Last Time...

1) Remotely sensed data may aid geologic studies.

2) Field calibration (ground truthing) of images is required when making quantitative inferences from the measured spectra but uncalibrated image stretches may be useful for geologic mapping in an area.

3) Remote imagery provides an reliable base from which to map due to the large coverage and geometric fidelity of images.

In Today's Class...

Relative Dating Methods and Radioactive Decay

I. Relative Dating Methods. These are good for determining the age between different geomorphic elements but do not necessarily place constraints on absolute age of features.

II. Radioactive decay.

Relative Dating Methods

1) Cross-cutting relationships.
- Often geomorphic elements display clear cross-cutting relations.

2) Clast Seismic Velocity

3) Weathering Rinds

4) Obsidian Hydration Rinds

5) Humid Climate Soil Development

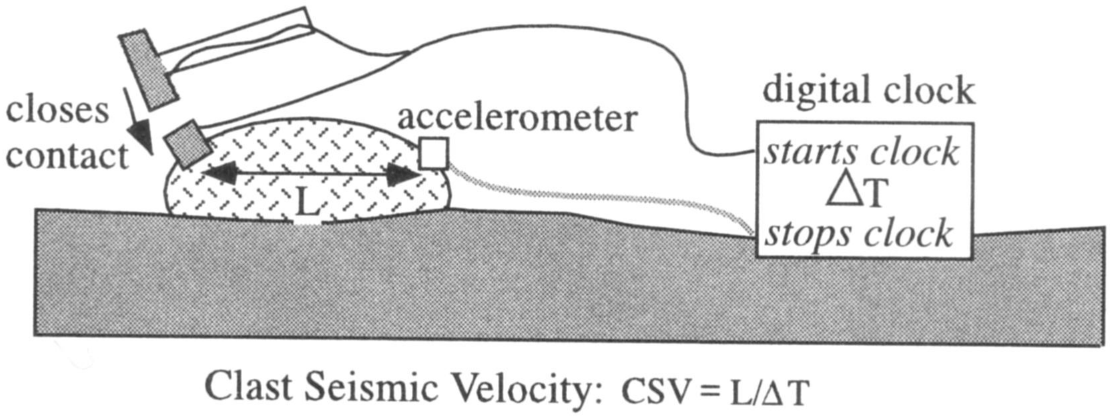
6) Pedogenic Carbonate Development

7) Lichenometry

Method	Age Range	Materials Needed	References
Clast seismic velocity	1–100 ka	Boulders	Crook, 1986; Gillespie, 1982
Obsidian hydration	1–500 ka	Obsidian lavas	Pierce et al, 1976
Soils	10–500 ka	Soils	Harden, 1982
Mineral weathering	10 ka–1 Ma	Boulders	Colman and Dethier, 1986
Landform modification	10 ka–1 Ma	—	Davis, 1899; Cotton, 1926

table from Burbank and Anderson, 2001

Clast Seismic Velocity Method



- Based on the observation that microcrack density of surface clasts tends to increase with time. As the microcrack density increases, seismic velocity decreases.

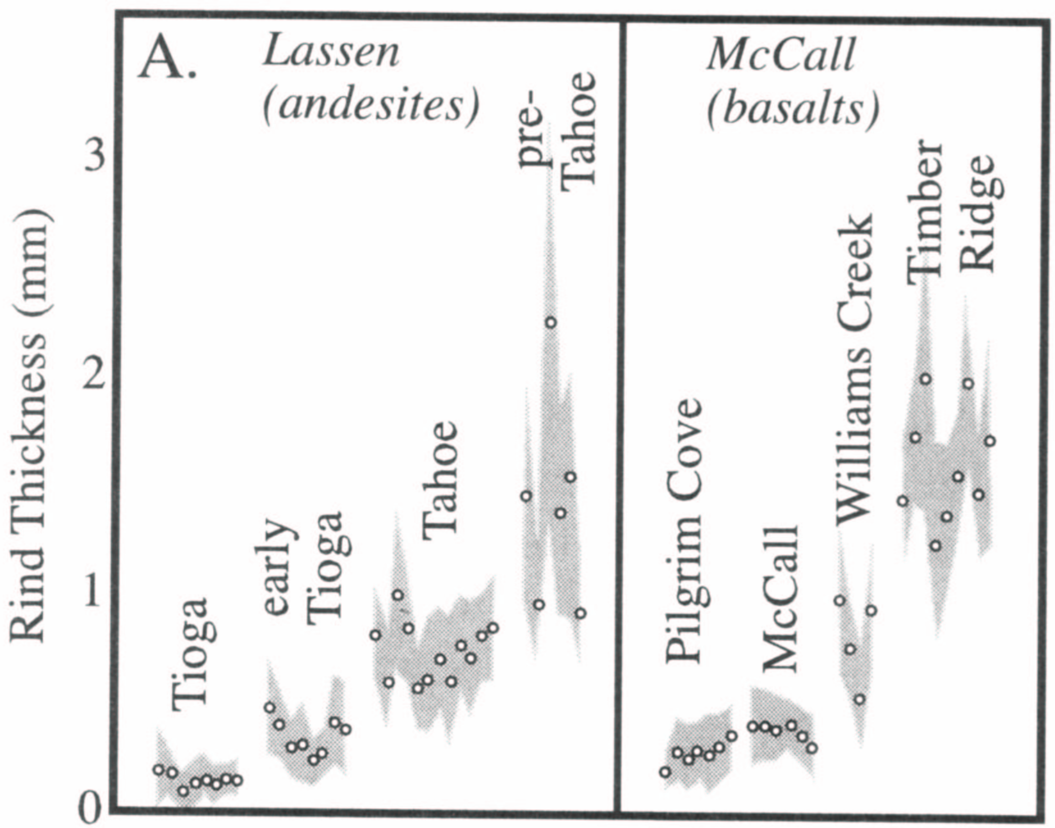
*** Rate of microcrack production is likely main controlling factor, and this varies with rock type. Must use same rock type on surface and calibrate for an absolute age.**

*** There is no theoretical model for all of the different possible modes of microcrack production; therefore, method is difficult to quantitatively apply.**

Figures from Burbank and Anderson, 2001 after Anderson and Anderson, 1990

Weathering Rind Method

*** Most weathering rind studies focus on easily weathered, more abradable clasts (e.g., andesites and basalts).**

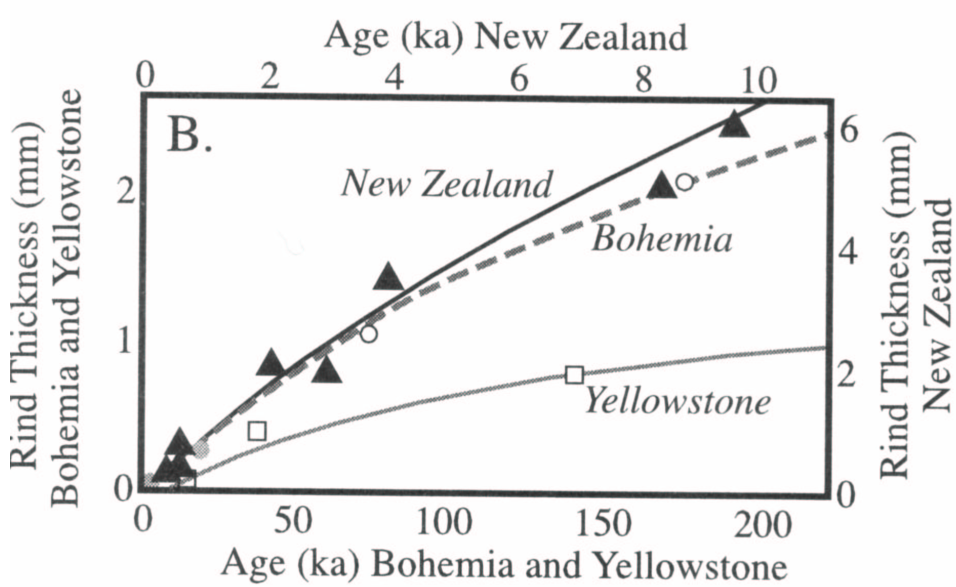


figures from Burbank and Anderson, 2001 after Coleman and Pierce, 1992

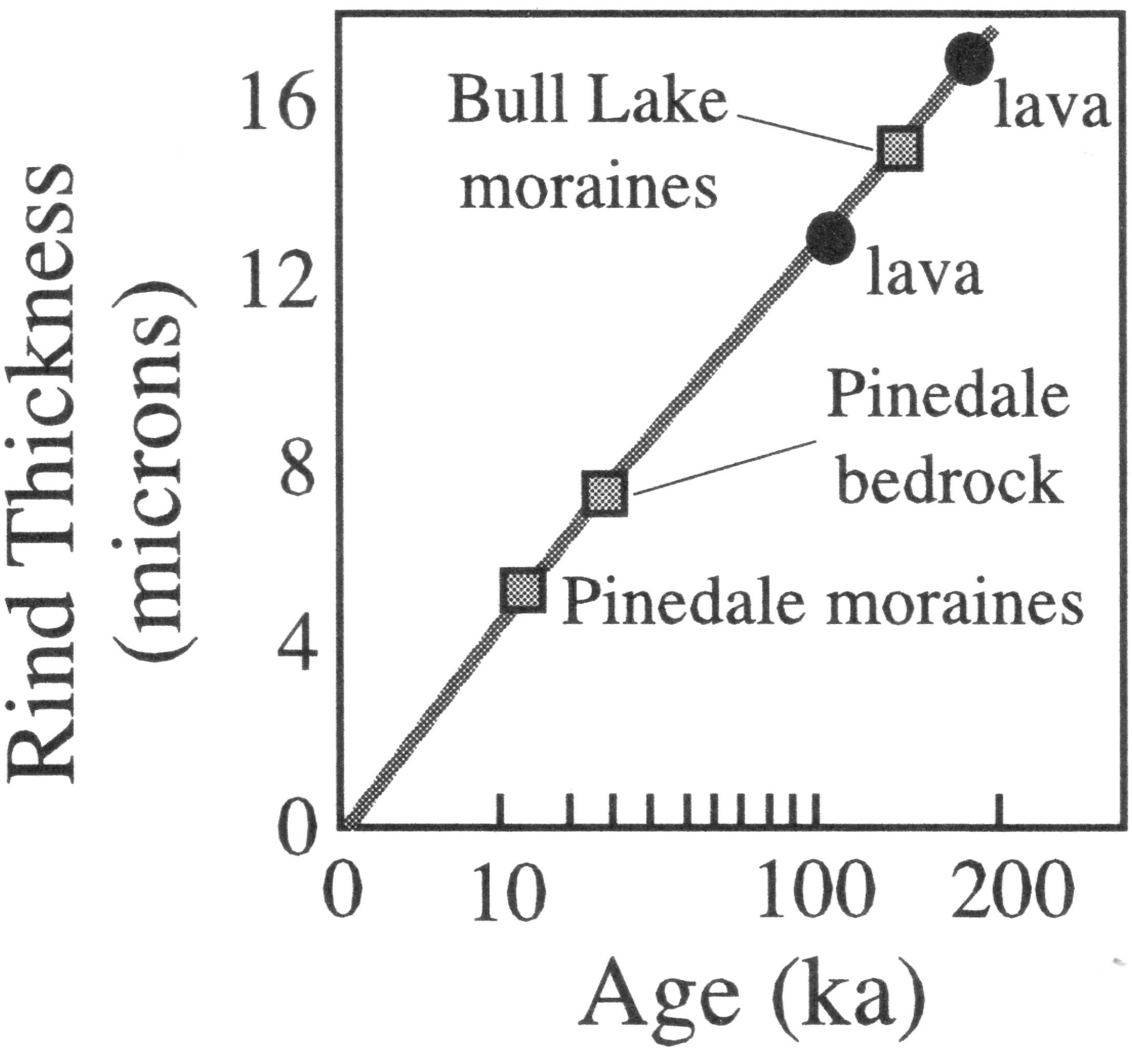
- Thickness of rind is related to time that clast has been exposed to chemical weathering.

*** Weathering rates are dependent on lithology, precipitation, and any rind that has been developed during a previous exposure.**

*** Apparently, in the western United States, weathering rind production rates have decreased through time. Therefore age ratios > rind ratios.**



Obsidian Hydration Rinds



- Obsidian glass hydrates when exposed to air, creating a hydration rind on the exterior of obsidian clasts.

- Thickness of weathered rind is measured by an abrupt change in the refractive index of the glass.

- Usually, rinds are only several microns thick.

*** Rate of hydration slightly dependent on composition of obsidian and probably influenced by the surface temperature of the clast during hydration. Also rate is probably dependent on climate.**

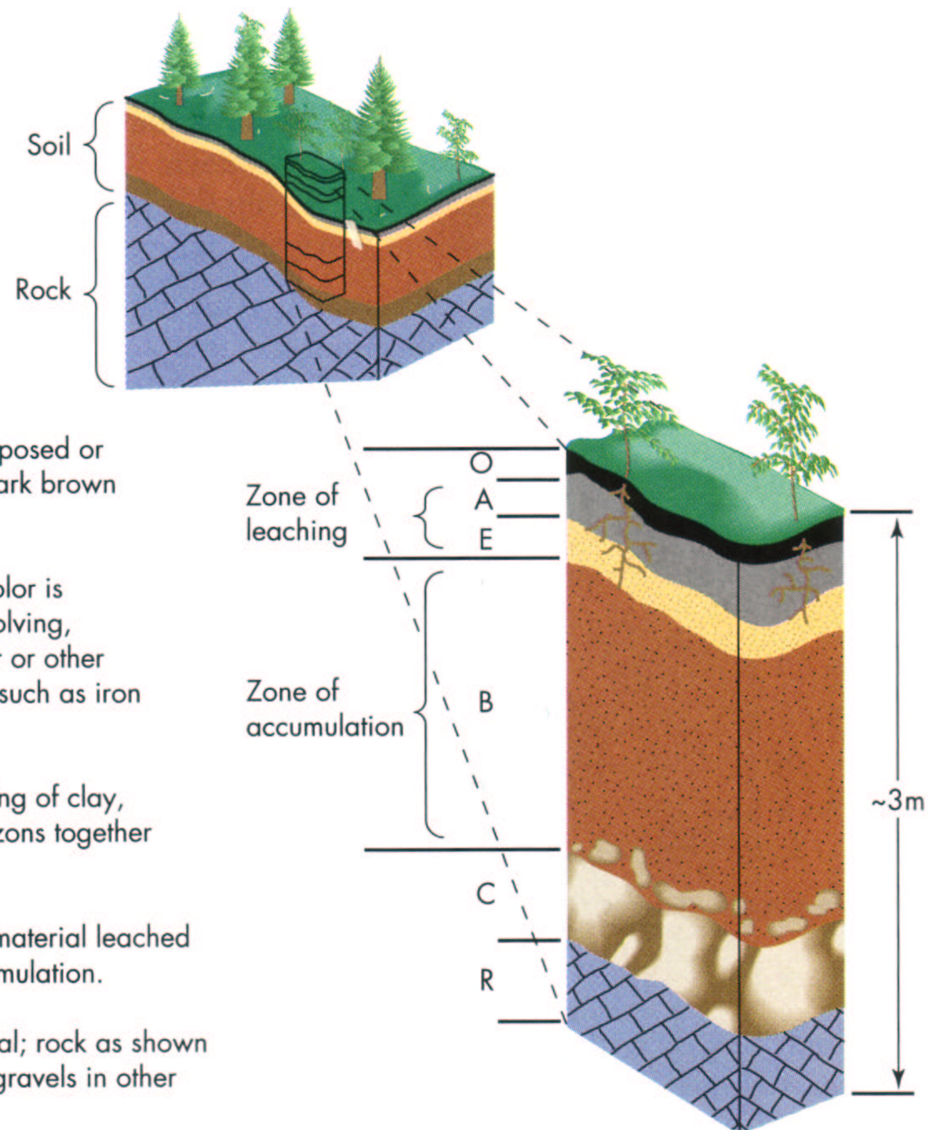
*** Calibration against known age features is necessary for absolute age.**

*** Main drawback is that climate has varied significantly over the Pleistocene, so rind development rates may also vary.**

figure from Burbank and Anderson, 2001 after Pierce et al., 1976

Dating Using Relative Soil Development

- This method is based on the idea that soils undergo consistent changes throughout time, reflected in their composition.



O. Horizon is composed mostly of organic materials, including decomposed or decomposing leaves, twigs, etc. The color of the horizon is often dark brown or black.

A. Horizon is composed of both mineral and organic materials. The color is often light black to brown. Leaching, defined as the process of dissolving, washing, or draining earth materials by percolation of groundwater or other liquids, occurs in the A horizon and moves clay and other material such as iron and calcium to the B horizon.

E. Horizon is composed of light-colored materials resulting from leaching of clay, calcium, magnesium, and iron to lower horizons. The A and E horizons together comprise the zone of leaching.

B. Horizon is enriched in clay, iron oxides, silica, carbonate or other material leached from overlying horizons. This horizon is known as the zone of accumulation.

C. Horizon is composed of partially altered (weathered) parent material; rock as shown here but the material could also be alluvial in nature, such as river gravels in other environments. The horizon may be stained red with iron oxides.

R. Unweathered (unaltered) parent material.

figures from Keller, 2000

Example of Soil Column

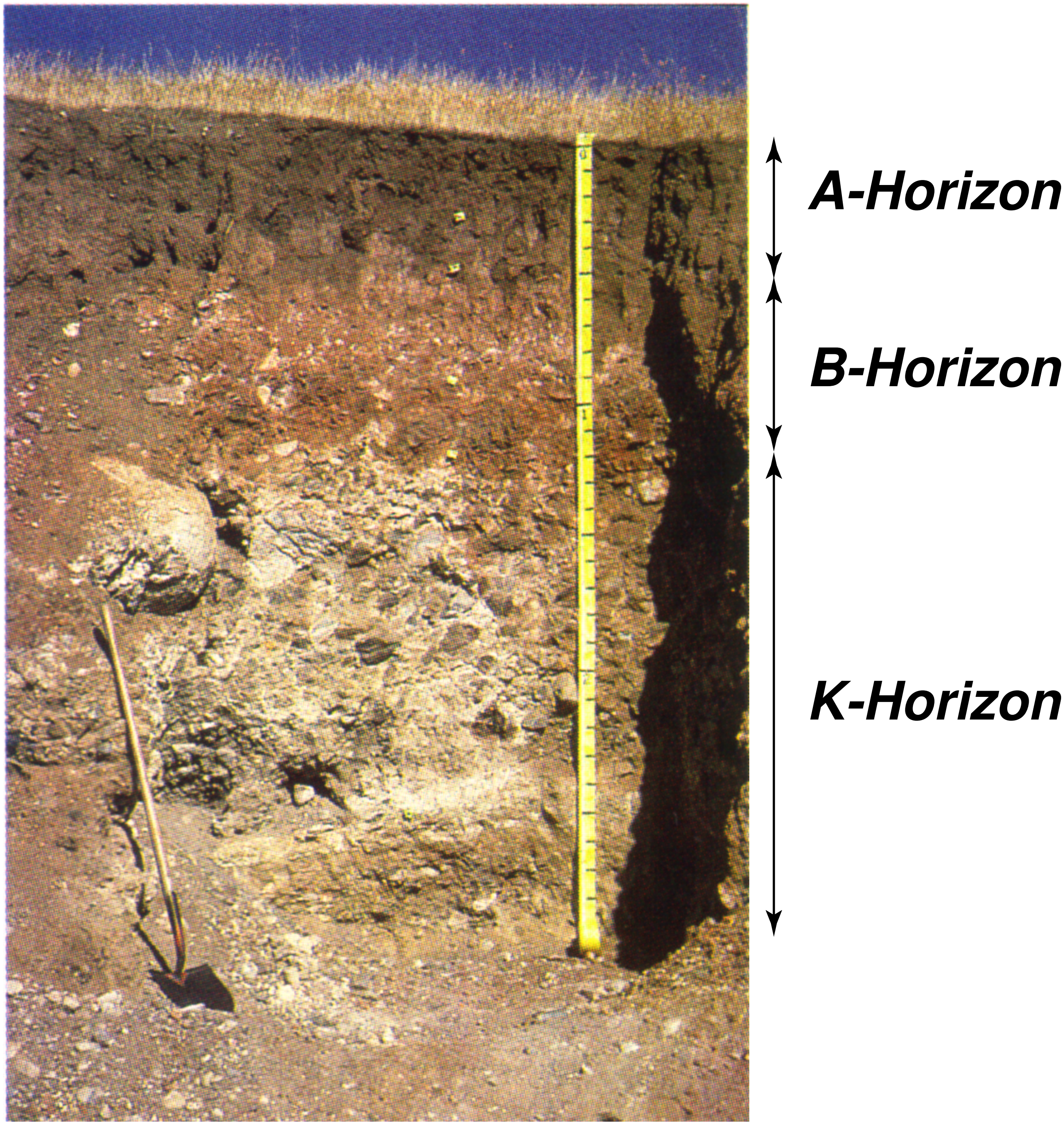


figure from Keller, 2000

- Often, in semi-arid and arid soils, a zone of carbonate accumulation will develop below the B-Horizon. Carbonate development on the clasts may be used to estimate the relative age of a soil column as well (later).

Characteristics of Soils

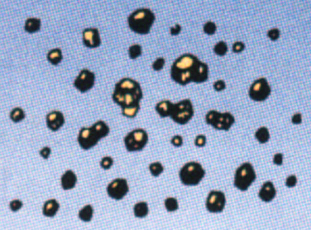
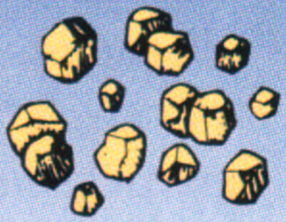
Type		Typical size range	Horizon usually found in	Comments
Granular		1–10 mm	A	Can also be found in B and C horizons
Blocky		5–50 mm	B_t	Are usually designated as angular or subangular
Prismatic		10–100 mm	B_t	If columns have rounded tops, structure is called *columnar*
Platy		1–10 mm	E	May also occur in some B horizons

table from Keller, 2000

Example of Relative Soil Dating

1) Weakly developed soil profile: A horizon directly over C horizon (no B horizon developed).

Approximate age: a few hundred to several thousand years old.

2) Moderately developed soil profile: A horizon overlying an argillic B horizon that overlies a C horizon. B horizon generally shows evidence of mineral translocation, moderately developed texture, and redder colors than weakly developed profiles.

Approximate age: > 10 kyr.

3) Well developed soil profile: Red colors (lots of clay translocation to B horizon. K horizon may be present.

Approximate age: 40 kyr - >100s kyr.

Carbonate Coating Thickness

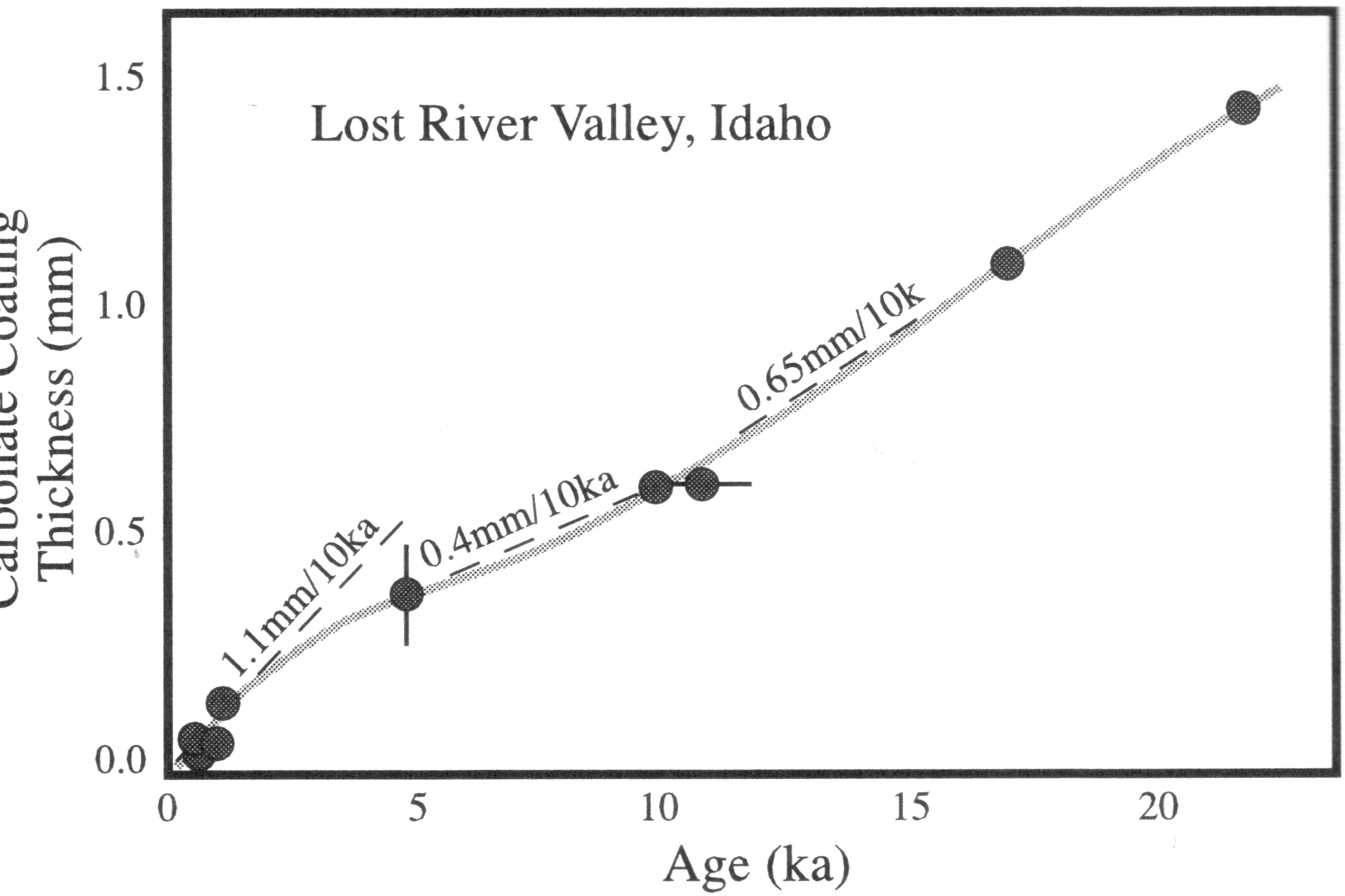


figure from Burbank and Anderson, 2001 after Vincent et al., 1994

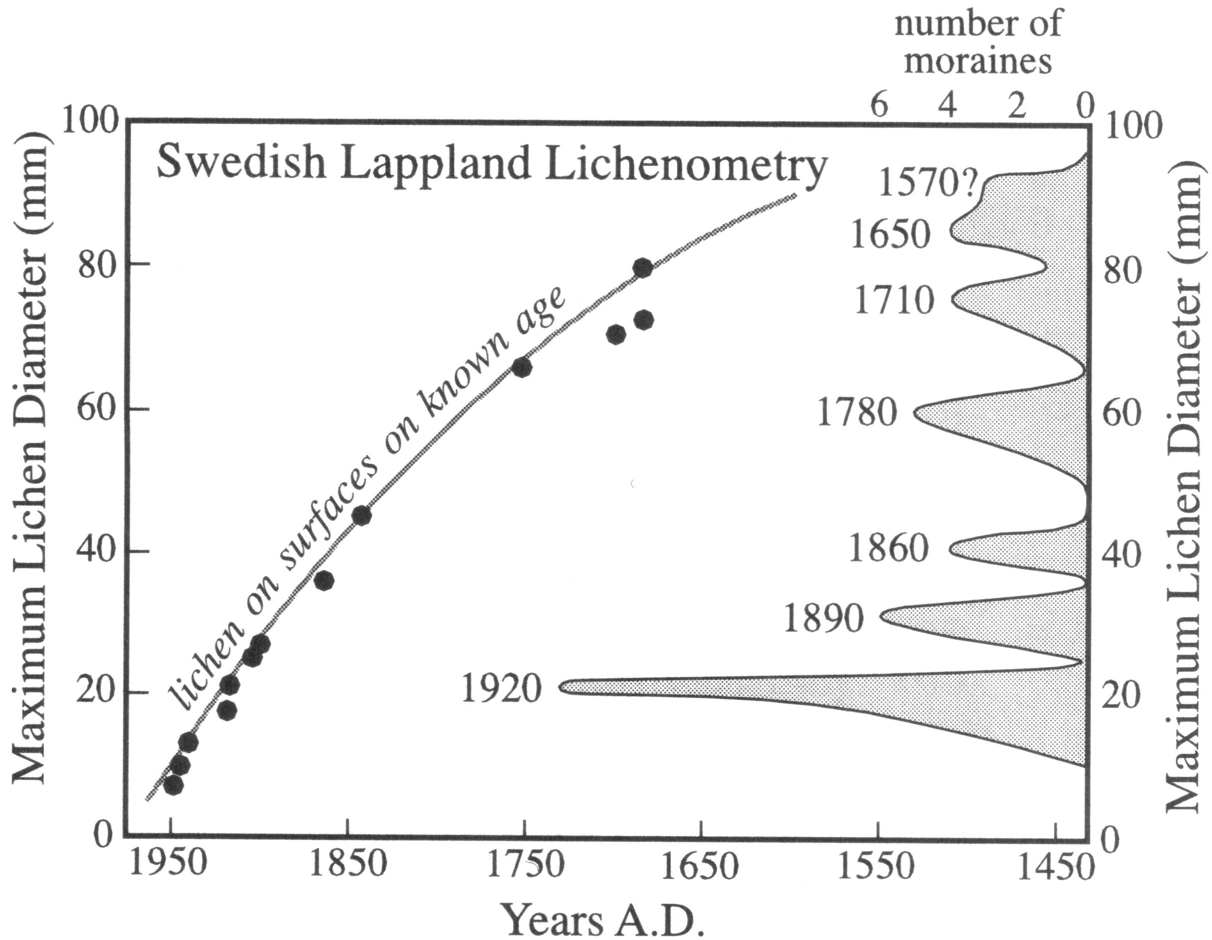
- Surface calcium dust is transported downward through soil by infiltrating rainwater. Also, mineral weathering picks up Ca on the way down.

- Ca is reprecipitated at depth on clasts as plant uptake, evaporation, or water temperature increases supersaturate Ca solution.

*** Local calibration is necessary to get absolute ages out of the method.**

*** Errors can be large.**

Lichenometry



figures from Burbank and Anderson, 2001 after Denton and Karlen, 1973

- The diameter of a specific species of lichen is used as a proxy for age the surface has been exposed at the surface.

- Usually, largest lichen diameters are used to get oldest estimate.

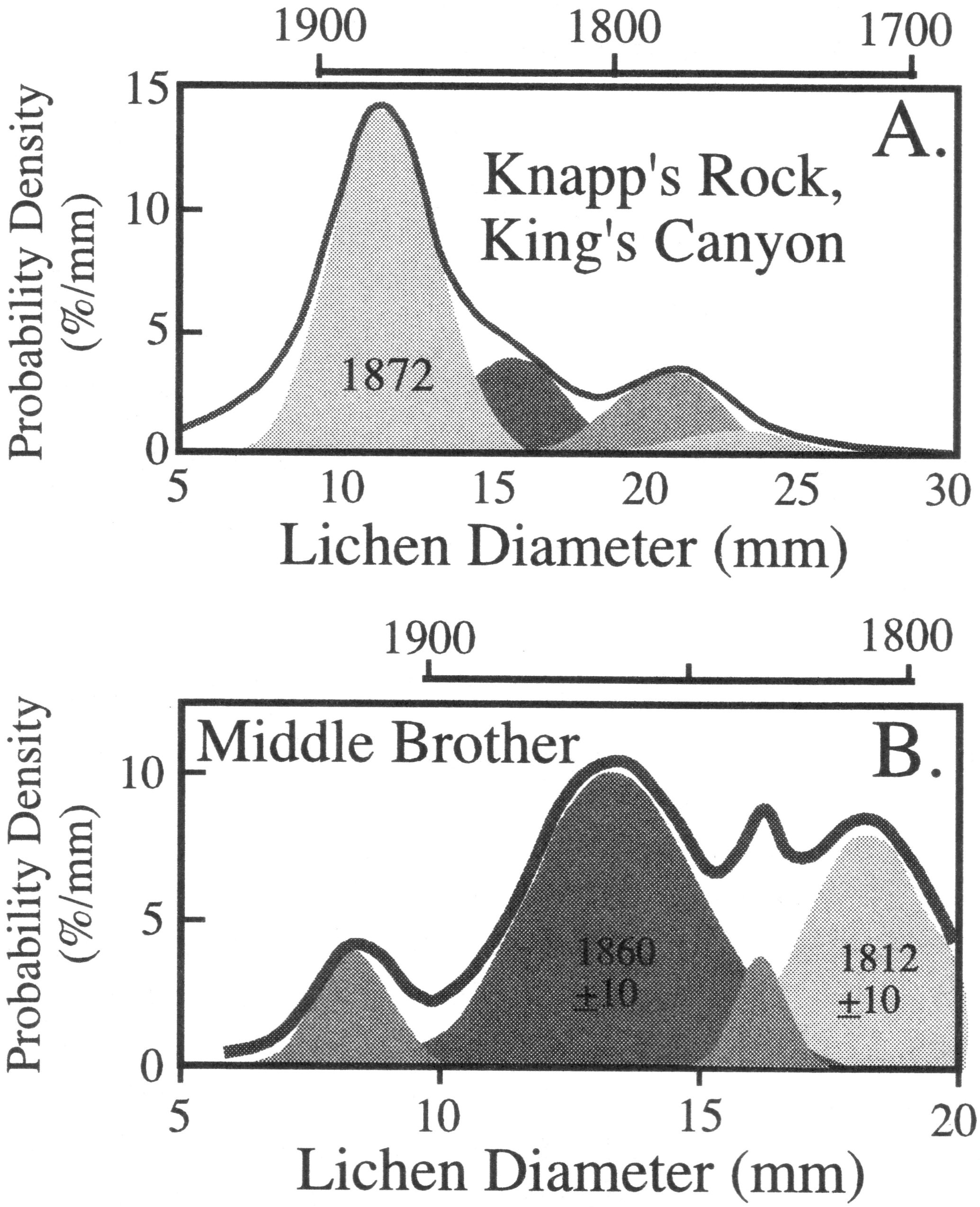
- Rhizocarpon is lichen most commonly employed in method.

*** Again, calibration is required to obtain lichen growth rates and absolute ages.**

*** Method can be quite precise when calibrated (+/- 3-10 yrs).**

*** Usually applicable to surface < 500 years old.**

High Resolution Lichenometry Used to Date Rockfalls Related to Earthquakes



- Numbered gaussian curves represent timing of historic earthquakes near sites.

figures from Burbank and Anderson, 2001 after Bull, 1996

Radioactive Decay

- Spontaneous transformation of one atom to another, resulting in the emission of particles and energy.

- Two important questions for (Quarternary) geochronology:

1) How does it happen?

2) How long does it take to happen?

** If we know these answers and can measure the amounts of transformed and untransformed atoms, we can estimate the absolute time since the system was closed.*

Radioactive Decay

- As atoms decay, they release various forms of particles and radiation to satisfy conservation of mass, energy, and momentum.

- Here are the "ground rules" for understanding the particle interactions leading to decay:

1) Some atoms are too "heavy" or too "light" for the number of protons that they have.

****For those that have too many neutrons, a neutron may be converted to a proton and a negatron (negatron decay).***

**** For those that have too many protons, a proton may be converted to a neutron by either emission of a positron, or combination of a proton and an electron captured from an orbital close to the nucleus (positron decay and electron capture, respectively).***

**** Sometimes, if the atoms are heavy enough, they are unstable and will just expel two neutrons and two electrons (alpha decay).***

2) Energy and mass must be conserved during the decay. When a particle is ejected from the nucleus, it can either:

**** leave the nucleus in an "excited" state (higher energy state), or***

**** emit a "neutrino" with the particle (this is true for positron and negatron decay). The neutrino has no charge and little or no mass, but contains the excess energy released by the decay.***

**** In the case that the atom is left in an energy state higher than its minimum, or "ground" state, energy is emitted from the atom as γ radiation. This radiation has no mass but is a high-energy radiation.***

Types of Radioactive Decay

- β- Decay (Negatron decay): When atoms are too "heavy" for the number of protons they have, they decay by converting one of their neutrons to a proton. As this happens, a proton and a negatively charged, light particle (negatron; equivalent to an electron) are created. The negatron is expelled from the nucleus and may fly out at different speeds.

**** Expelled negatron may have any kinetic energy between its maximum and zero. What happens to the rest of this energy? Another particle, the "antineutrino", is expelled with the negatron, balancing the energy.***

**** Extra energy often leaves atom in excited state. γ-radiation is emitted as it returns to its new ground state.***

- β+ Decay (Positron decay): When atoms are too "light" for the number of protons they have, they decay by converting one of their protons to a neutron by expelling a positron (similar in mass to an electron, but with a positive charge).

**** Positron often collides with an electron, annihilating the two particles and expelling 2 γ rays in opposite directions.***

**** Like β- decay, neutrino can also be emitted, balancing energy.***

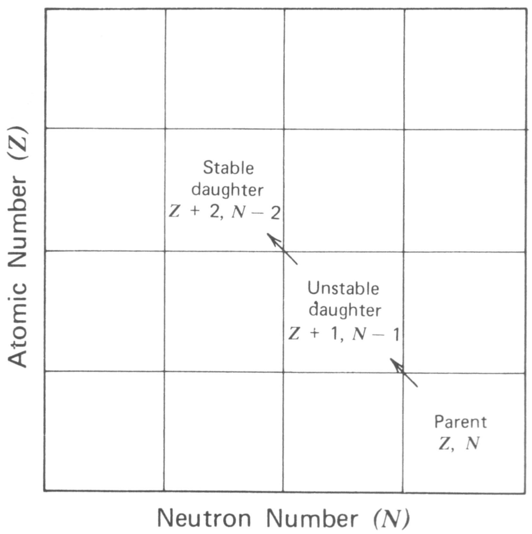
**** Also, extra energy stored in atom may be released as γ radiation.***

- Electron capture: Occurs under similar conditions as β+ decay. However, instead of protons decaying to a neutron, an electron close to the nucleus is grabbed by the nucleus and merges with a proton and forms a neutron.

**** May release neutrino in electron capture.***

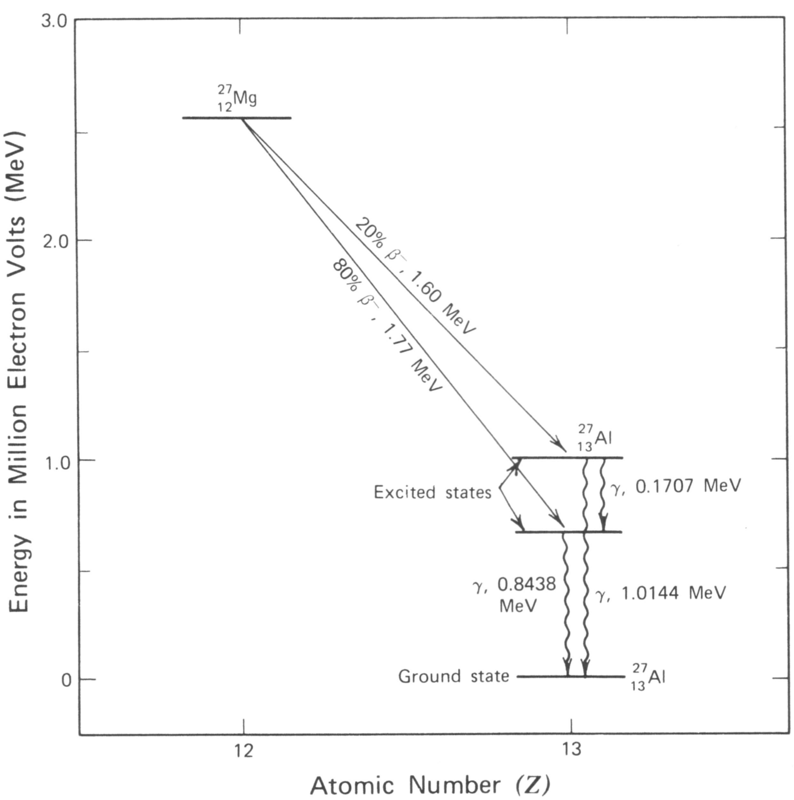
**** γ radiation may be emitted if new atom is left in an elevated energy state.***

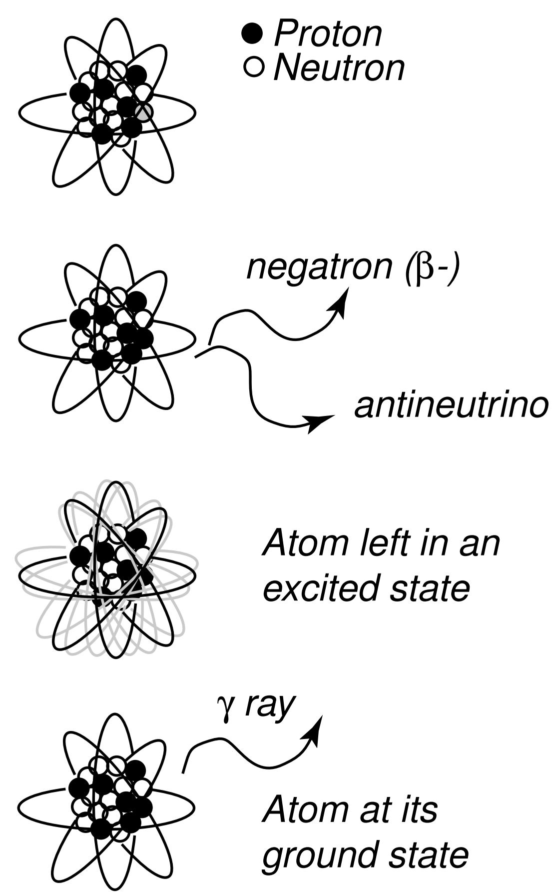
β- *Decay (Negatron Decay)*



- Results in increase of number of protons by 1 and decrease in number of neutrons by 1.

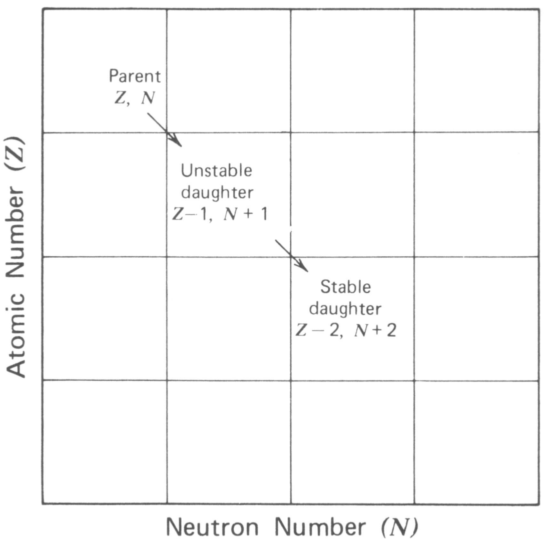
** Gamma radiation and antineutrinos may be emitted.*





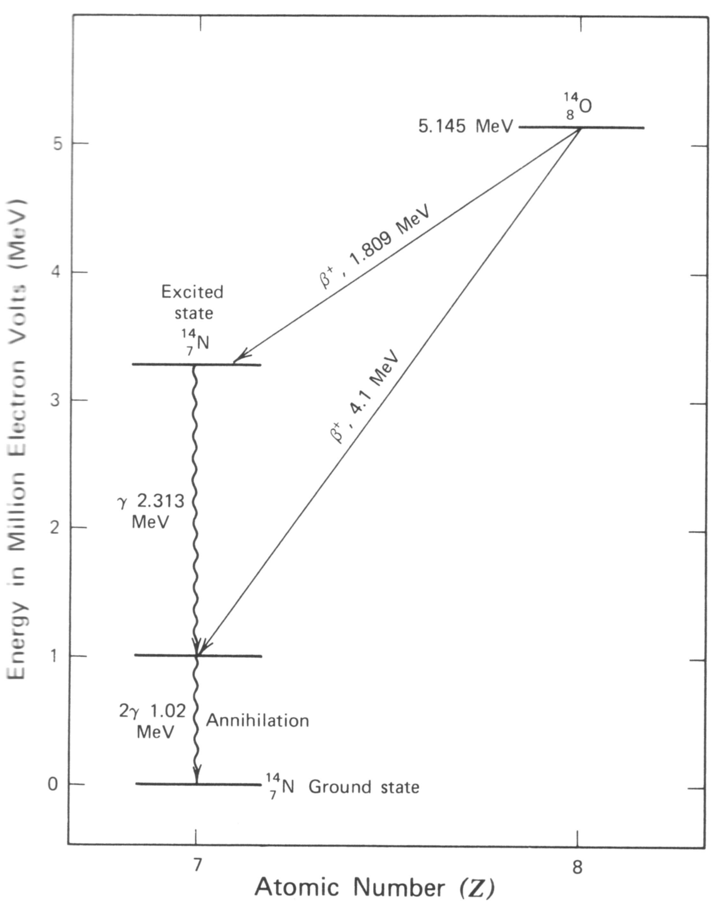
figures from Faure, 1986

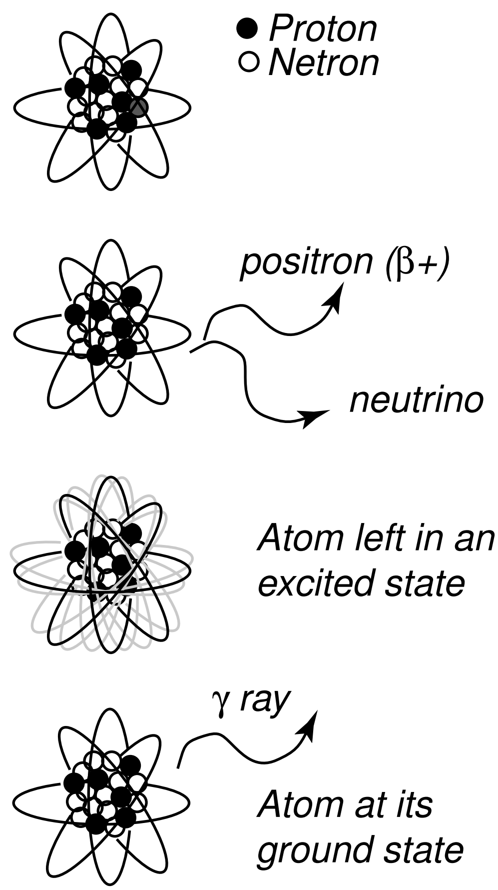
β+ *Decay (Positron Decay)*



- Results in decrease of number of protons by 1 and increase in number of neutrons by 1.

** Gamma radiation and neutrinos may be emitted.*





figures from Faure, 1986

Electron Capture Decay

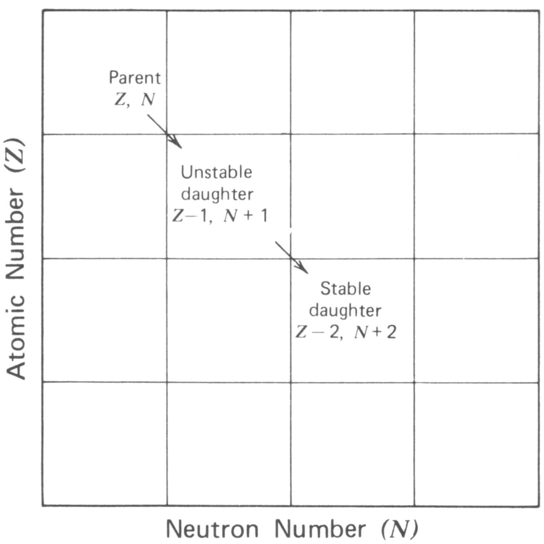
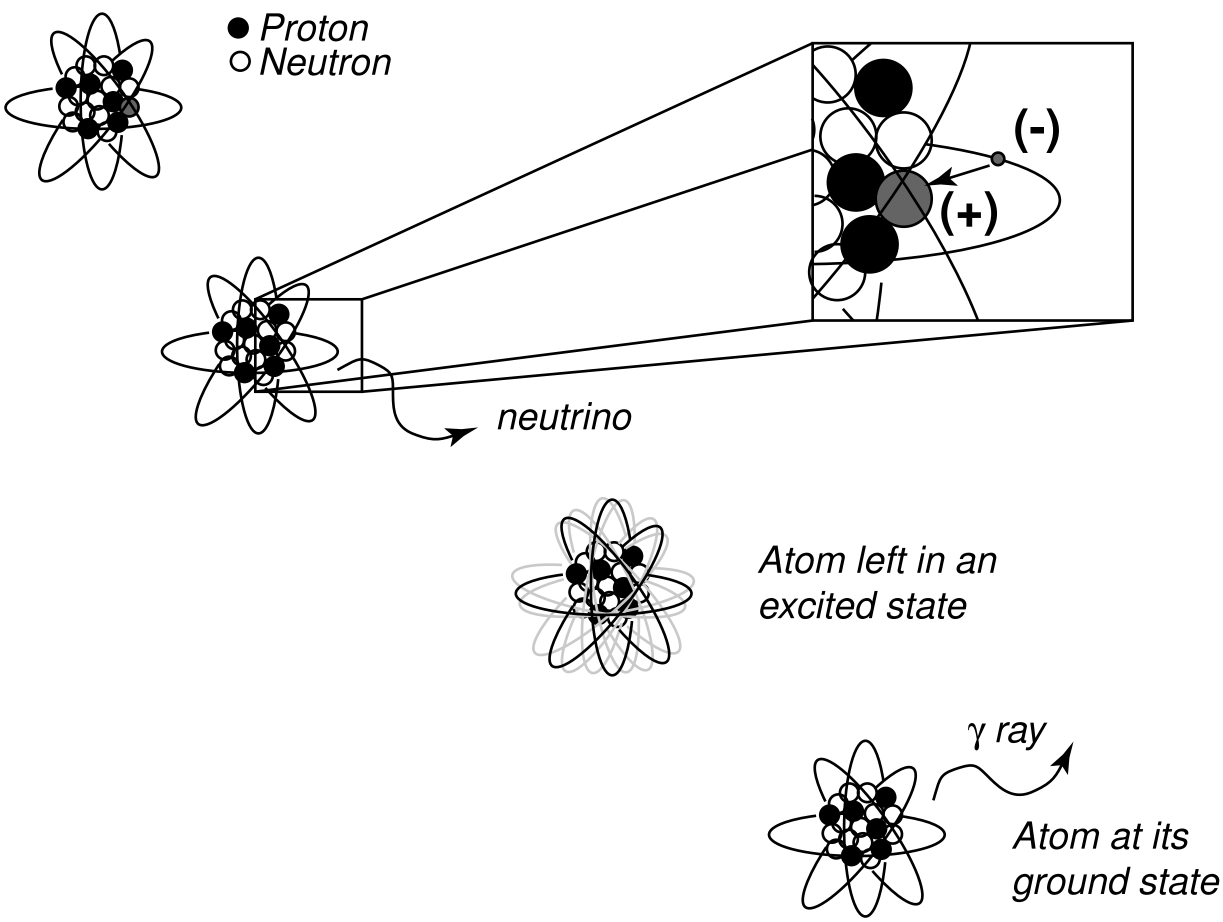


figure from Faure, 1986

- Results in decrease of number of protons by 1 and increase in number of neutrons by 1.

* Gamma radiation and neutrinos may be emitted.



Branched Decay

- Atoms in heightened energy state may decay by either β+ or electron capture, or by β- decay.

** Gamma radiation, neutrinos, and antineutrinos may be emitted.*

** Daughter products of two decays are different!*

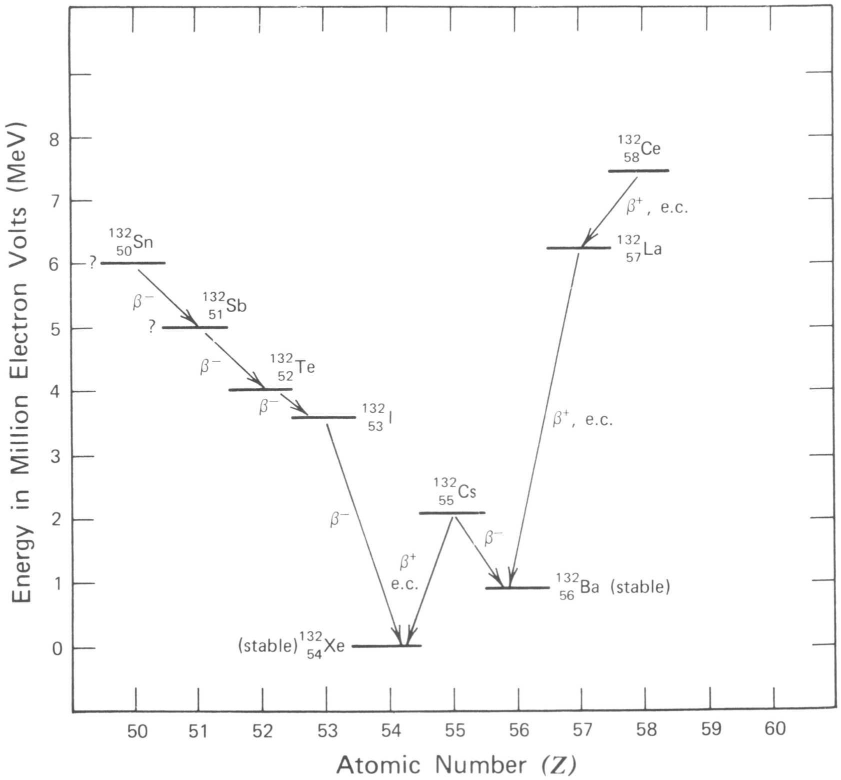
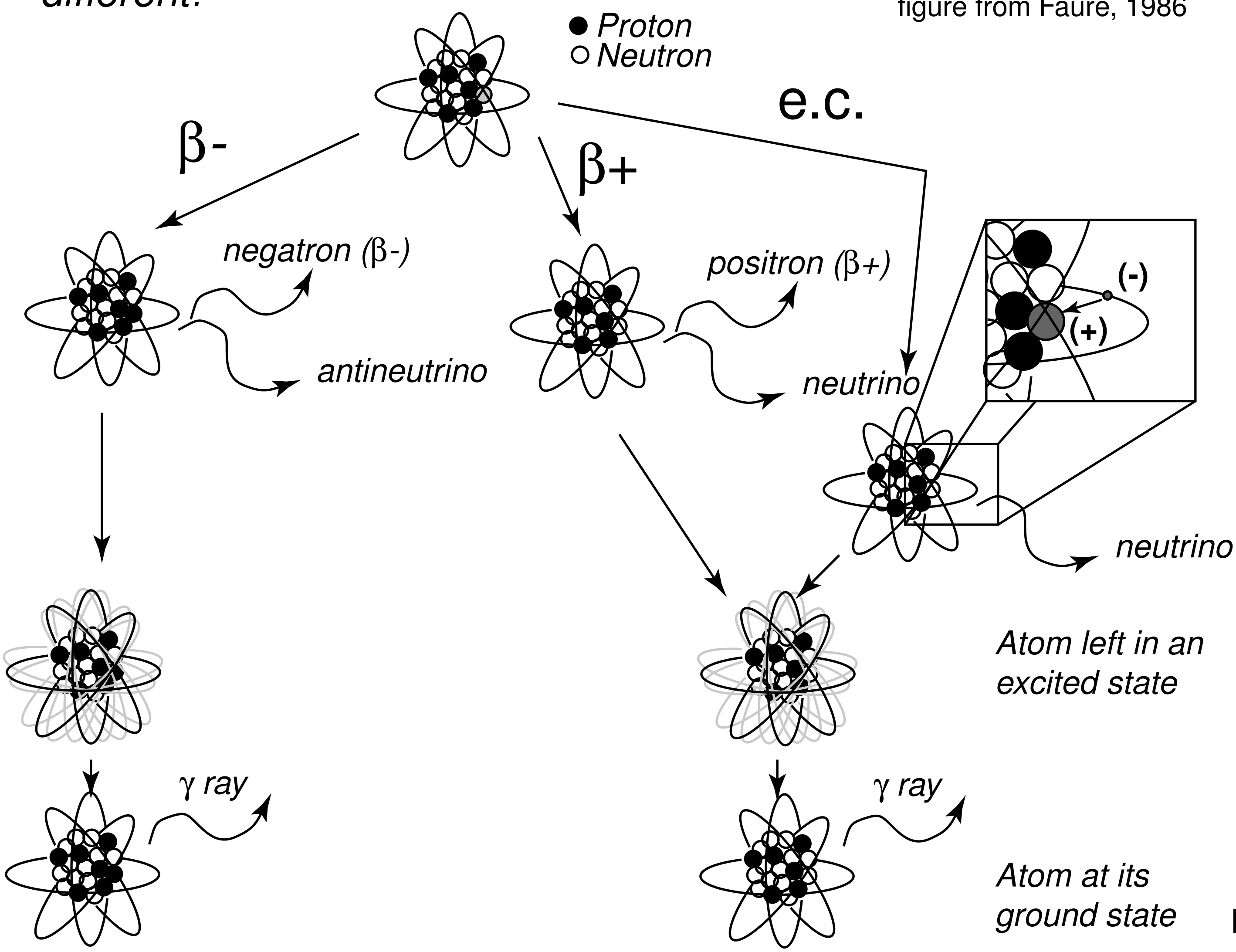
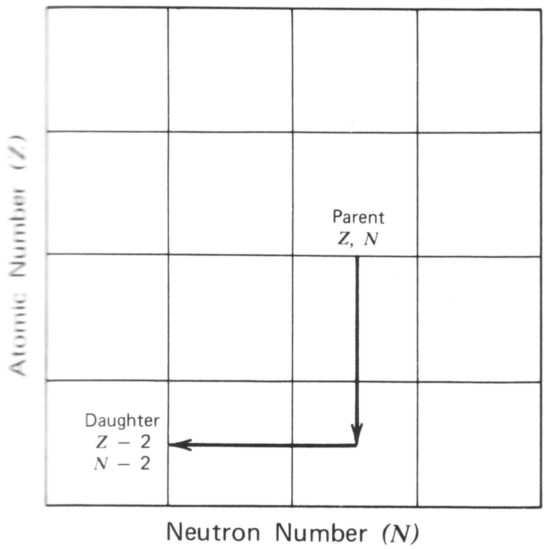


figure from Faure, 1986

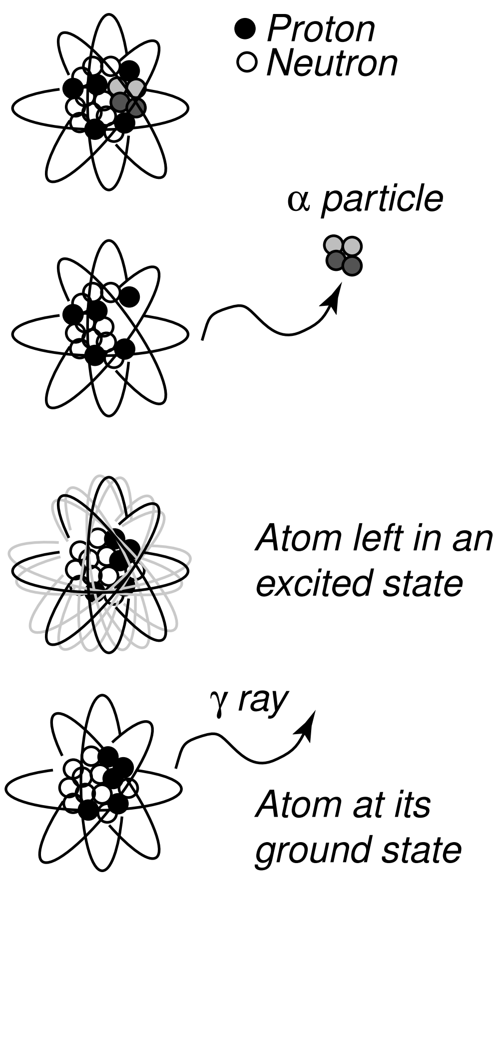


Alpha Decay



- Results in decrease of number of protons by 2 and decrease in number of neutrons by 2.

** Gamma radiation and α particles may be emitted.*



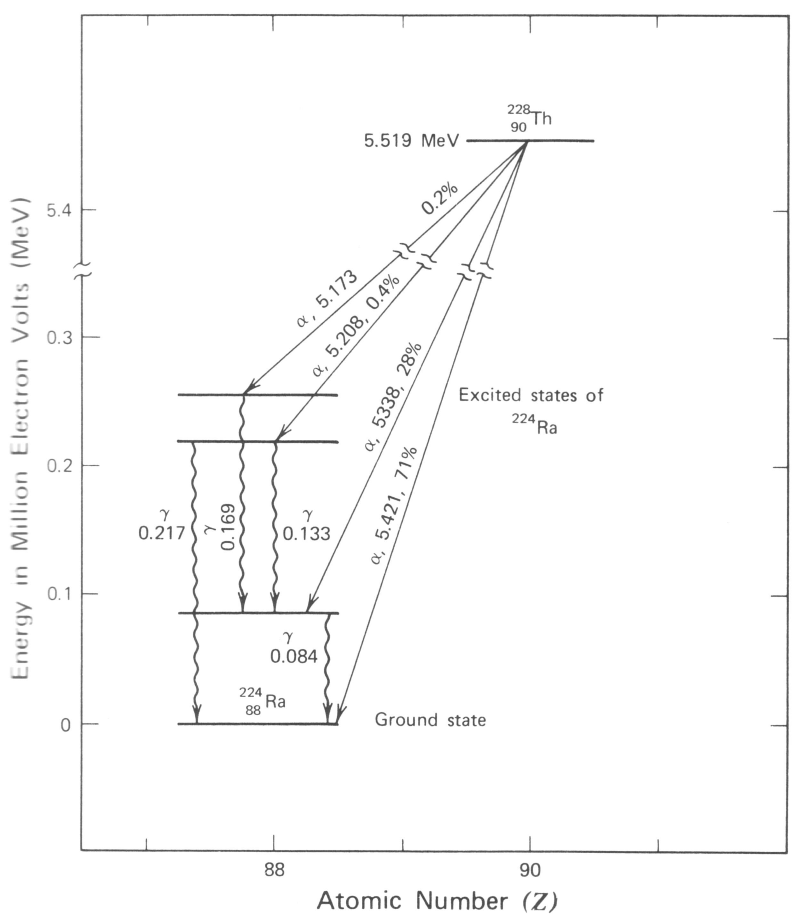


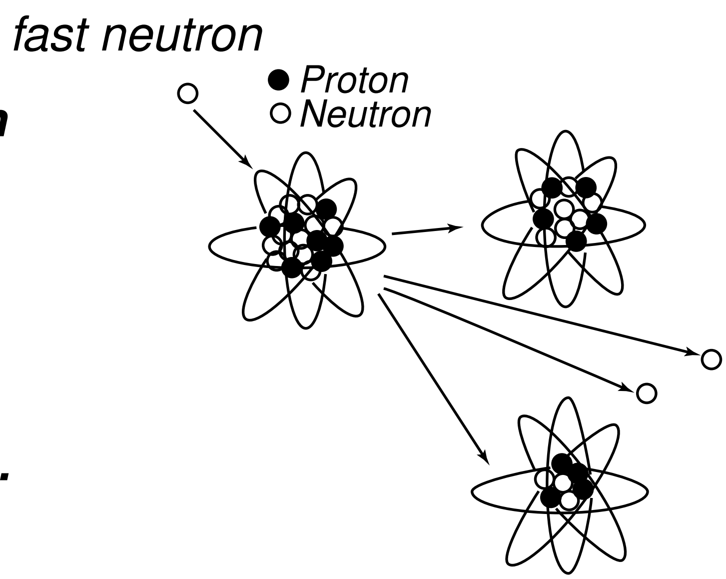
figure from Faure, 1986

Fission, Spallation, and Thermal Neutron Activation

Fission and Spallation

- Occurs when a neutron hits a large nucleus and creates two daughters from the parent.

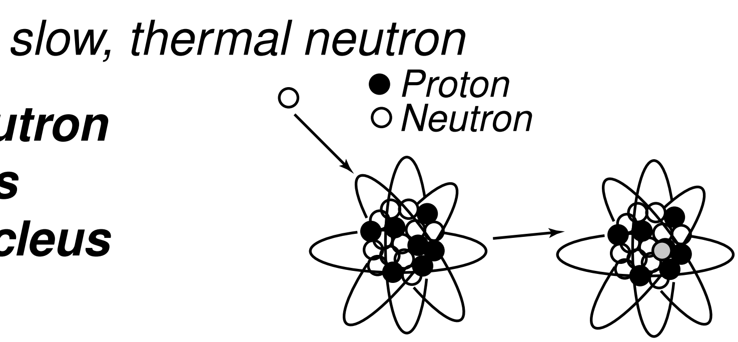
**** Neutrons may be liberated in this process.***



Thermal Neutron Activation

- Occurs when a neutron hits a nucleus and is absorbed by the nucleus

**** Increases neutron number by one without changing number of protons.***



Radioactive Decay and Production Rates

Decay Term:

$(dN/dt)_d = -\lambda N$

where t is the time

N is the number of atoms

l is a proportionality constant related to the rate of radioactive decay.

Production Term:

$(dN/dt)_p = P$

where P is the production rate

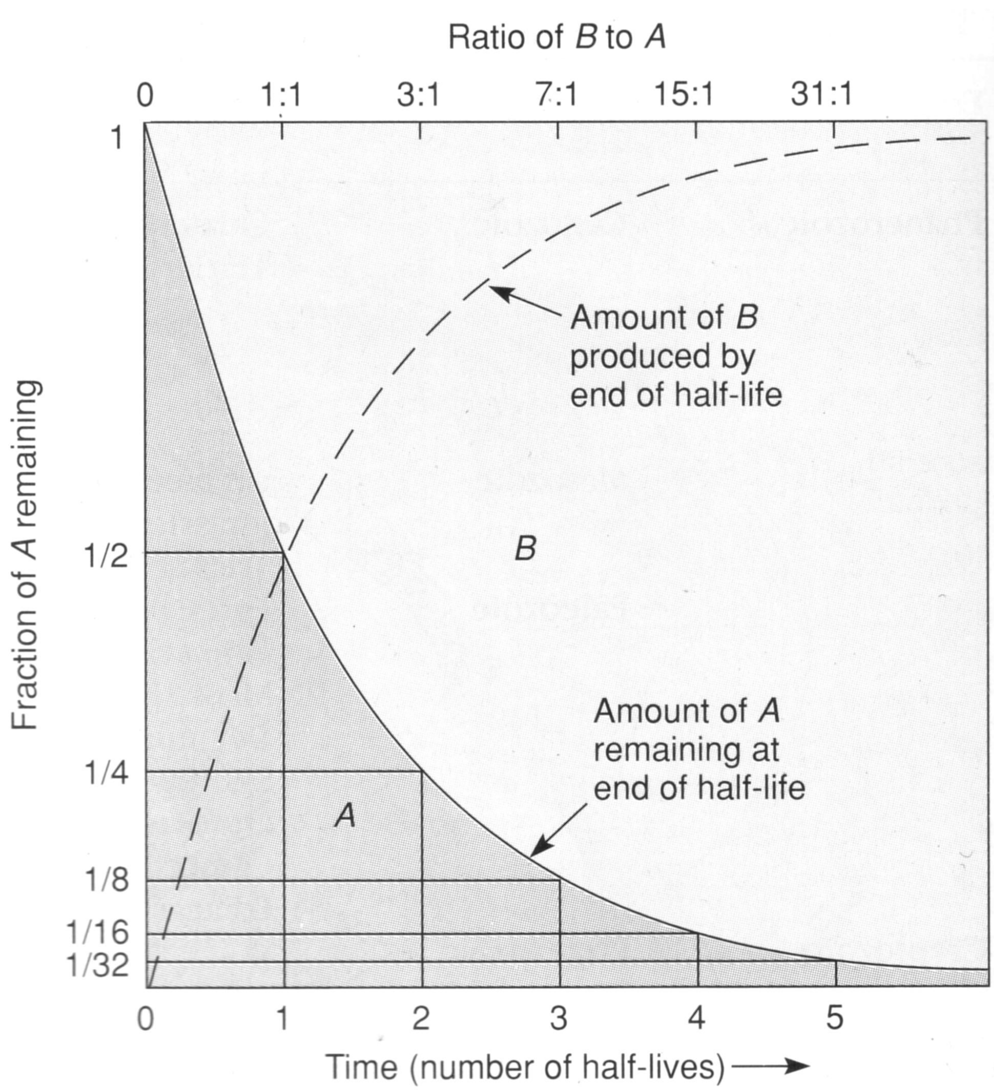
$(dN/dt) = (dN/dt)_d + (dN/dt)_p = -\lambda N + P$

if production is constant:

$N = P/\lambda\ (1 - e^{-\lambda t}) + N_o e^{-\lambda t}$

N_o = number of atoms at t = 0. Where there is no production, $N = N_o e^{-\lambda t}$

Radioactive Decay Rates



- No production of radioactive material after t=0.

- Smoothly varying exponential decline in parent product, while daughter product increases asymptotically.

* Note concentrations become small after about 4-5 half-lives. This constitutes the useful limits of the radioactive isotopes for dating.

figure from Laing, 1991

Element	Half-life (years)	Effective Range (years BP*)	Decay Product	Minerals	Rock Types
Carbon-14 (^{14}C)	5,730	<60,000	Nitrogen-14 (^{14}N)	Organisms	
Uranium-235 (^{235}U)	713×10^6	$>100 \times 10^6$	Lead-207 (^{207}Pb)	Zircon	Granite, gneiss
Potassium-40 (^{40}K)	1300×10^6	$>0.1 \times 10^6$	Argon-40 (^{40}Ar)	Biotite, muscovite, K-feldspar	Igneous, metamorphic
Uranium-238 (^{238}U)	4510×10^6	$>100 \times 10^6$	Lead-206 (^{206}Pb)	Zircon	Granite, gneiss
Rubidium-87 (^{87}Rb)	$47{,}000 \times 10^6$	$>100 \times 10^6$	Strontium-87 (^{87}Sr)	Same as ^{40}K	

table from Laing, 1991

Important Points...

** Important relative dating methods include:*

- *Seismic velocity method*
- *Weathering Rind method*
- *Obsidian Hydration Rind method*
- *Soil Profile Development method*
- *Carbonate Coating method*
- *Lichenometry*

** Radioactive decay may be an important tool for establishing absolute ages. The two important questions to answer when attempting this are: 1) What are the mechanisms by which atoms radioactively decay?; and 2) How fast do parent atoms decay into their daughter products?*

Important Points...

** Radioactive decay often occurs by:*

- *Negatron decay*
- *Positron decay*
- *Electron capture decay*
- *Branched decay*
- *Alpha decay*
- *Fission/ spallation*
- *Thermal neutron capture*

(there are other mechanisms, but these will be discussed on a case-by-case basis)

** Amount of parent and daughter product is related to the decay constant (l) for a given isotope. Differences in this rate allow specific isotopes to be used for age determinations over different time frames.*

Next time...

Absolute Dating Methods in Tectonic Geomorphology