Attempts to Measure Geologic Time Numerically

$$\text{Time} = \frac{\text{Quantity of Something}}{\text{Rate Quantity changes with time}}$$

For example, Rates of sedimentation & thickness of sedimentary rocks

Problem: did not account for past erosion differences in sedimentation rates

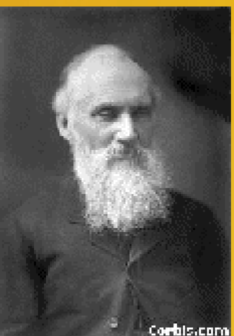
Rates of Deposition of Sediments

- Because of poor estimates of rates of deposition, this method gave a very wide range of results.

- This method generally suggests that the **earth is at least 10's of millions of years old** (based on both fossil evidence and rates of deposition of sediments).

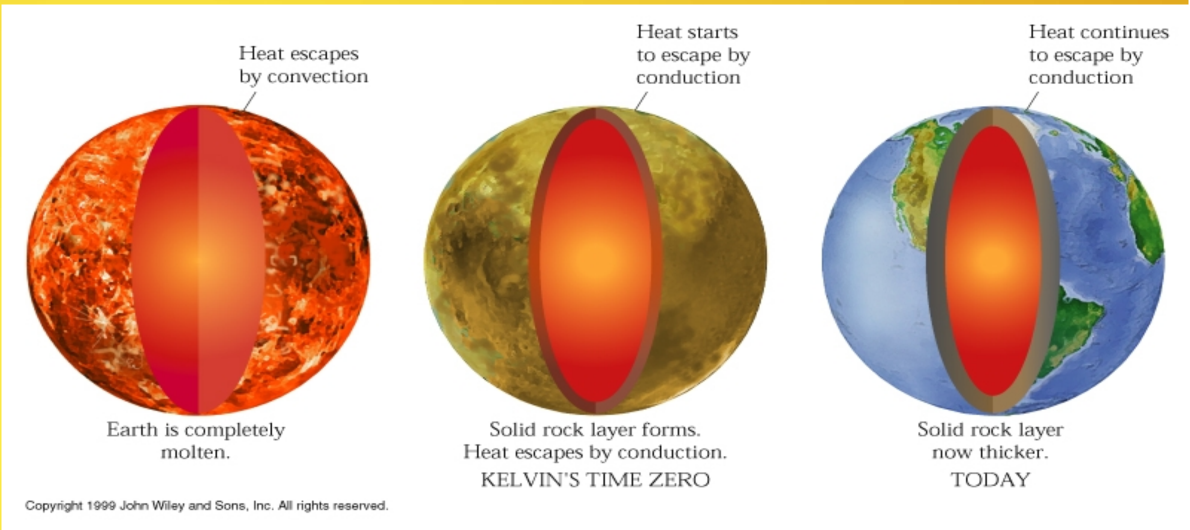
- Many geologists and biologists in the 1800's concluded that the earth was **several hundreds of millions of years old**.

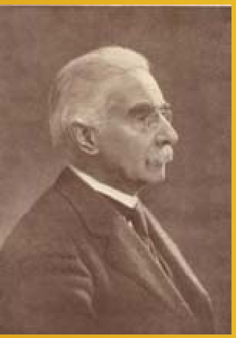
Early Dating Attempts
Quantitative



William Thomson, Lord Kelvin (1824-1907)

- method: cooling rate of molten Earth through conduction and radiation
- Result: 50-100 million years

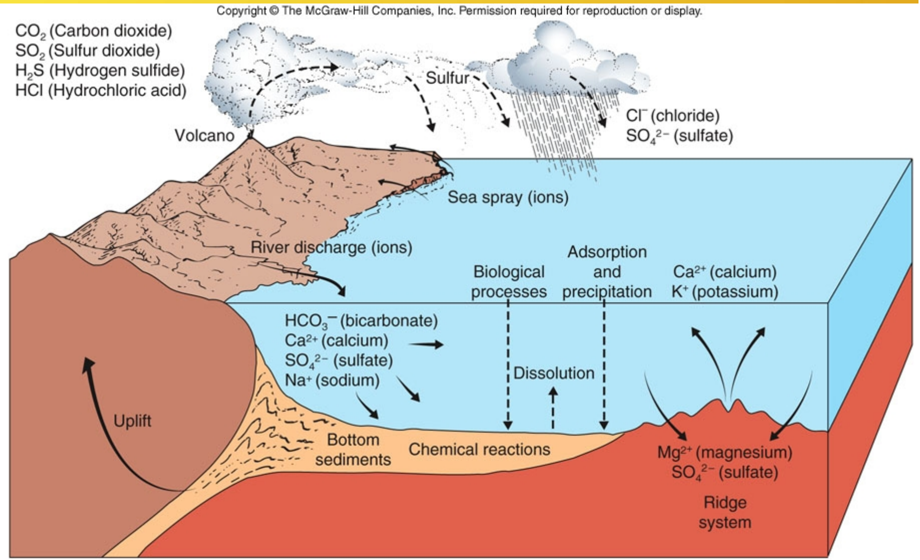




John Joly (1857-1933)

- method: rate of delivery of salt to the ocean
- result: 90-100 million years

Total salts in ocean / rate of addition = age



Cooling of the Earth from a Molten State

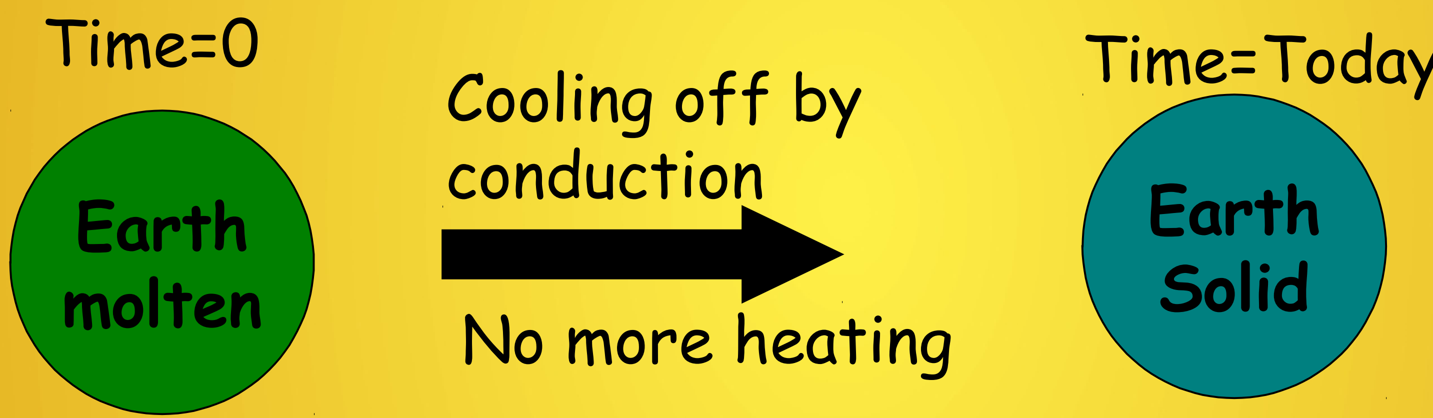
Kelvin's Analysis:

1. Assume that the Earth cooled from a molten state.
2. Assume that cooling followed ordinary laws of heat conduction and radiation (uniformitarianism).
3. Apply laws of heat conduction and radiation, and calculate the number of years it would take for the earth to cool from a hot molten mass to it's present state.

Kelvin's Result: Earth is **50** to **100** million years old.

Early Attempts to Measure Geologic Time Numerically

- Lord Kelvin (1897's), a physicist, attempted to calculate the time Earth has been a solid body.



Theory of heat conduction
Experimental data (melting temp. of rocks, size of Earth) → **Answer:50-100 million years**

Too Young for Geologists!

Early Attempts to Measure Geologic Time Numerically

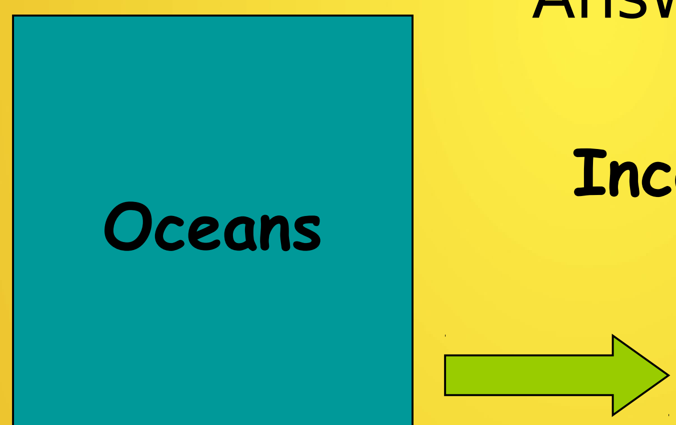
Saltiness of Seawater (date the ocean)

Salt rivers

Edmund Halley (1715)
John Joly (1889)

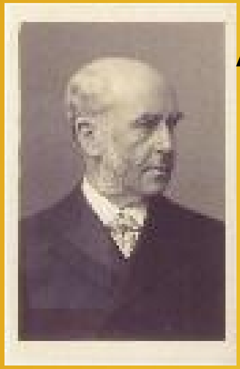
Answer: ~ 90-100 million years

Incorrect!!!



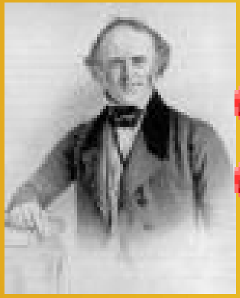
Salts are added both by erosion and by submarine volcanism, but salts are also removed by solution.

Early Dating Attempts
Quantitative



Archibald Geikie (1835-1924); many others

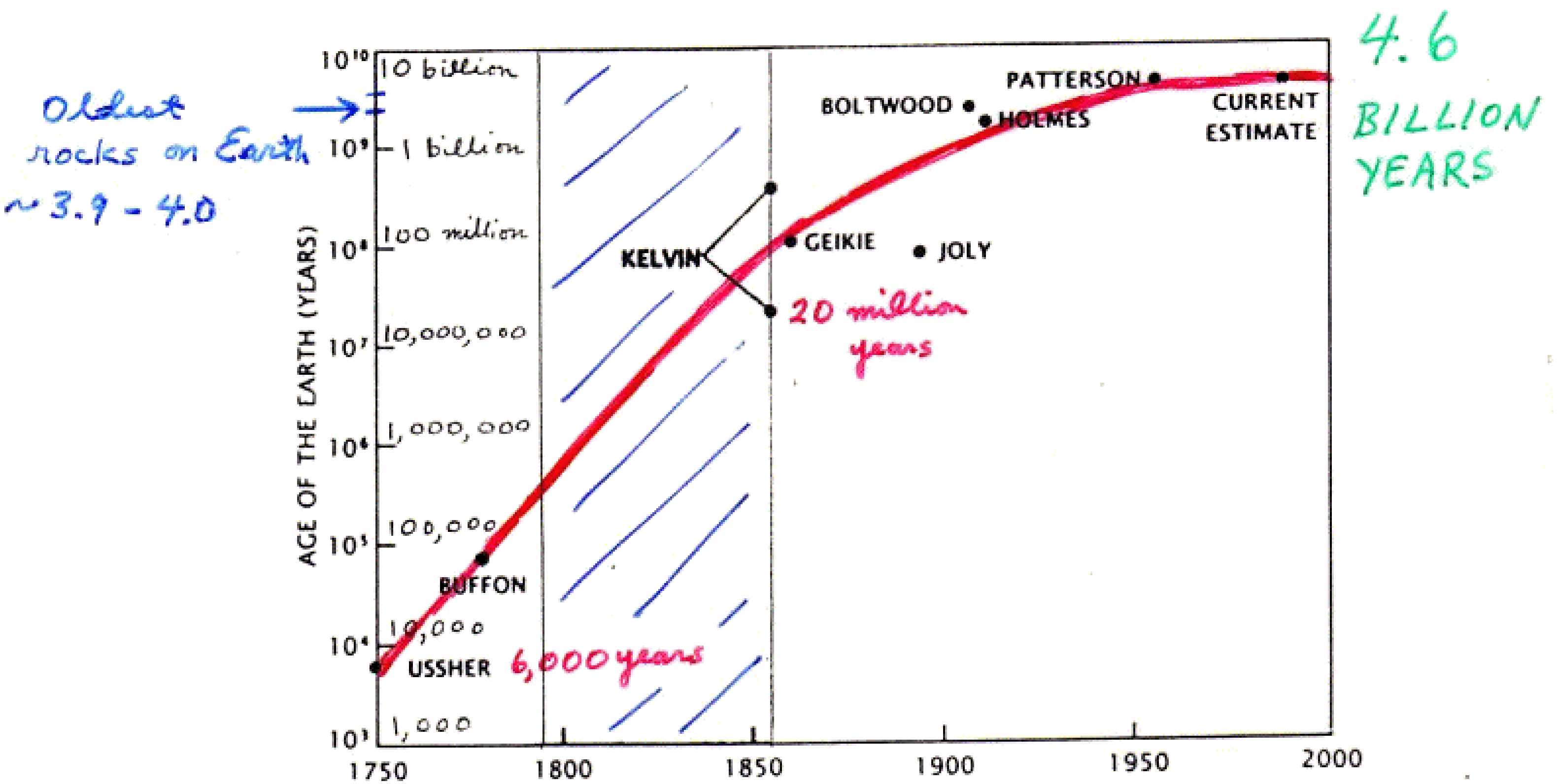
- method: sedimentation rates
- result: 3-1500 million years



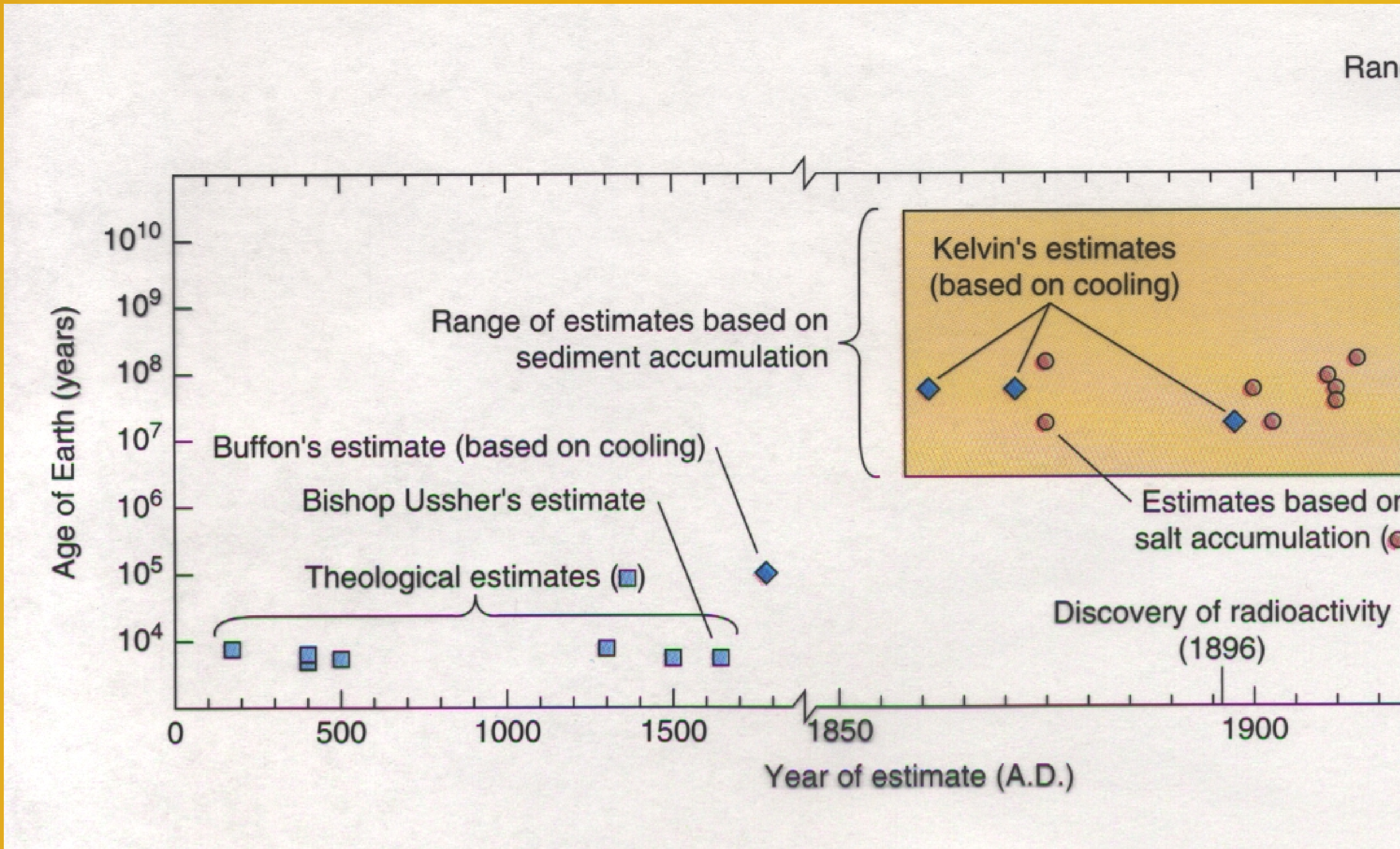
Charles Lyell (1797-1895)

- method: evolution of marine mollusks
- result: Cenozoic Era - 80 million years

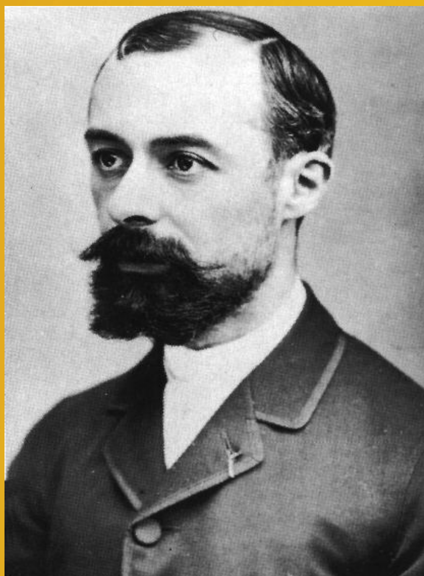
Age of the Earth



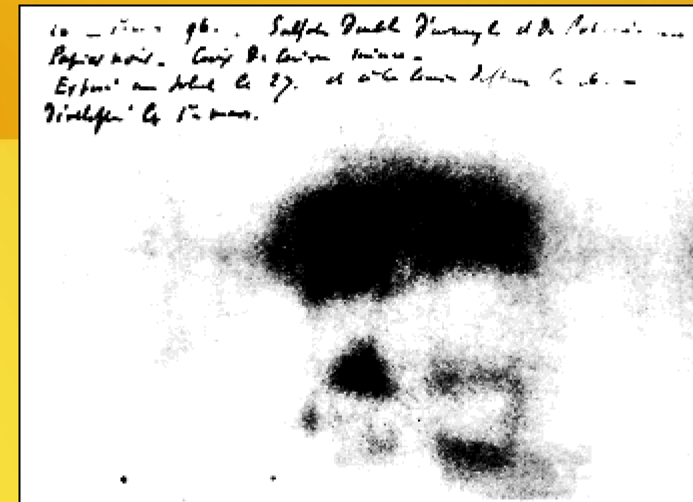
GEOLOGISTS AND PHYSICISTS have advanced the earth's age from hundreds of human generations to billions of terrestrial revolutions. The red point marks the biblical estimates for the earth's age. Between 1795 and 1862 most geologists believed the earth had existed for eternity or at least a period beyond measurement.


Rang
Kelvin's estimates (based on cooling)
Range of estimates based on sediment accumulation
Buffon's estimate (based on cooling)
Bishop Ussher's estimate
Theological estimates
Estimates based on salt accumulation
Discovery of radioactivity (1896)
Age of Earth (years)
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
0
500
1000
1500
1850
1900
Year of estimate (A.D.)

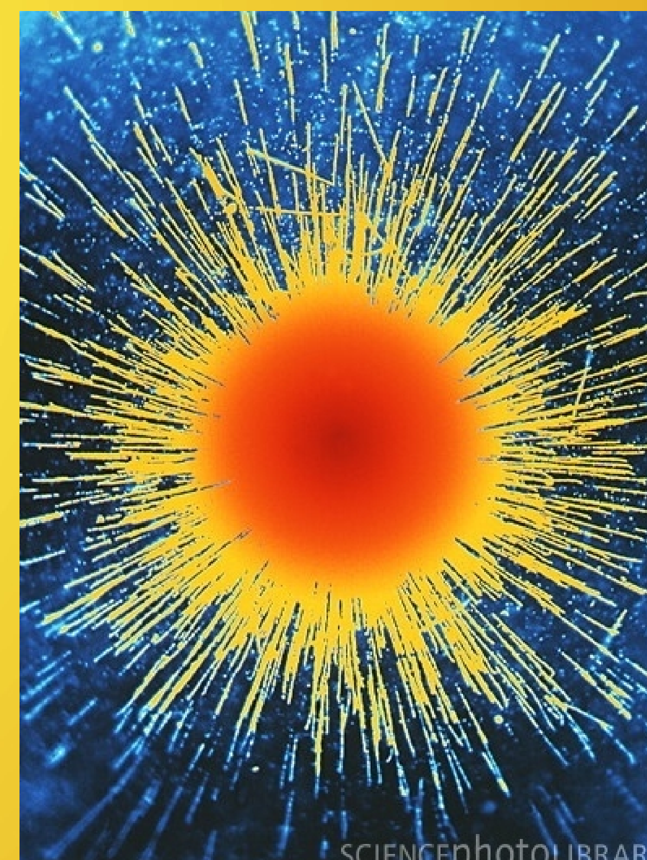
The Discovery of Radioactivity



Henri Becquerel (1852-1908)



Marie Curie (1867-1934)
Pierre Curie (1859-1906)

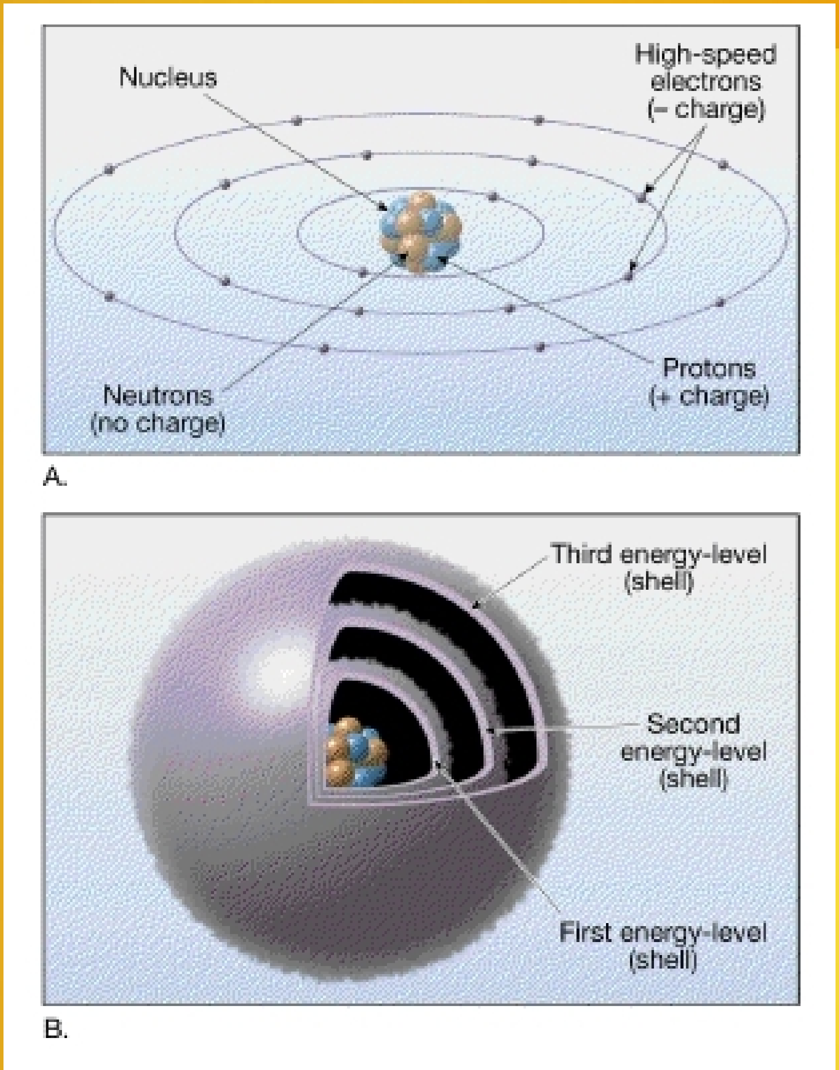


DISCOVERY OF RADIOACTIVITY

1) Henri Becquerel – studies phosphorescent minerals that glow when exposed to light and even afterward. Uses a phosphorescent uranium crystal to expose a photographic plate. Uranium exposes plate even if the plate is wrapped and in complete darkness of a drawer. Mineral is emitting a “strange ray”. His student Marie Curie. They call the uranium rays “radioactivity”.

2) Marie Curie – Discovers the radioactive elements Thorium, Polonium, and radium.
1903 – Nobel Prize in physics.
1911 – Nobel Prize in chemistry (only person ever to win both!)
1934 – Dies from leukemia contracted from years of exposure to radiation.

WHAT IS RADIOACTIVITY?

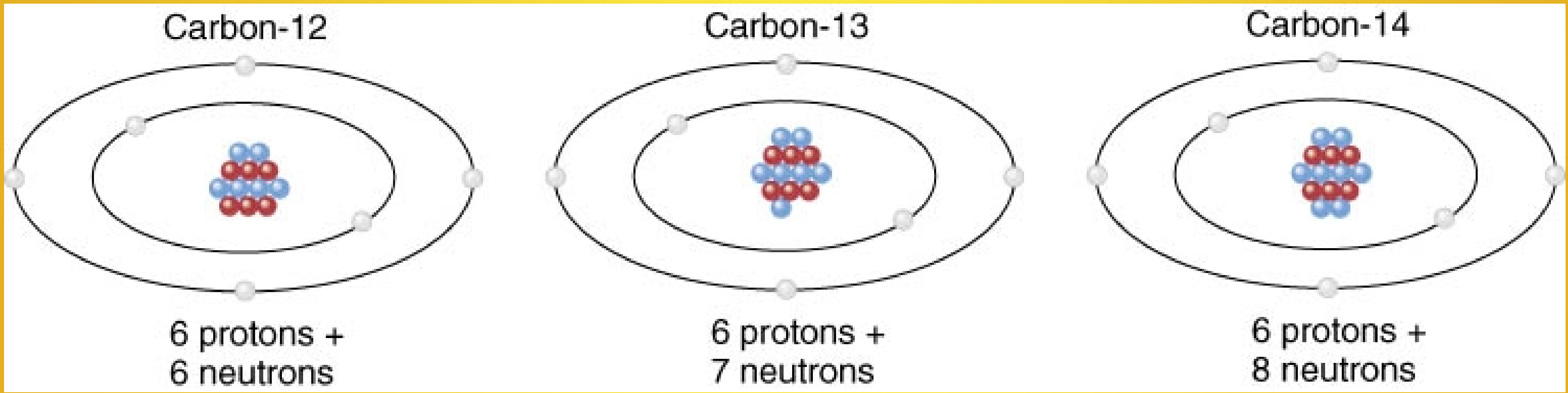


REVIEW: DEFINITIONS

1) Atom – the smallest particle that retains all the given properties of an element.
2) Element – a substance that cannot be broken down into a simpler substance by ordinary chemical or physical processes
3) Atomic Structure – protons (+), neutrons ( ) & electrons (-)

Isotopes

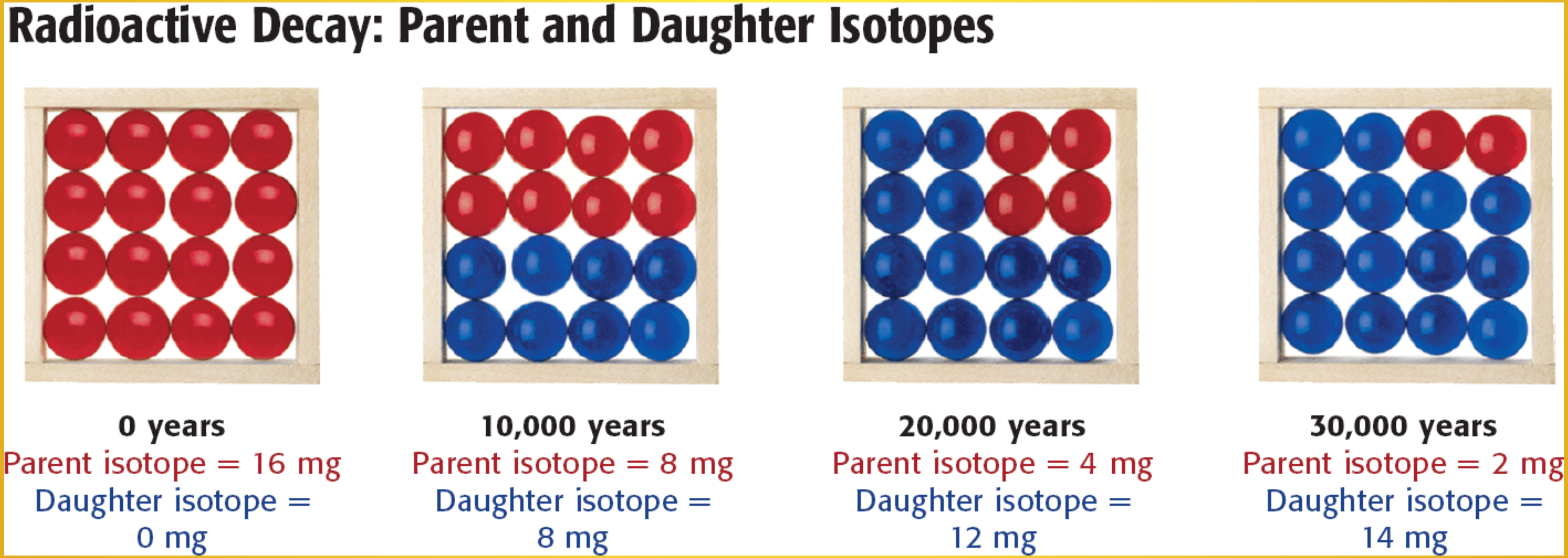
isotopes - atoms of the same element that have different numbers of neutrons but the same number of protons



Parent: 16 ◊ 8 ◊ 4 ◊ 2
Daughter: 0 ◊ 8 ◊ 12 ◊ 14

- In this example, each time this happened, **10,000 years** had gone by.
- So if it happened **3 times**, then the object is:

3 x 10,000 = 30,000 yrs old

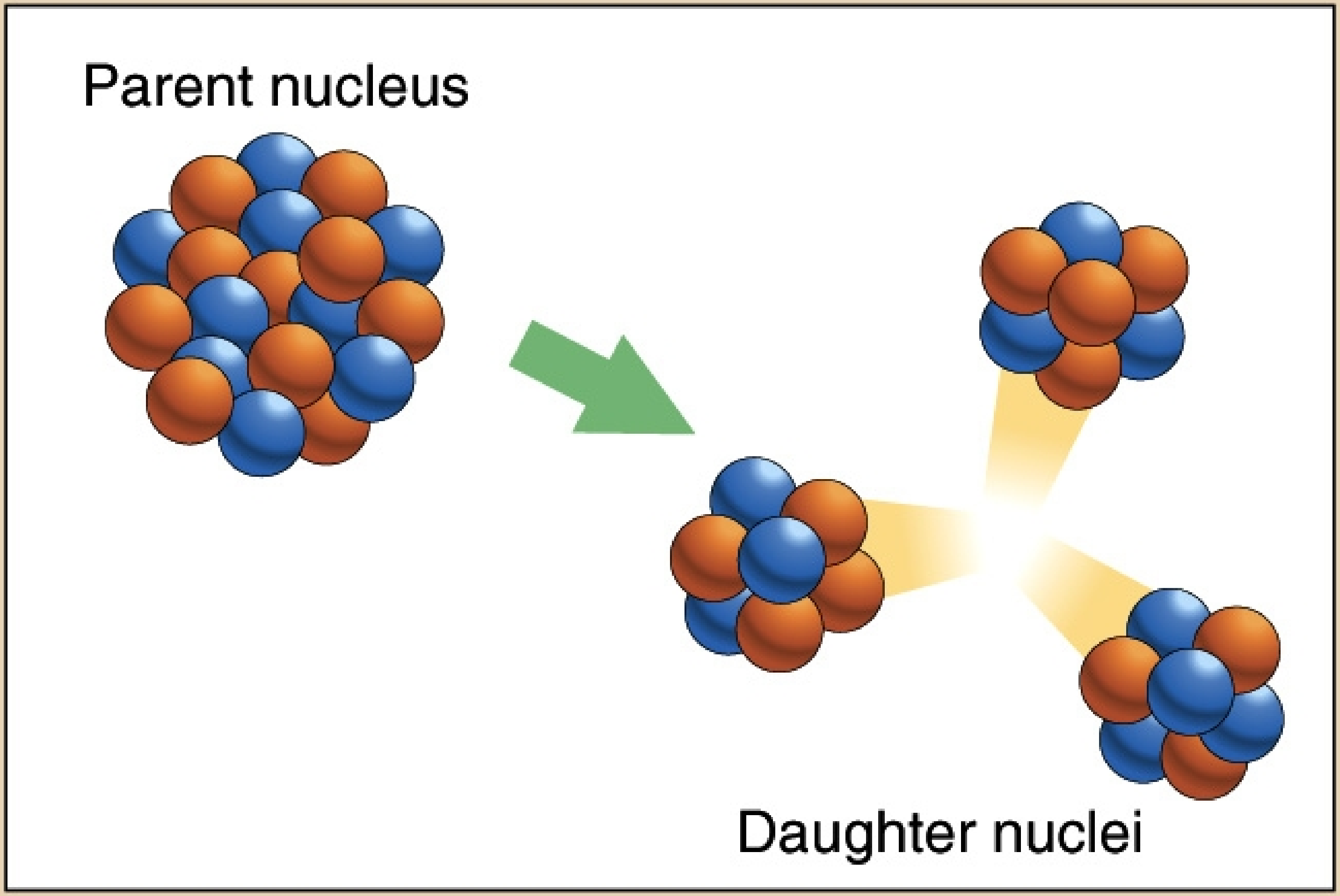


Pop Quiz

1) What method is used to figure out if a rock is **older or younger** than other rocks?
   RELATIVE DATING
2) What methods has helped scientists determine the **exact age** of Earth?
   ABSOLUTE DATING
3) Fill in this **table**:

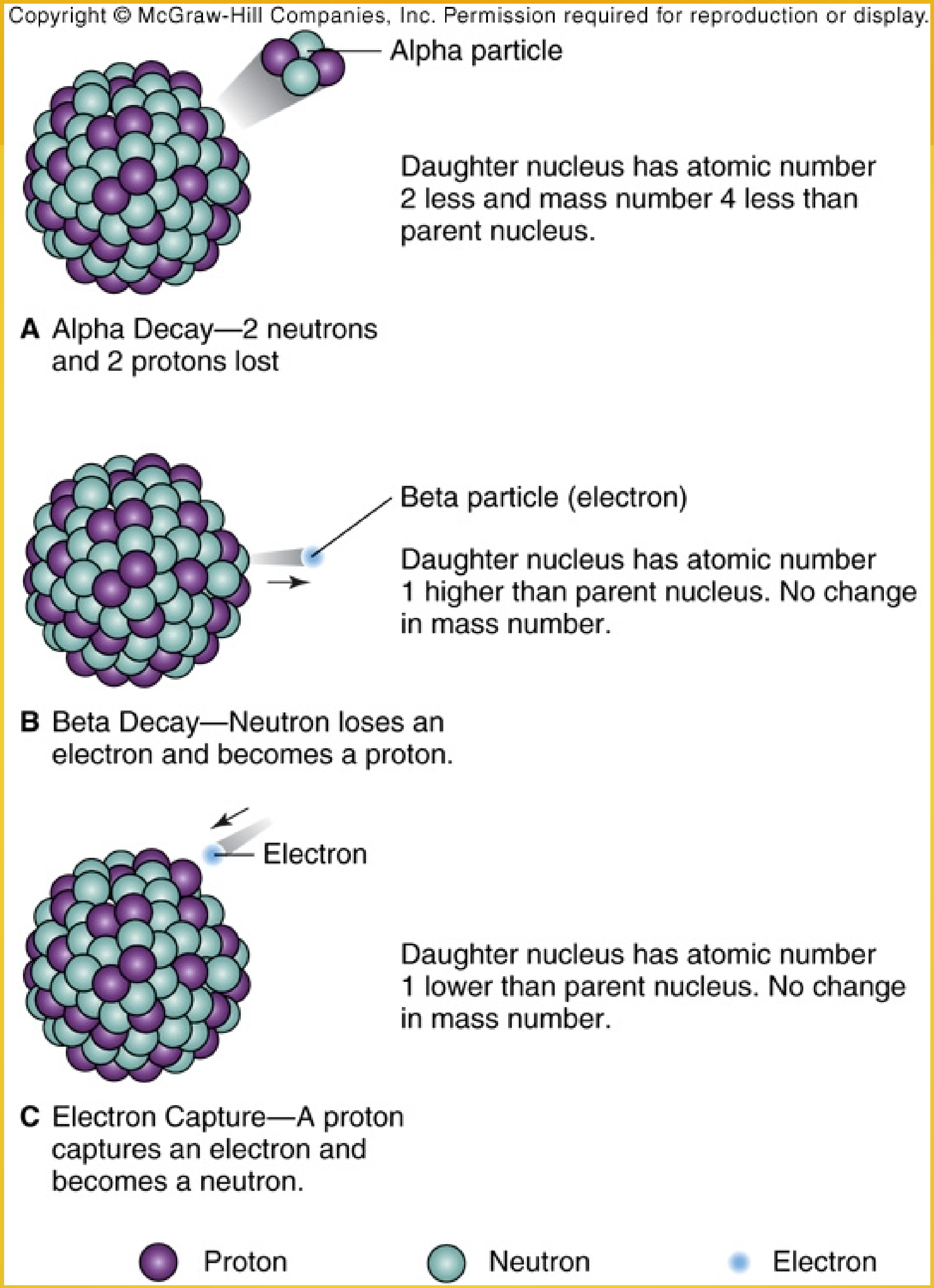
Isotope Ratios		
	Parent isotope (mg)	Daughter isotope (mg)
Rock forms	20	0
20,000 years	10	10
40,000 years	5	15

WHAT IS RADIOACTIVITY?

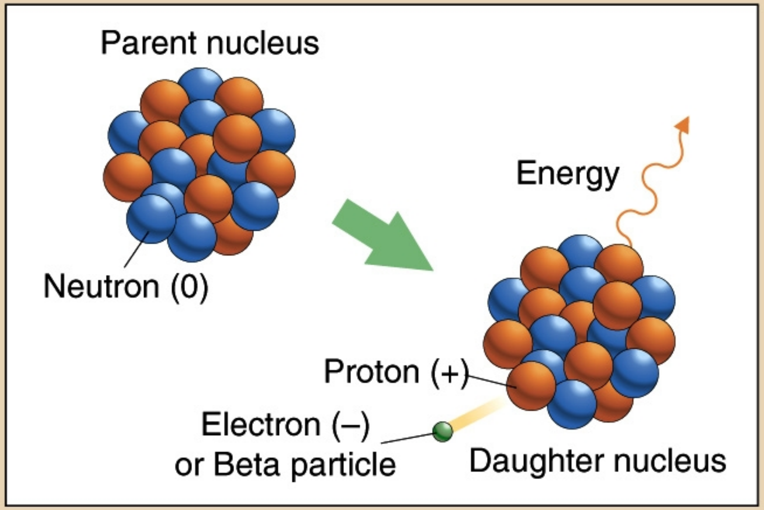


(E) Spontaneous fission
(Example: uranium to various elements)

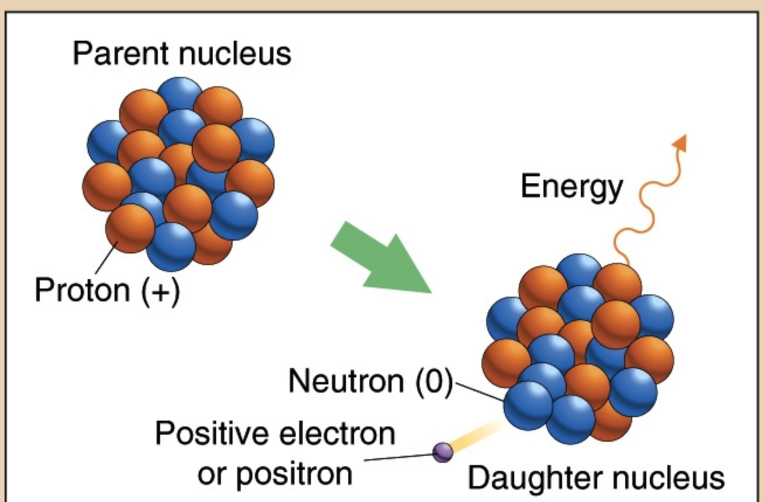
Radioactive Decay Types



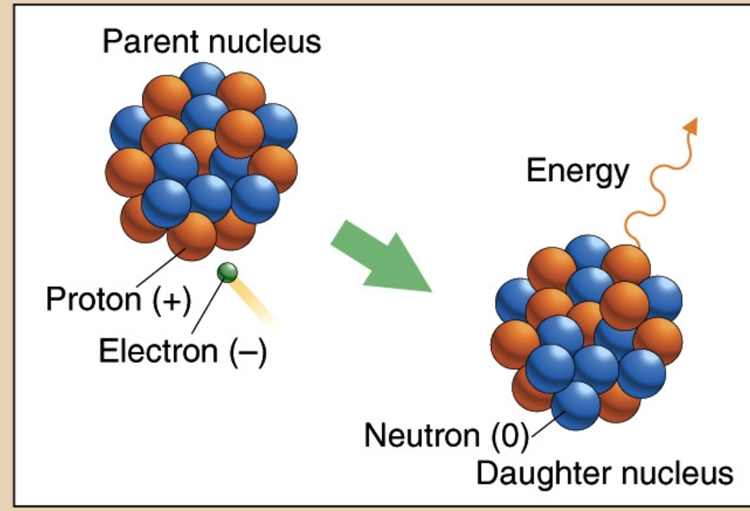
Types of Radioactive Breakdown



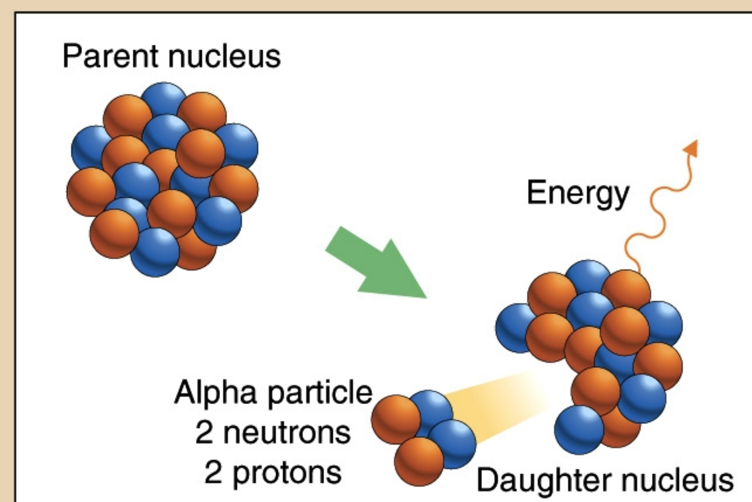
(A) Beta emission
(Example: rubidim to strontium)



(B) Positron emission
(Example: nitrogen to carbon)



(C) Electron capture
(Example: potassium to argon)

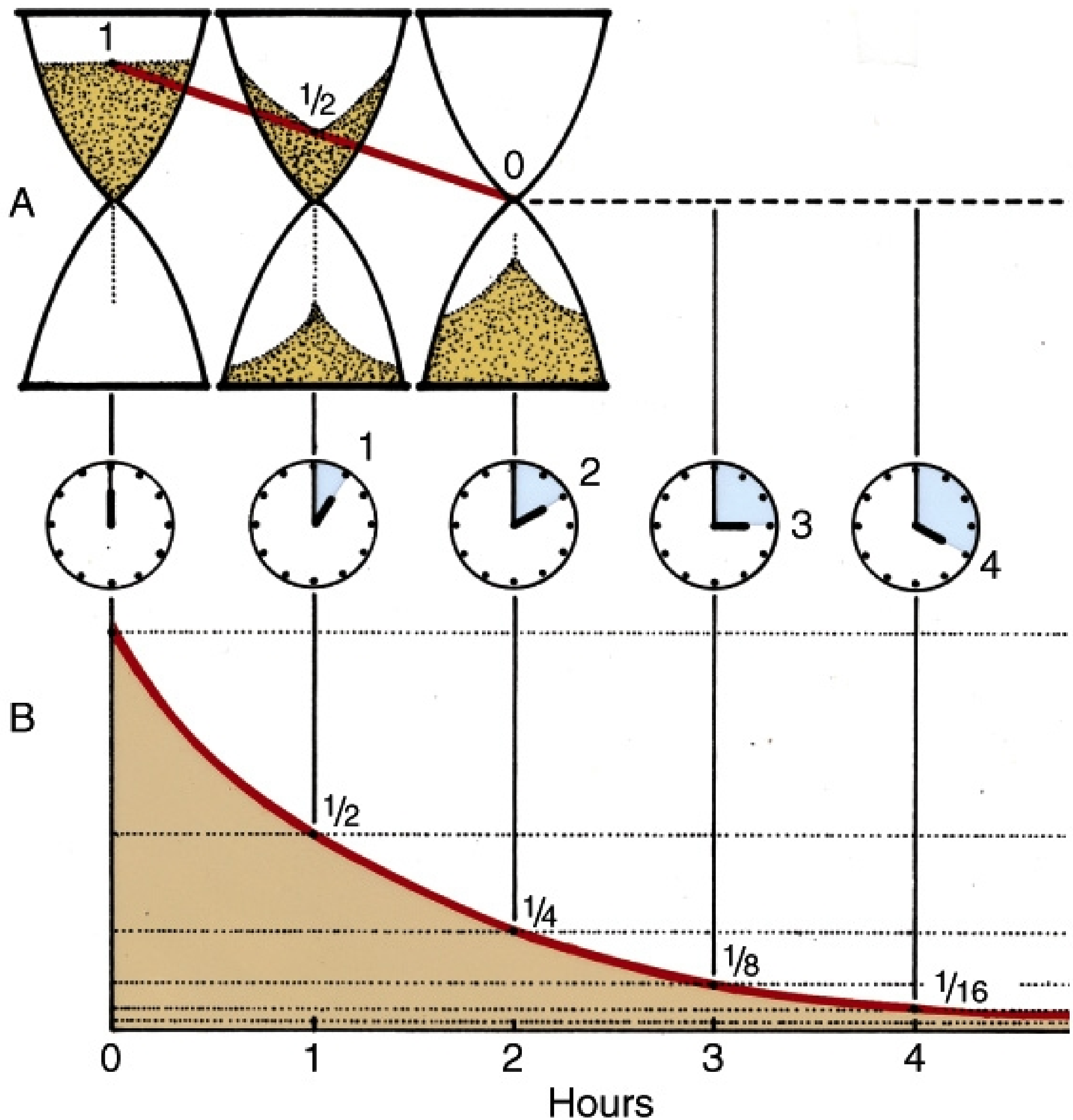


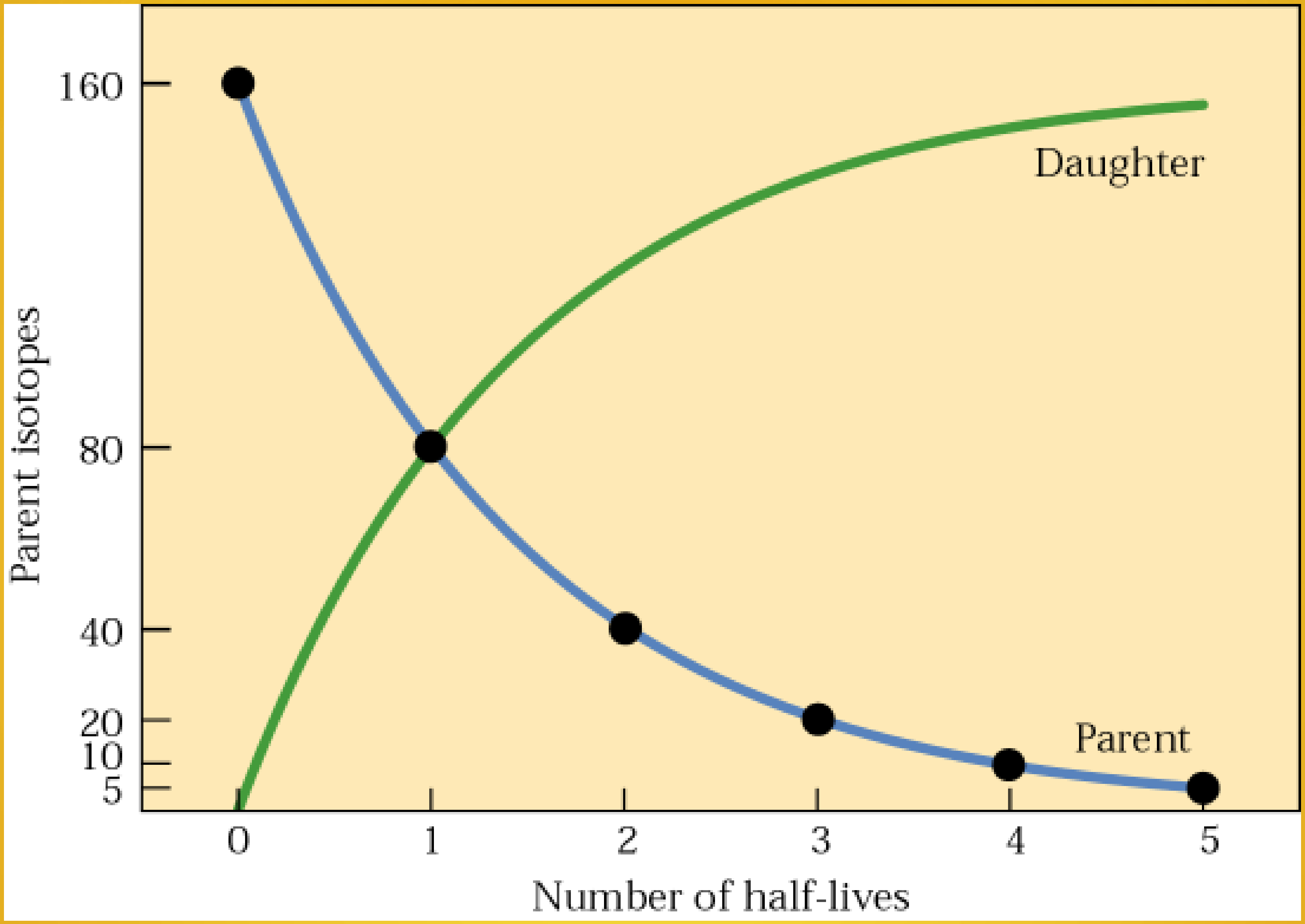
(D) Alpha emission
(Example: uranium to thorium)

The work of Becquerel and Curie attracts the interest of Ernest Rutherford (1871-1937).

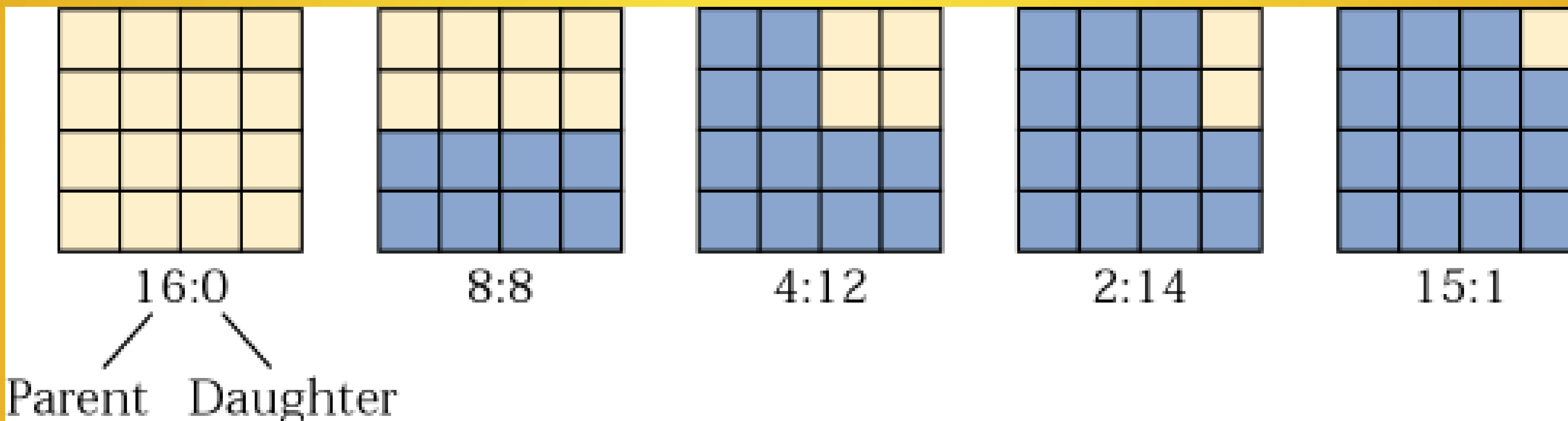
1) Rutherford discovers that there are different types of uranium rays. By passing rays through a magnetic field some veer right and some left. They are oppositely charged, and he names them alpha (+) and beta rays (-). Beta rays are electrons.
2) Using Thorium gas, Rutherford & Soddy measured how much radioactivity is produced and found something amazing!! After 54.5 seconds the level of radioactivity dropped by half. No matter how much gas he began with, after 54.5 seconds the activity dropped by 50%. After 109 seconds it was only ¼ of original value. After 163.5 seconds it was 1/8 of original value.
3) They had discovered the property of radioactive decay and the concept of a half-life.

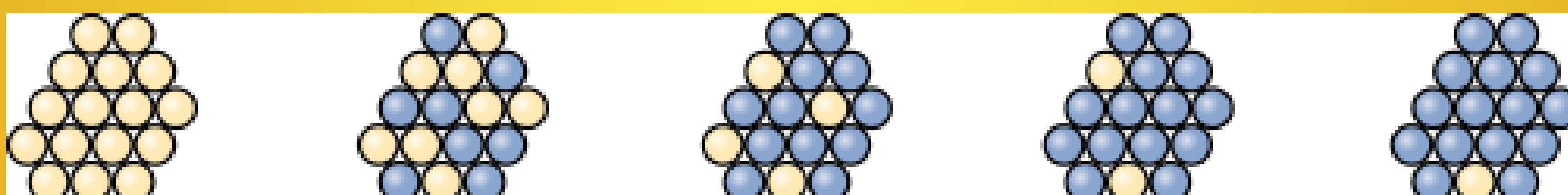
Half-life and the Exponential Decay Curve





160
80
40
20
10
5
Parent isotopes
Daughter
Parent
0
1
2
3
4
5
Number of half-lives


16:0
8:8
4:12
2:14
15:1
Parent
Daughter



A strange new world where substances transform themselves into different substances at highly regular rates. Atoms are not immutable!!

Radioactivity is a property of atoms not molecules or minerals. So radioactive minerals are minerals that contain radioactive elements.

Rutherford & Soddy published a classic paper in 1902 that laid the foundation for calculating the age of the Earth using radioactivity. A procedure we call Radiometric Dating.

RADIOACTIVITY

The atoms of radioactive elements are unstable and break down spontaneously to other elements (daughter products) accompanied by the emission of sub-atomic particles.

1.
2. The decay process is a statistical process based on probability. Each atom has exactly the same probability of decaying as any other atom of that substance. No one can predict when any one atom will decay, but large numbers decay at highly predictable rates. There ia an huge number of atoms in most mineral samples.
3. 1/100,000 of a gram of potassium has 150,000 trillion atoms!

3. The number of atoms that decay per time unit is *exactly* proportional to the number of atoms present. This is the basis for calculating a half-life.

RADIOACTIVITY

4. Radioactive decay produces heat. Pierre Curie (Marie's husband) discovered that 1 gram of radium produces 100 calories/hr. – enough to raise the temperature of 1 gram of water from freezing to boiling. Great Store Houses of Energy!!
5. Alpha particles – the particles produced by alpha decay are helium nuclei.

Lord Kelvin dies in 1907, never accepting radioactivity as an internal source of heat for the Earth. Because he never admitted that radioactivity questioned his basic assumptions, Kelvin never got close to calculating the real age of the Earth.

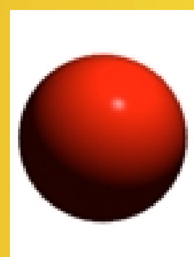
“Geology needs an independent time clock that runs at a uniform rate, just as we need it in our everyday life, and the physicist needs it in his laboratory”

G.D. Louderback, 1936

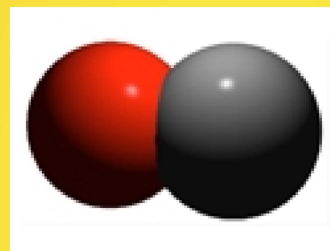
How does Radiometric Dating Work?

1) Elements come in different varieties called isotopes. Isotopes differ from one another by the number of neutrons in their nucleus.

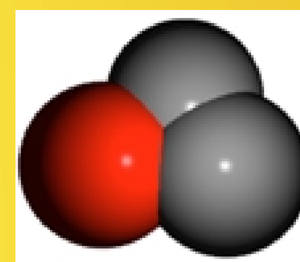
ISOTOPES OF HYDROGEN



Hydrogen
0 neutrons



Deuterium
1 neutrons



Tritium
2 neutrons

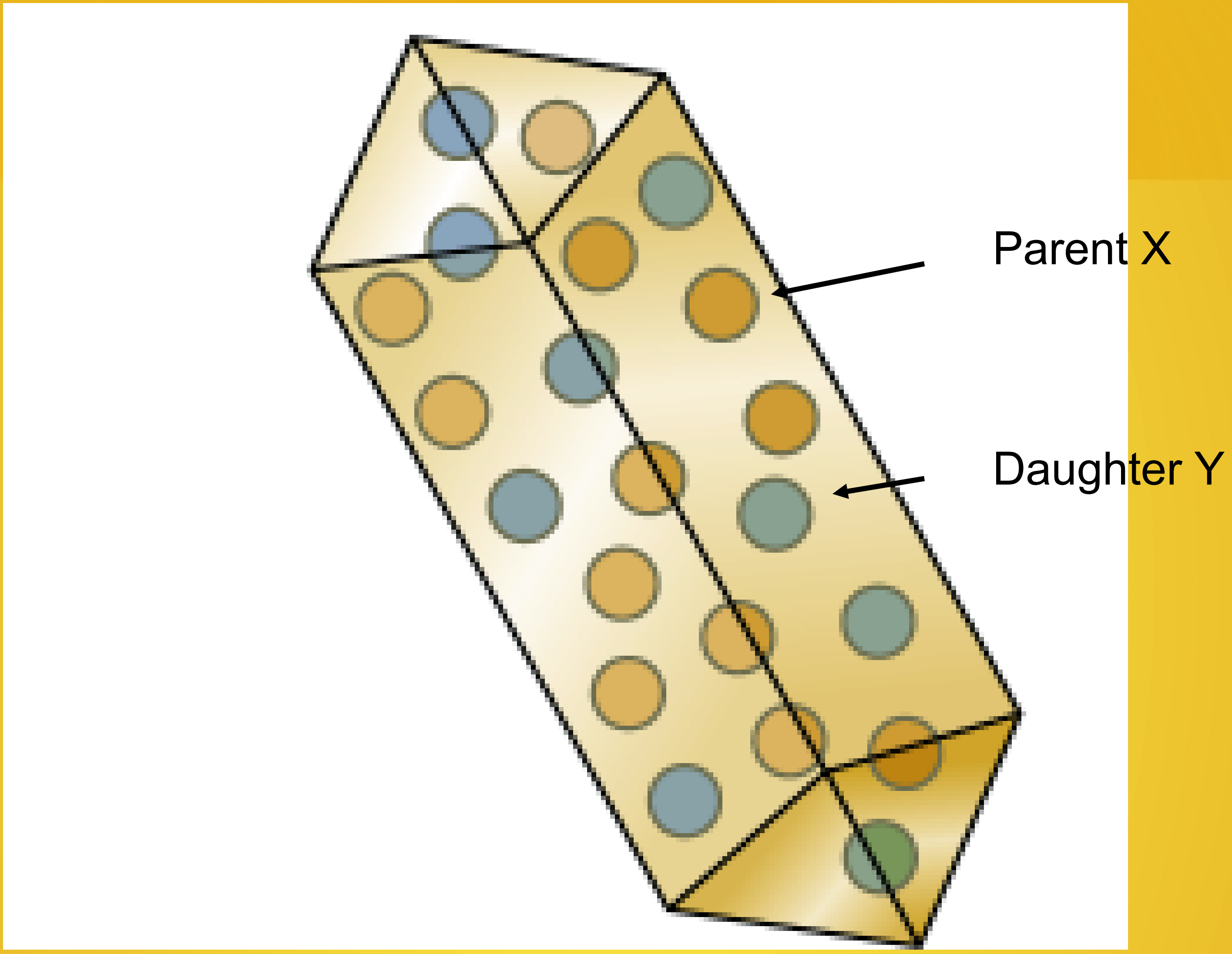
Radioactive isotopes spontaneously break down to more stable products at rates that can be measured experimentally. The unstable isotope is called the parent and the decay product is called the daughter.

2. Decay rates do not vary over time no matter what the physical or chemical conditions occur. This is a fundamental, and testable assumption.

3. Each parent – daughter pair constitutes an independent clock in which atoms of the parent are transformed into atoms of the daughter at a constant and predictable rate.

4. In principle, then, the amount of parent and daughter in a rock, along with a known decay rate provide the information necessary to calculate the time elapsed since the rock formed – the age of the rock.

5. 339 naturally occurring isotopes of 84 elements in nature.
   269 are stable, 70 are radioactive.
      18 have long half-lives and have existed since the formation of our solar system. These are the basis of radiometric dating



- **Radioactive element decaying in a crystal**

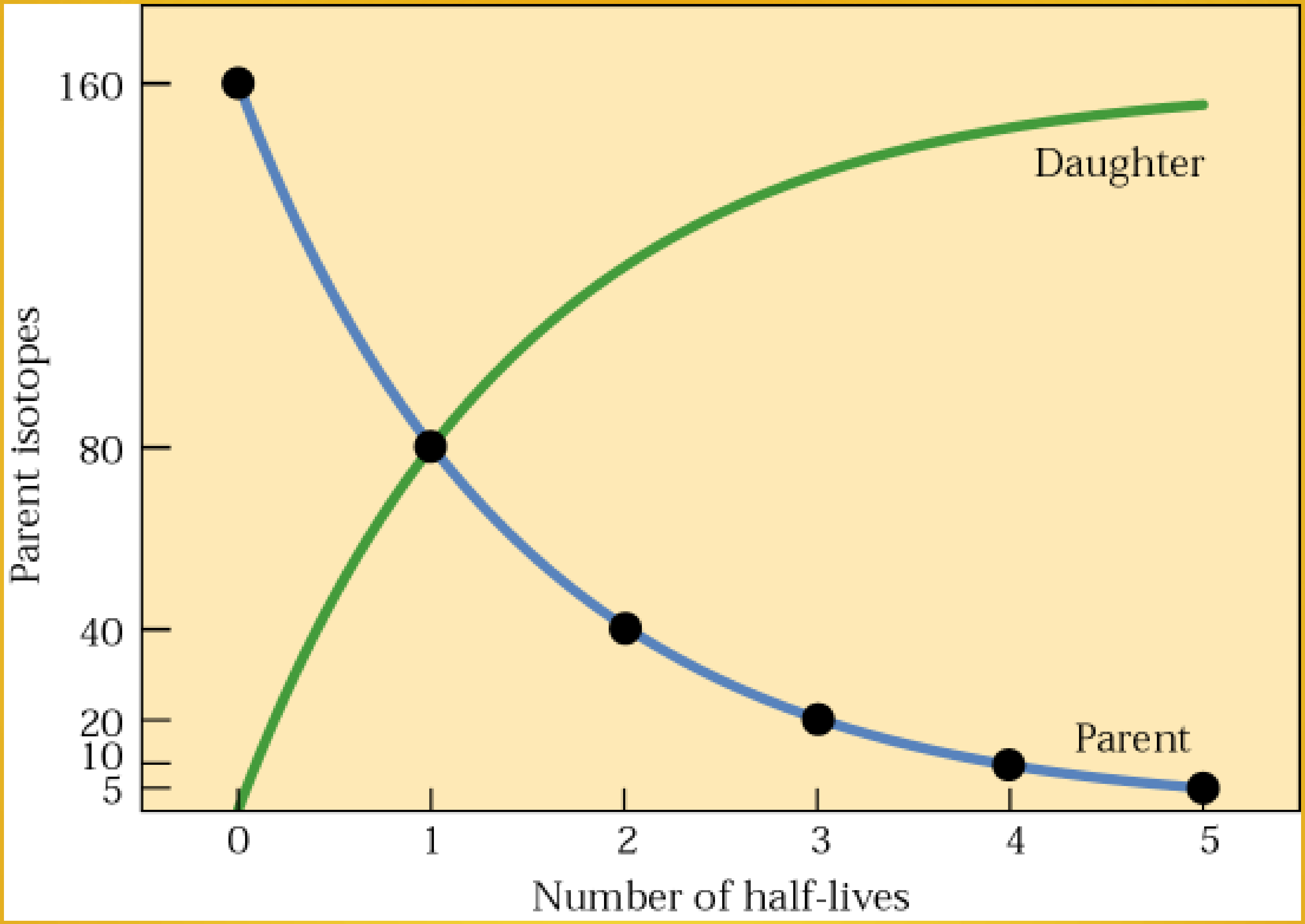
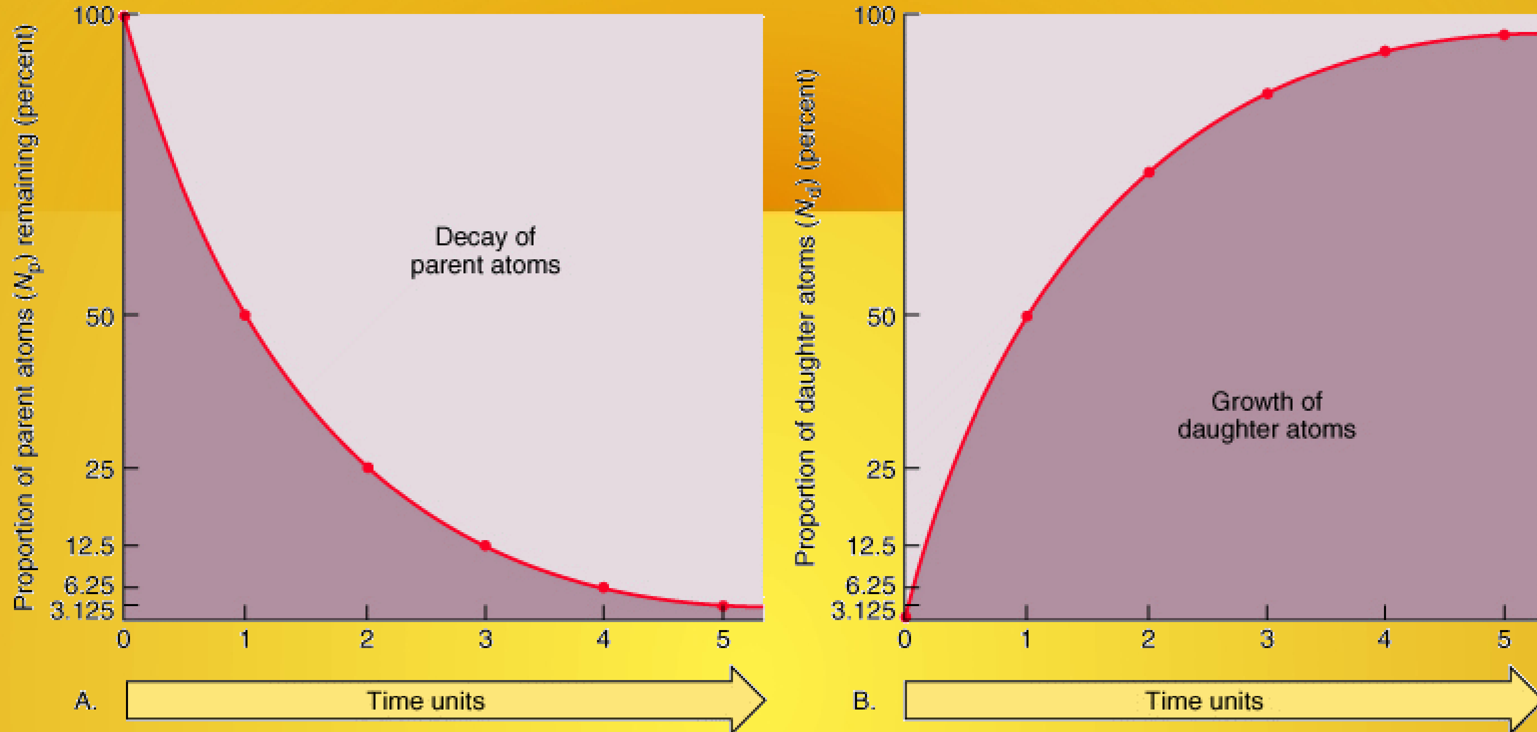

160
80
40
20
10
5
Parent isotopes
Daughter
Parent
0
1
2
3
4
5
Number of half-lives

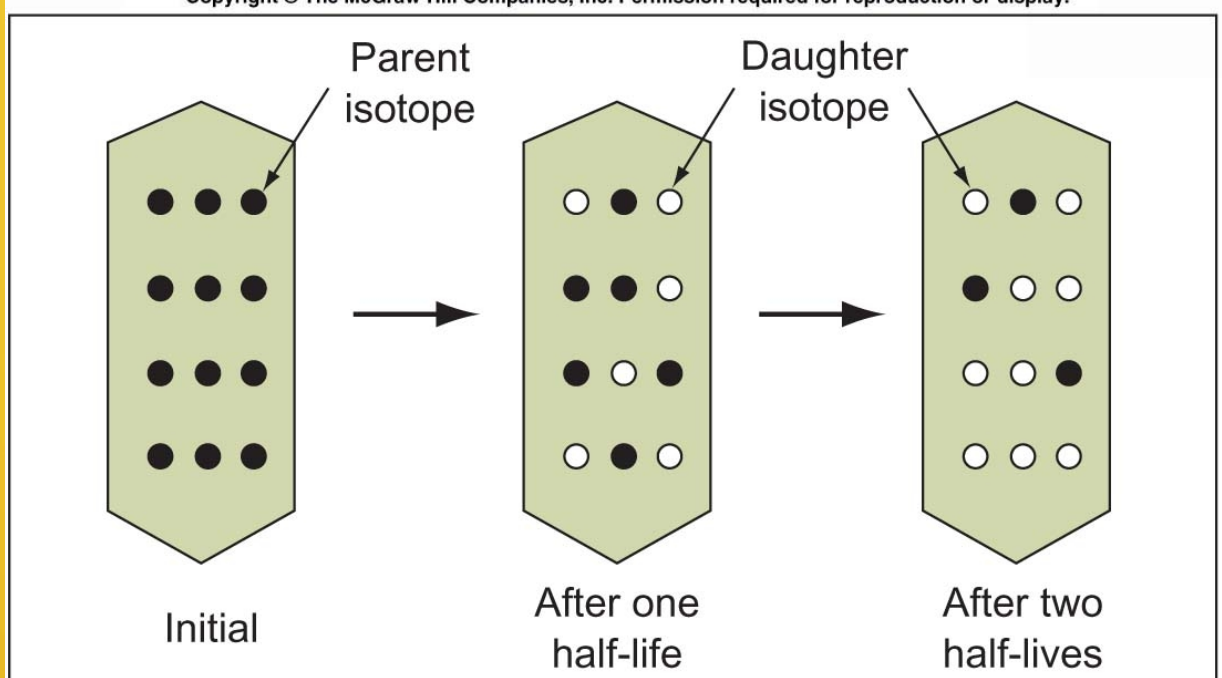
TABLE 8.1 Radioactive Isotopes Commonly Used in Radiometric Dating

Parent Isotope	Daughter Isotope	Half-life (years)
Uranium-238	Lead-206	4.5 billion
Uranium-235	Lead-207	704 million
Thorium-232	Lead-208	14.0 billion
Samarium-147	Neodymium-143	106 billion
Rubidium-87	Strontium-87	48.8 billion
Potassium-40	Argon-40	1.25 billion
Carbon-14	Nitrogen-14	5,730
Hydrogen-3	Helium-3	12.3

Half-Life

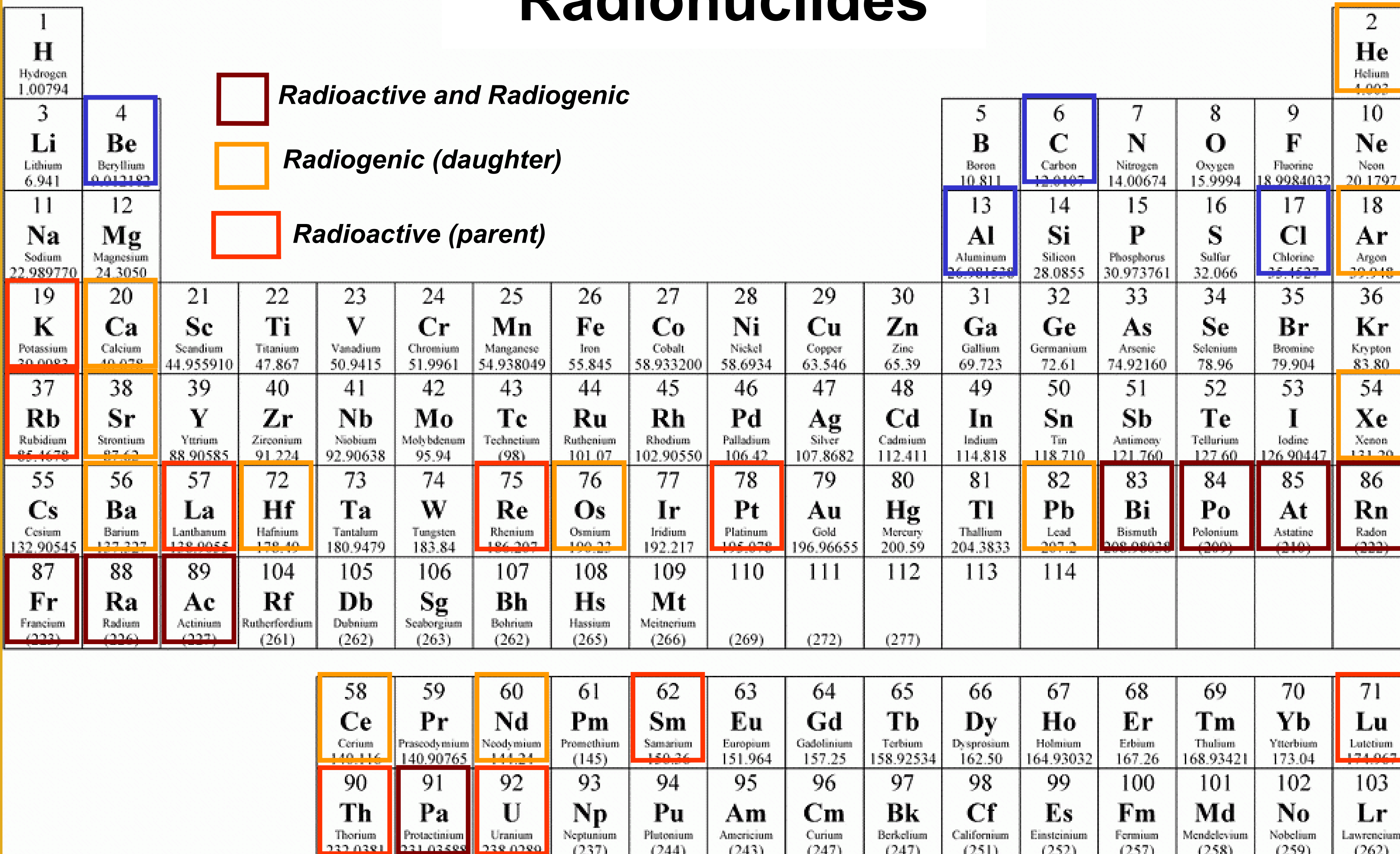


Proportion of parent atoms (N_p) remaining (percent)
100
50
25
12.5
6.25
3.125
0
1
2
3
4
5
Decay of parent atoms
A.
Time units
Proportion of daughter atoms (N_d) (percent)
Growth of daughter atoms
B.
Time units



Parent isotope
Daughter isotope
Initial
After one half-life
After two half-lives

Radionuclides



Cosmogenic:
Isotopes created when high-energy cosmic ray interacts with nucleus of an in situ Solar System atom, causing cosmic ray spallation.

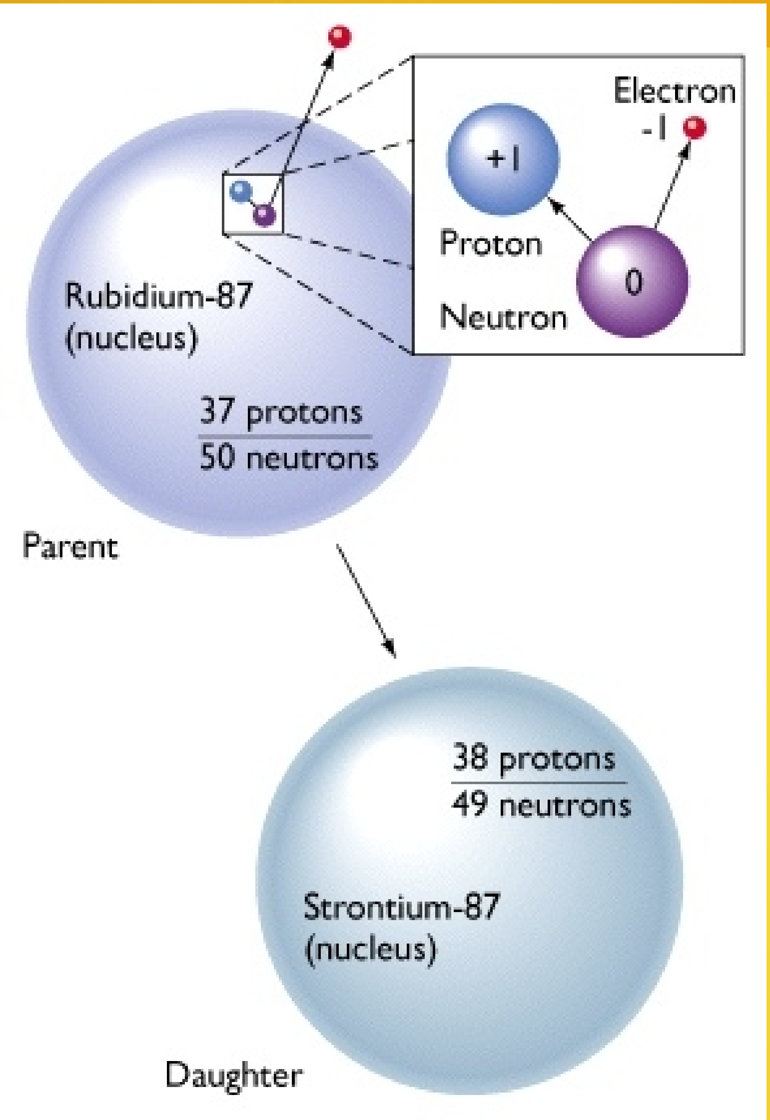
Radioactive Decay Systems

Isotopes Commonly used for Radiometric Dating

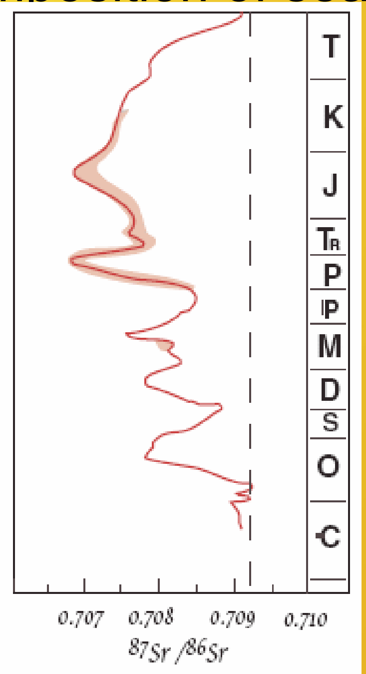
Isotopes		Half-life (years)	Effective Dating Range (years)
Dating Sample	Key Fission Product		
Lutetium-176	Hafnium-176	37.8 billion	early Earth
Uranium-238	Lead-206	4.468 billion	10 million to origin of Earth
Uranium-235	Lead-207	704 million	10 million to origin of Earth
Rubidium-87	Strontium-87	48.8 billion	10 million to origin of Earth
Potassium-40	Argon-40	1.277 billion	100,000 to origin of Earth
Carbon-14	Nitrogen-14	5730 ± 40	0-100,000

Radioactive Decay Systems

$^{87}Rb \rightarrow$ ^{87}Sr

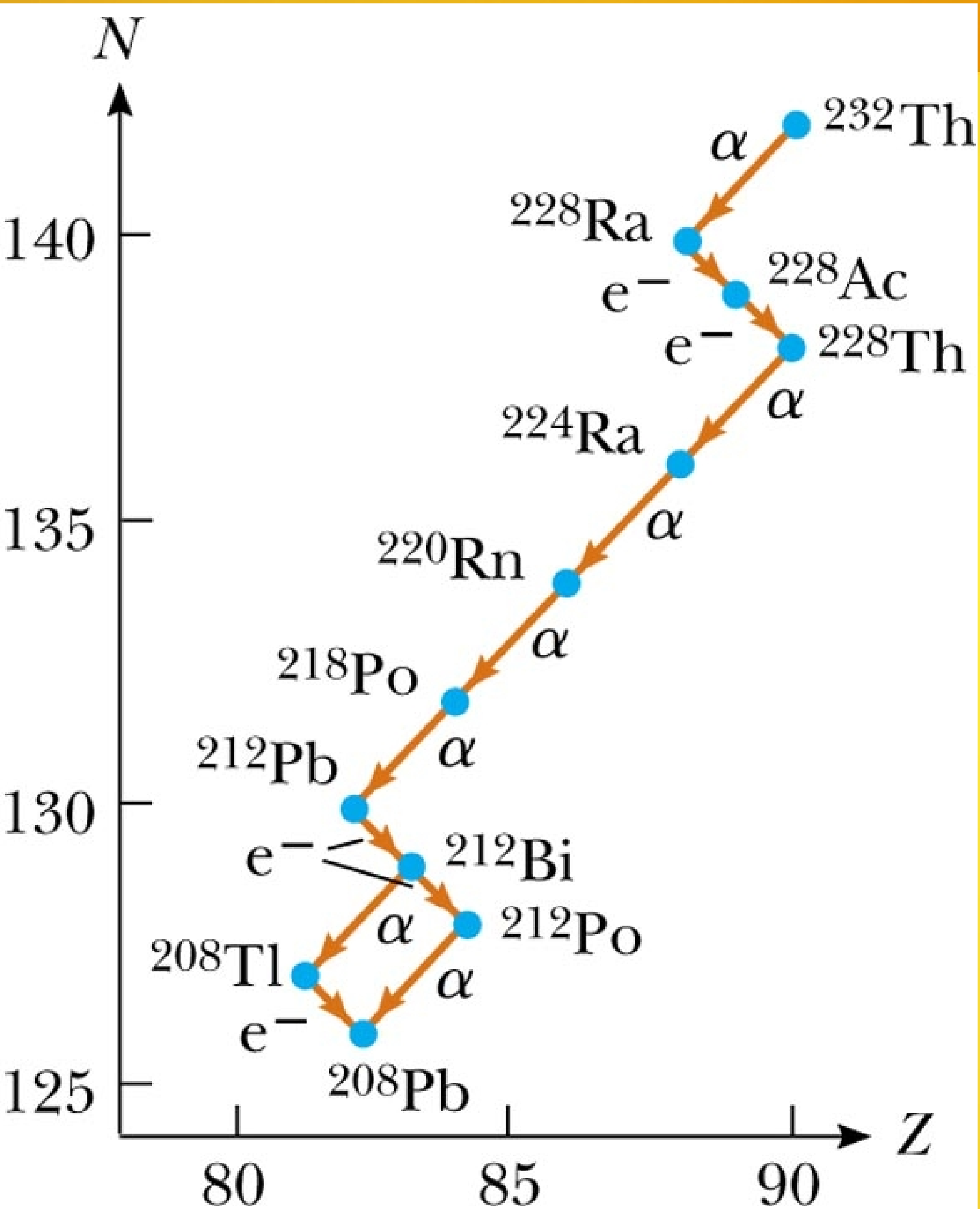


- Half -life: 49 billion years
- Effective Range: >10 million years
- Source Materials: Potassium mica, Potassium feldspar, biotite, glauconite, whole metamorphic or igneous rock
- Uses: Igneous rocks
  - Carbonates - Sr composition of sea water through time
  - Meteorites



Radioactive Decay Systems

^{232}Th → ^{208}Pb



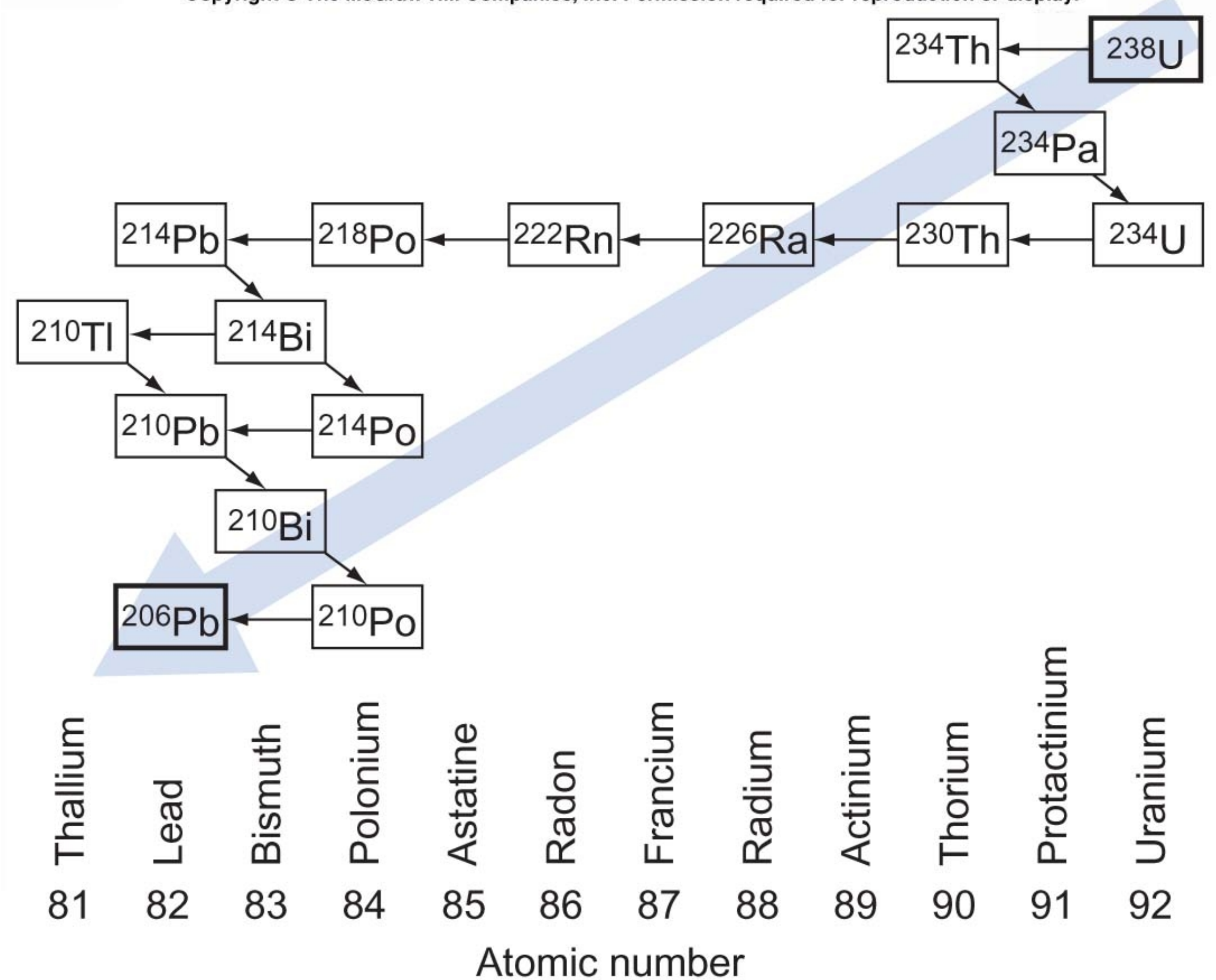
- Half -life: 14 billion years
- Effective Range: >10 million years
- Source Materials: thorite, monazite, thorogummite, huttonite in granites and basalts
- Uses: stellar ages
  - sea floor nodules

Radioactive Decay Systems

$^{238}U \rightarrow {}^{206}Pb$

URANIUM 238 (U238) RADIOACTIVE DECAY

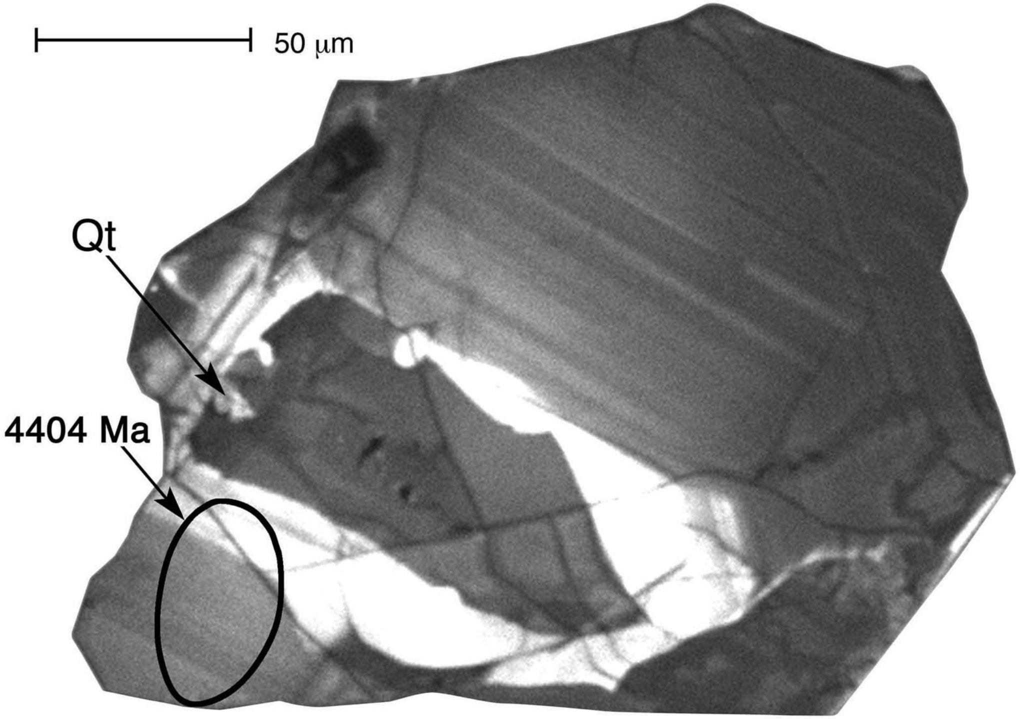
type of radiation	nuclide	half-life
	uranium—238	4.5 x10^{9} years
α	thorium—234	24.5 days
β	protactinium—234	1.14 minutes
β	uranium—234	2.33 x10^{5} years
α	thorium—230	8.3 x10^{4} years
α	radium—226	1590 years
α	radon—222	3.825 days
α	polonium—218	3.05 minutes
α	lead—214	26.8 minutes
β	bismuth—214	19.7 minutes
β	polonium—214	1.5 x10^{-4} seconds
α	lead—210	22 years
β	bismuth—210	5 days
β	polonium—210	140 days
α	lead—206	stable



Radioactive Decay Systems

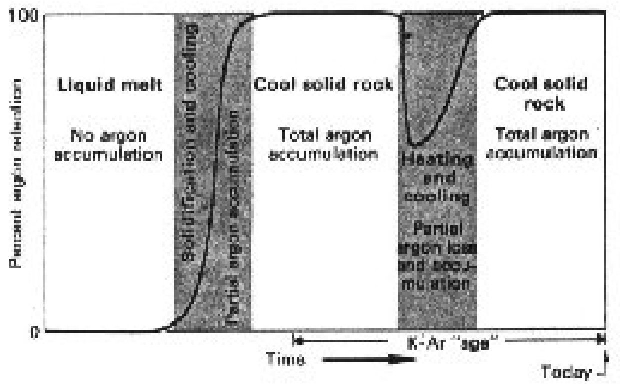
$^{238}U \rightarrow {}^{206}Pb$

- Half -life: 4.5 billion years
- Effective Range: >10 million years
- Source Materials: Zircon, uraninite, pitchblende
- Uses: age of Earth
    - meteorites

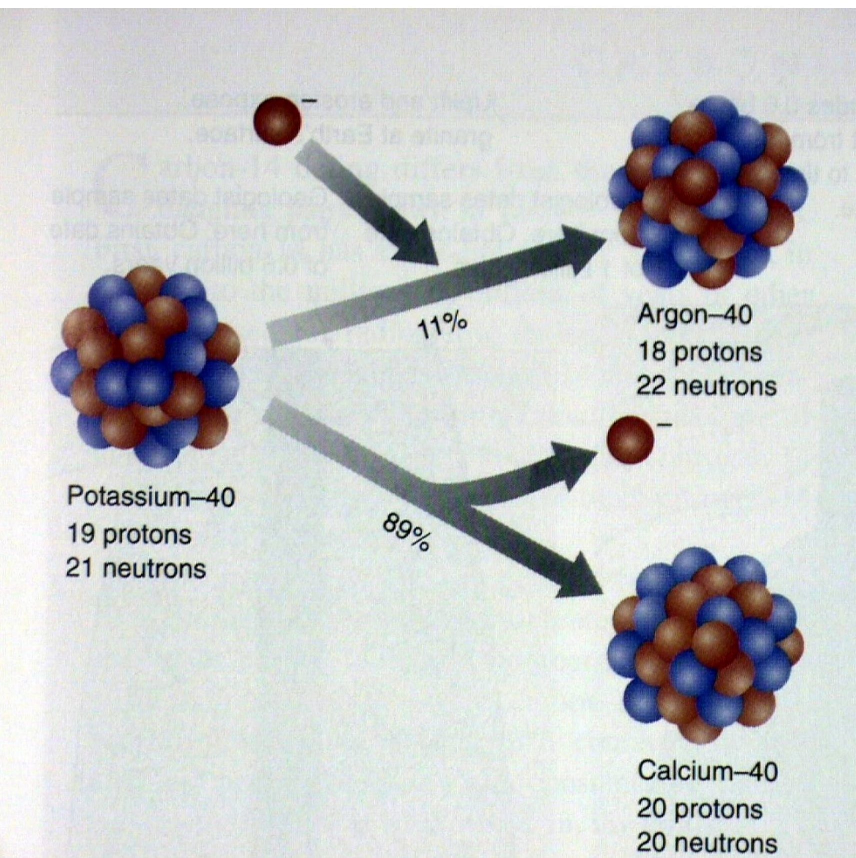


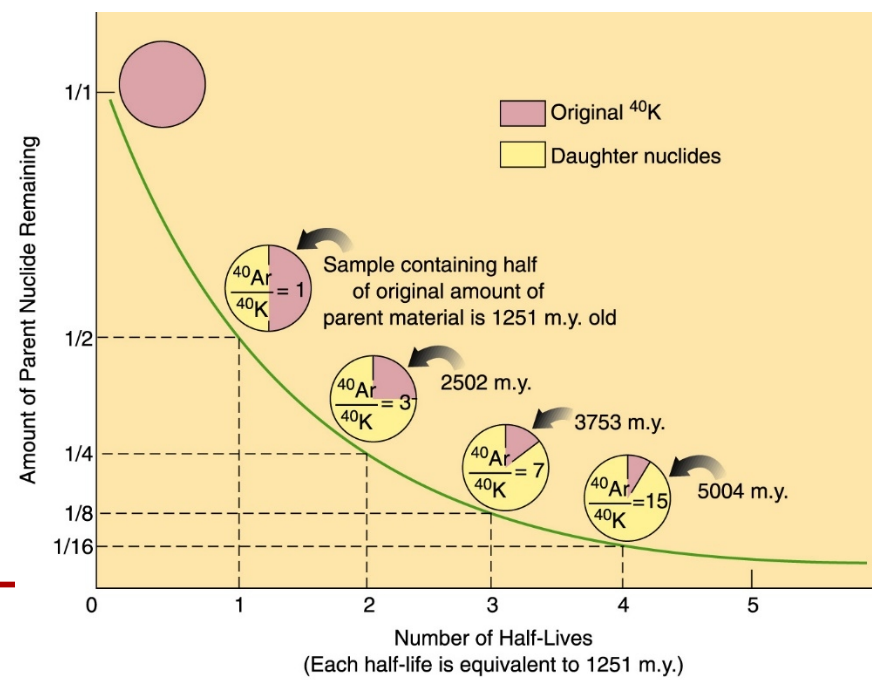
Radioactive Decay Systems

$^{40}K \rightarrow\ ^{40}Ar$



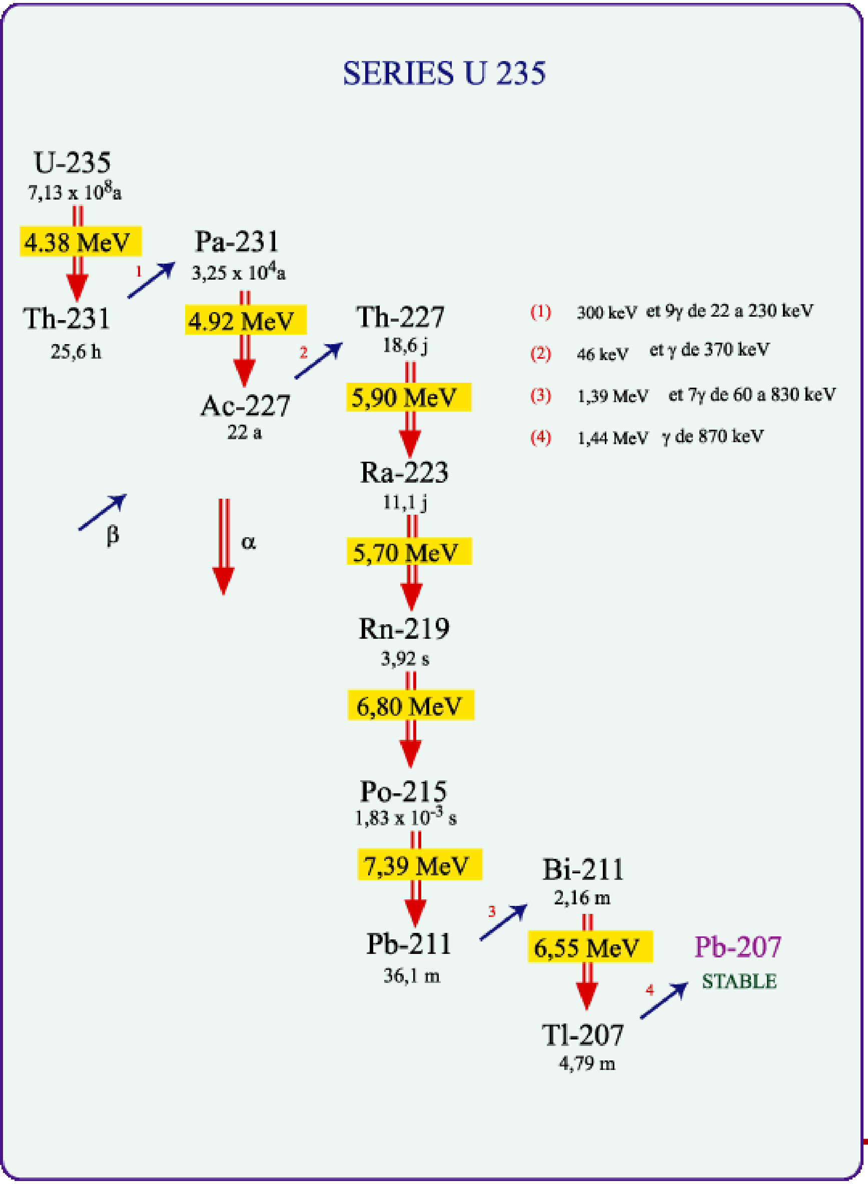
- Half -life: 1.25 billion years
- Effective Range: >100,000 years
- Source Materials: Muscovite, biotite, hornblende, volcanic rock, glauconite, potassium feldspar
- Uses: very old archaeological materials





Radioactive Decay Systems

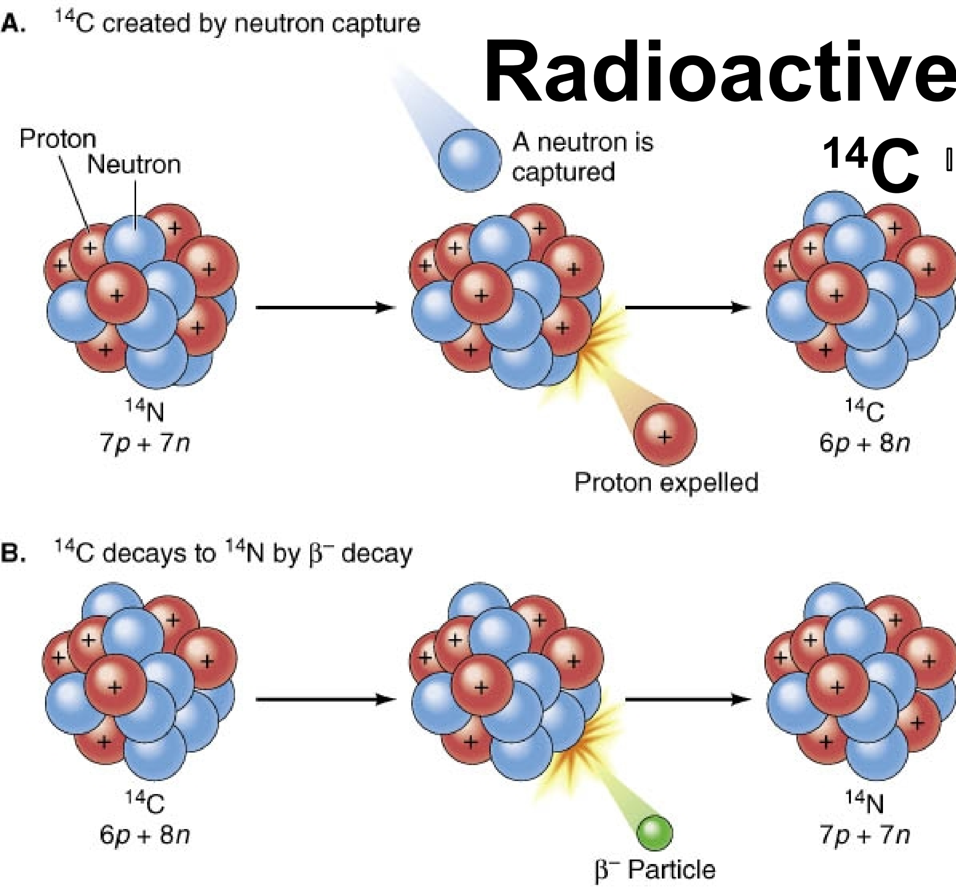
$^{235}U \rightarrow {}^{207}Pb$



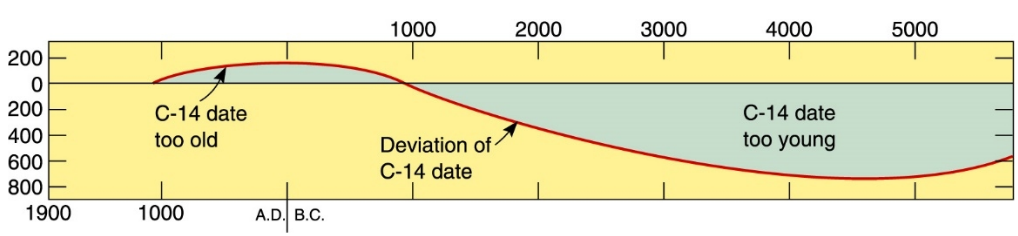
- Half -life: 700 million years
- Effective Range: >10 million years
- Source Materials: zircon, urananite, monazite, apatite
- Uses: dinosaur fossil dating

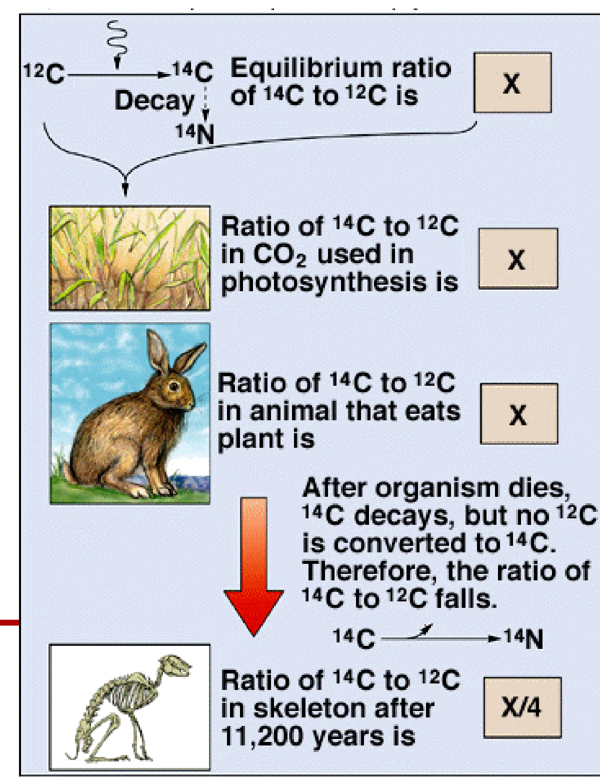
Radioactive Decay Systems

$^{14}C \Rightarrow {}^{14}N$



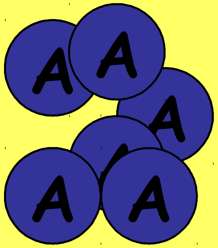
- Half -life: 5,730 years
- Effective Range: 100-40,000 years
- Source Materials: Organic Matter
- Uses: Radiocarbon Dating





Decay Rates

- Decay rates are unaffected by geological processes (mainly chemical)
- Once radioactive atoms are created they start to act like ticking clock



Know the decay rate

Count the daughter atoms

Count the Parent atoms

Calculate the time since the atomic clock started ticking

Instruments and Techniques

- **Mass Spectrometry:** measure different abundances of specific nuclides based solely on atomic mass.

  - Basic technique requires ionization of the atomic species of interest and acceleration through a strong magnetic field to cause separation between closely similar masses (*e.g.* ^{87}Sr and ^{86}Sr).
    Count individual particles using electronic detectors.

  - TIMS: thermal ionization mass spectrometry
  - SIMS: secondary ionization mass spectrometry - bombard target with heavy ions or use a laser

- **Sample Preparation:** TIMS requires doing chemical separation using chromatographic columns.

Clean Lab - Chemical Preparation

http://www.es.ucsc.edu/images/clean_lab_c.jpg

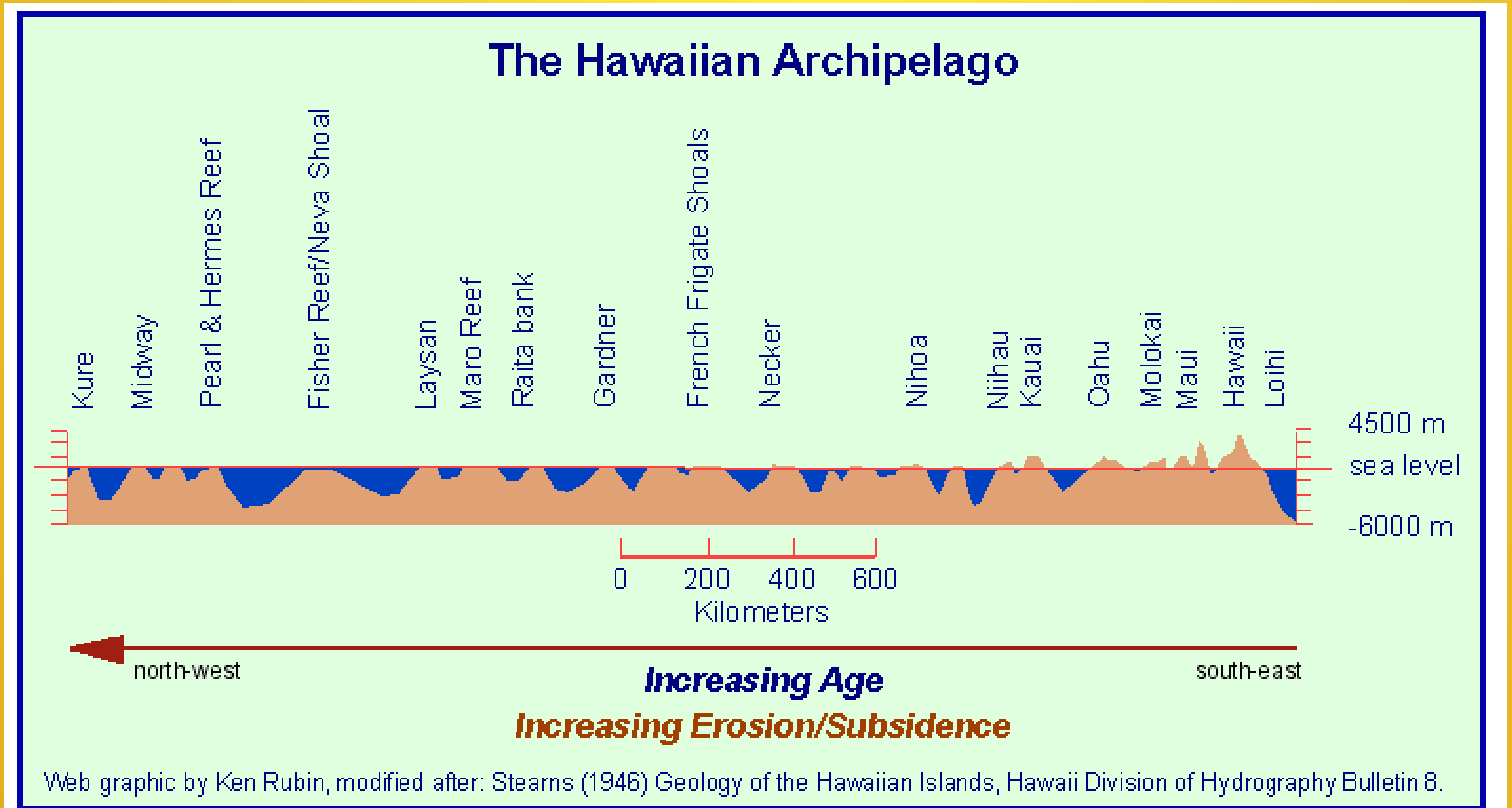
Thermal Ionization Mass Spectrometer

From: http://www.es.ucsc.edu/images/vgms_c.jpg

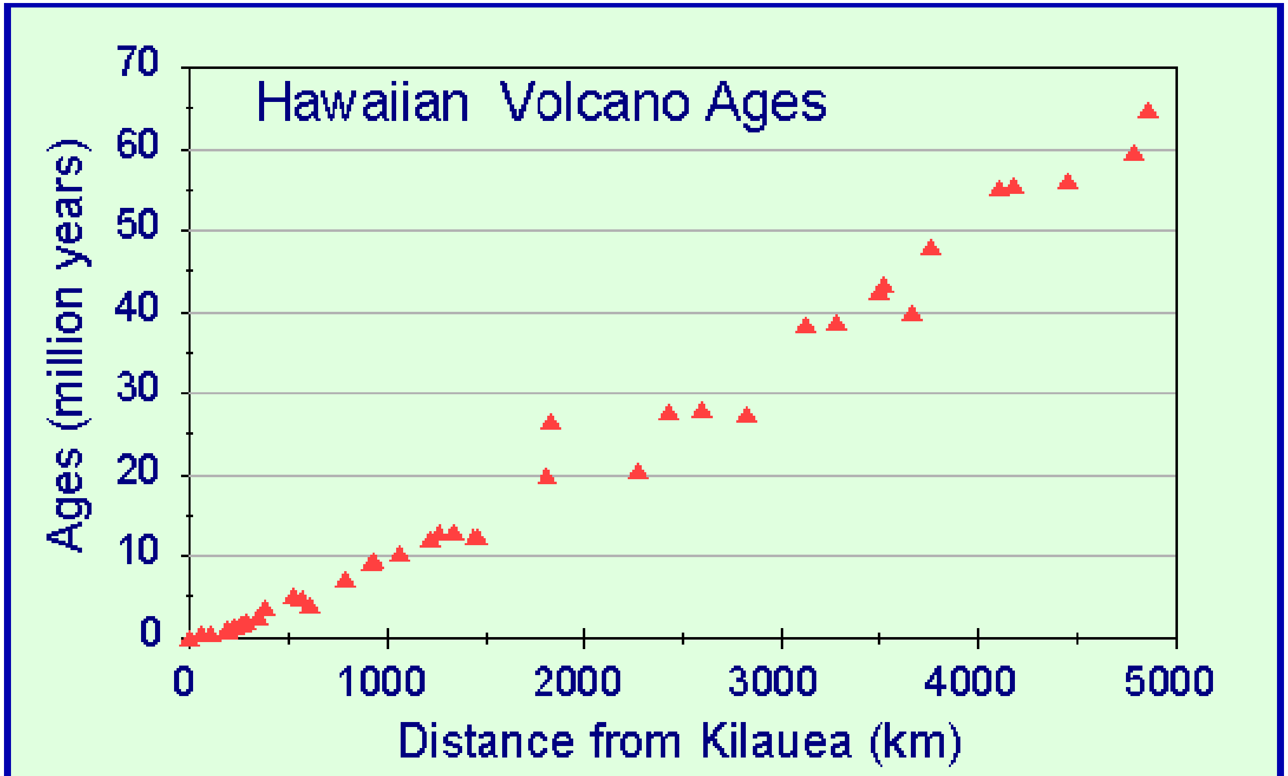
Independent Checks on Radiometric Ages

- **Correlation of erosion** with age on Hawaiian Island Chain: Dates increase in age to the NW as does erosion.

The Hawaiian volcanoes were produced by the Hawaiian hot spot, which is presently under the Big Island of Hawaii. The islands of the Hawaiian chain and the intervening shallows, banks and reefs along a line from southeast to northwest. Note that the islands of Lanai and Kahoolawe are not shown because they would "overlap" with Molokai and Maui, respectively (see the map of the Islands on the Hawaiian Volcanoes page) In general, when you move along the island chain from southeast (Hawaii) to northwest, (Kure), the volcanoes become older and older.



The aging of the islands with distance from the current hot spot is demonstrated in the diagram below, where distance along the chain is approximated as distance away from Kilauea volcano (the youngest above-sea-level Hawaiian volcano). In fact, even beyond Kure the Hawaiian chain continues as a series of now-submerged former islands known collectively as the Emperor seamounts. The two primary volcanoes that make up Oahu (where Honolulu is) have not erupted for well over a million years!



Web Graphic by Ken Rubin and Rochelle Minicola using data from: Clague and Dalrymple (1987) USGS Pro. Paper 1350 Ch 1; Garcia et al. (1987) Lithos, vol 20; and Clague (1996) page 33-50 in The Origin and Evolution of Pacific Island biotas ...

Annual growth bands in Devonian corals: 400/yr yields date that is similar to radiometric date. Consistent with slowing of Earth rotation with time.

Sclerochronology is the study of physical and chemical variations in the accretionary hard tissues of invertebrates and coralline red algae, and the temporal context in which they formed. It is particularly useful in the study of marine paleoclimatology.

Familiar examples include annual bandings in reef coral skeletons or annual, fortnightly, daily and ultradian growth increments in mollusk shells as well as annual bandings in the ear bones of fish, called otoliths. Sclerochronology is analogous to dendrochronology, the study of annual rings in trees, and equally seeks to deduce organismal life history traits as well as to reconstruct records of environmental and climatic change through space and time.

Independent determination of **Pacific plate motion** yields age progression that is consistent with K/Ar dates of the island chains formed by “hotspots”.

Agreement between magnetic “age” from deep marine sediments and radiometric ages of tuffs in East African Rift

Other dating methods: dendrochronology

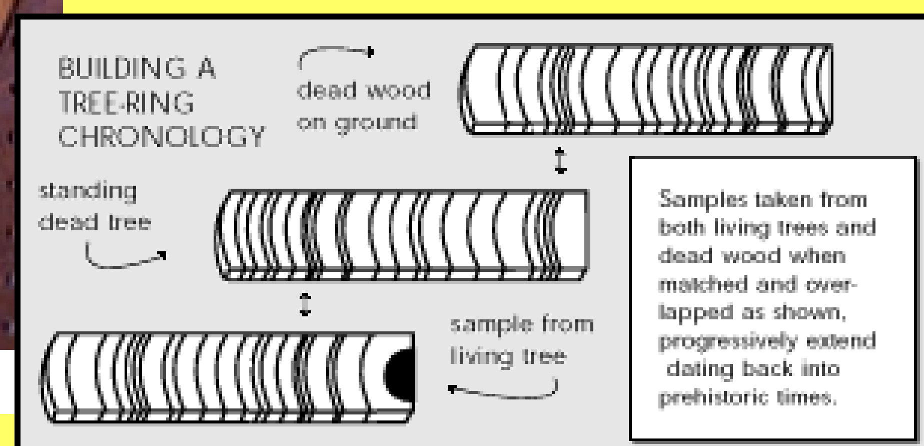
annual growth of trees produces concentric rings

...dating back to 9000 years is possible...

- rings need to be calibrated against C-14 dates to yield “true” numerical age

- other information may also be obtained from rings, including rainfall and temperature

- can develop composite chronologies for specific regions of interest for climate studies



Age of Earth

- Oldest dated rocks 3.94 by
- Oldest dated material 4.2 by
- Moon Rocks & Meteorites 4.4-4.58 by

age of the Earth

early methods: long debated

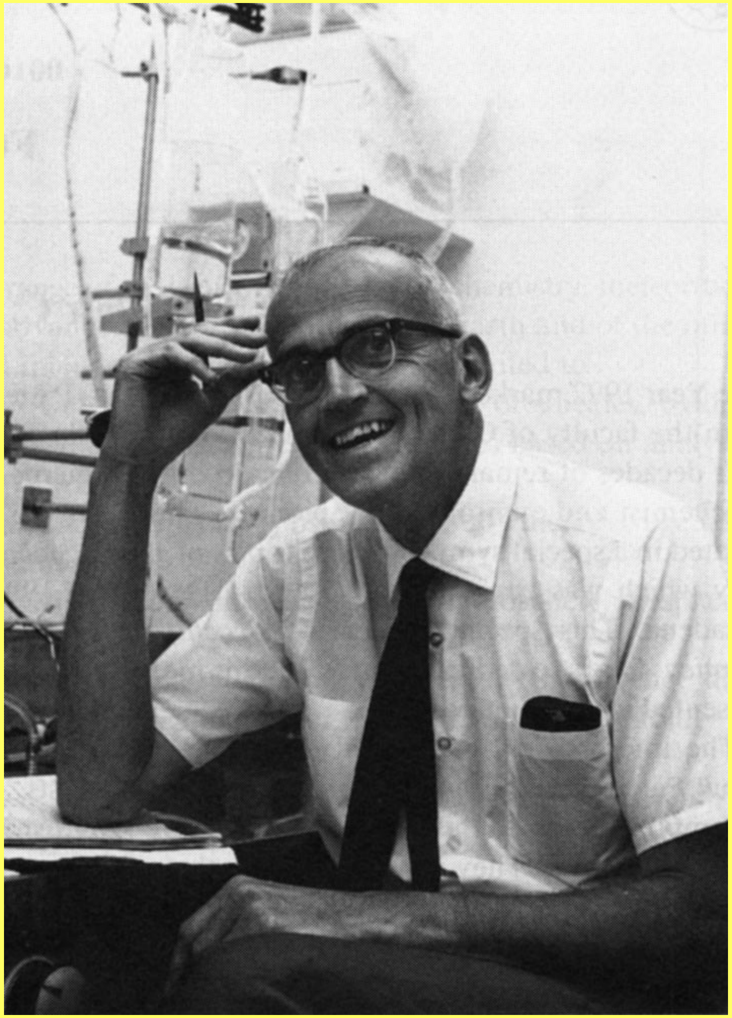
- 1625: Archbishop Usher determined Earth was created in 4004 B.C. by counting generations in the Bible
- Hindus regarded Earth as old: 2000 A.D. is 1.97 million years according to Hindu calendar
- 1866: Lord Kelvin calculated age by assuming that Earth was molten and cooled to a solid; age between 20-40 million years old.
  - did not know about radioactive decay (makes heat)
  - assumed all heat dissipated by conduction
- 1905: first crude estimates yielded 2 billion year age
- meteorites gave dates of 4.5 to 4.6 billion years old
- modern uranium/lead methods yield values of 4.55 billion years

In early 1950's, Clair Patterson was a graduate student at the University of Chicago.

Wanted to use lead isotope ratios to determine the Earth's age,

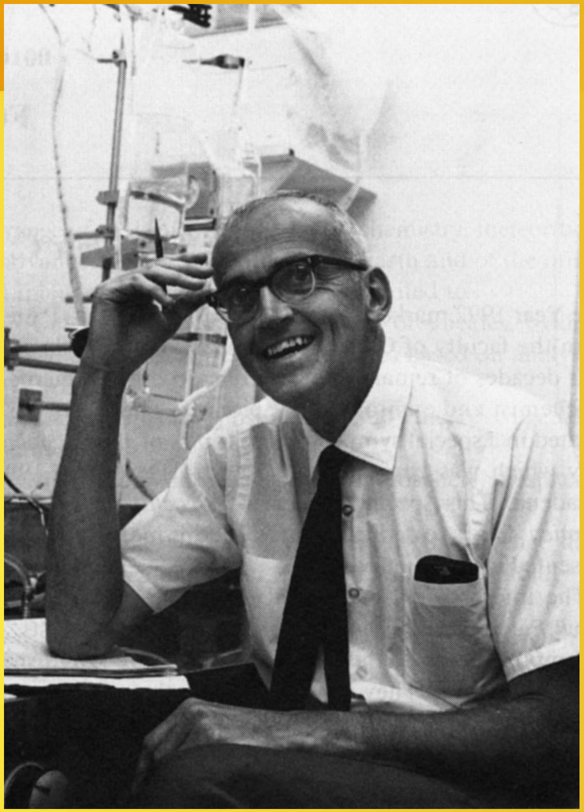
but the background level of lead contamination was too high

Lead used in gasoline, paints, plumbing, solder (cans for food) and pesticides.

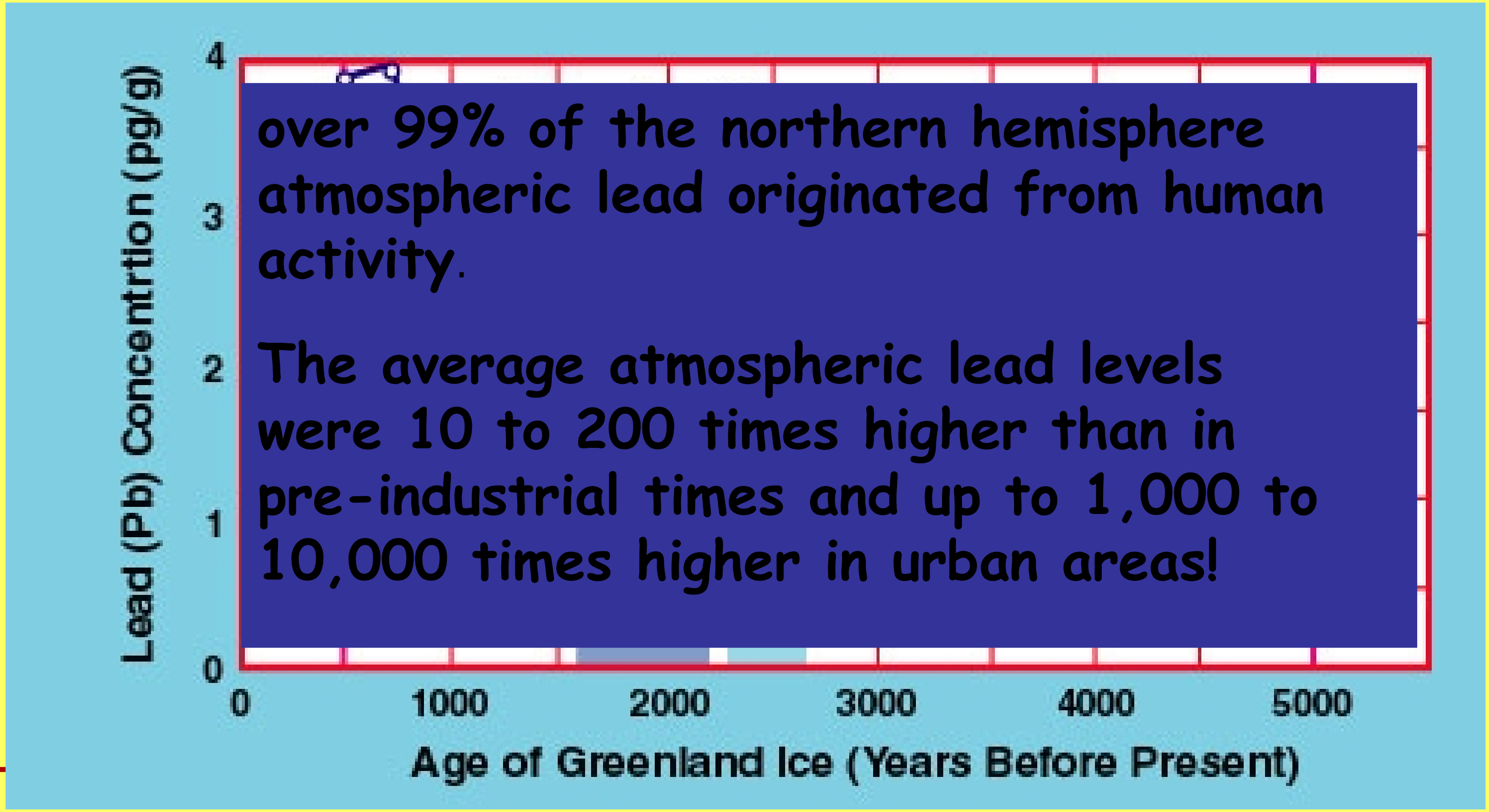


To accurately measure very low lead concentrations, Patterson created the modern laboratory ‘clean room’.

- in 1953, published estimate of Earth’s age as 4.55 BY
- (previously estimated at 3.3 BY)



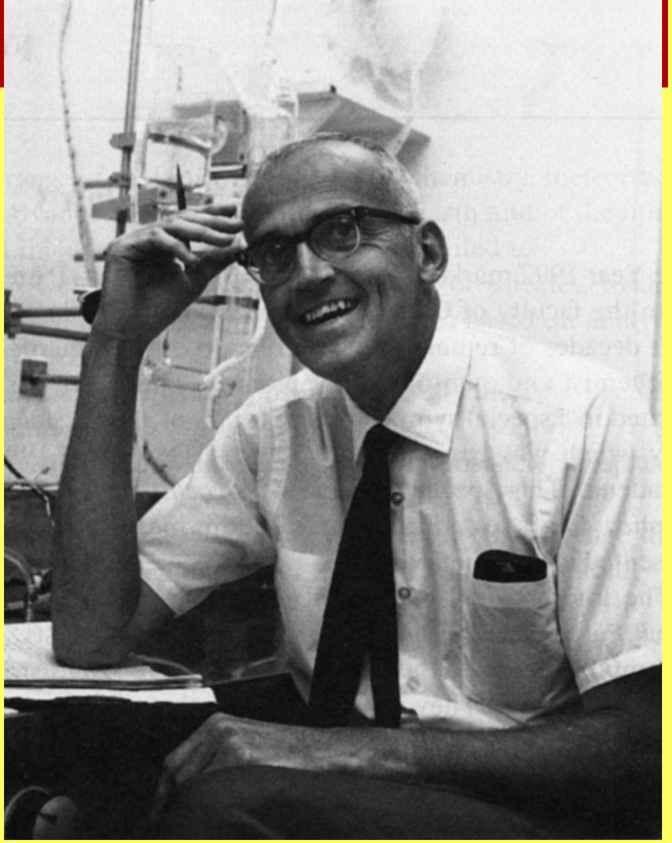
- By 1960's, Patterson began to worry about the extent of lead contamination in our environment.
- Patterson discovered that modern humans had 700 to 1,200 times as much lead in their bones as pre-Columbian Incas.
-



over 99% of the northern hemisphere atmospheric lead originated from human activity.

The average atmospheric lead levels were 10 to 200 times higher than in pre-industrial times and up to 1,000 to 10,000 times higher in urban areas!

- First recognition of the global scale and early history of lead pollution
- First recognition that essentially EVERYONE in 1950's-60's society suffered from low-level lead poisoning.
- Patterson campaigned extensively for lead removal, but was vigorously opposed by industry labs and some other scientists.



Eventually, scientific data accumulated by Patterson and others led to the 1970 Clean Air Act

By 1991, lead levels in Greenland snow had fallen by a factor of 7.5

How to synchronize clocks: Relative & absolute time scales

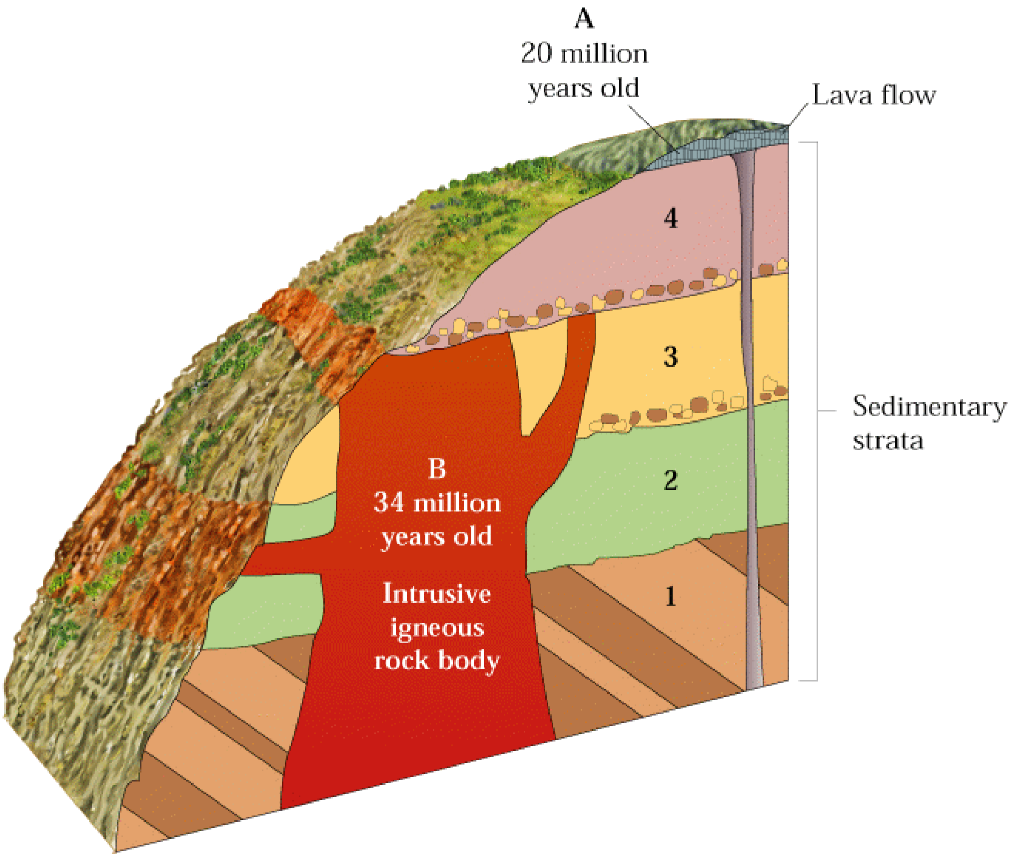
- Main problem: not all rocks can be dated radiometrically. Radiometric dating can be used for igneous and some metamorphic rocks, but not often suitable for sedimentary rocks.
- Igneous rocks: formed from crystallisation of magma. All the minerals in the rock are formed at about the same time and radiometric dating will give that age.
- Metamorphic rock: formed from pre-existing (parent) sedimentary, igneous or even other metamorphic rocks by the process of metamorphism.
- Radiometric ages from metamorphic rocks are difficult to interprete: they can be ages of parent rock or the time when the metamorphism took place.

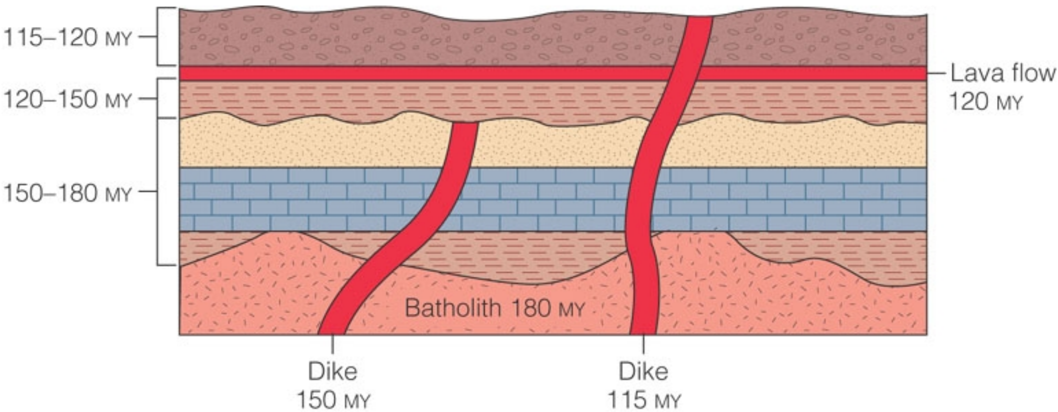
Sedimentary rocks: formed from materials derived from pre-existing rocks by the process of weathering, transportation and sedimentation, together with materials of organic origin.

They are generally not suitable for radiometric dating. Dating will give the ages of parent rocks and not the age of sedimentation. A sedimentary rock may contain mineral grains from parent rocks of diverse ages.

Exception when there are ash beds, volcanic clasts, organic materials (C-14) in the sedimentary strata.

Using Absolute and Relative Dating





Using Absolute and Relative Dating