Last Time...

1) Important relative/ semi-quantitative methods for Quarternary age control:

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

2) Radioactive decay is an important tool for establishing absolute ages. Must know: What are the mechanisms by which atoms radioactively decay?; and How fast do parent atoms decay into their daughter products?

In Today's Class...

Absolute Dating Methods

I. Dating Methods including:

- Biological methods

- Chemical methods

- Atomic methods.

Absolute Dating Methods

** Biologic:*
- Tree Ring Dating

** Biochemical:*
- Amino Acid Racemization

** Atomic:*
- Radiocarbon Dating
- U-Th Series Dating
- Fission Track Dating
- Thermoluminescence Dating
- Cosmogenic Radionuclide Dating (CRN)

Different Absolute Methods and Their Application

Method	Useful Range	Materials Needed	References: Classic and recent
Radioisotopic			
14C	35 ka	wood, shell	Libby, 1955; Stuiver, 1970
U/Th	10–350 ka	carbonate (corals, speleothems)	Ku, 1976
Thermoluminescence (TL)	30–300 ka	quartz silt	Berger, 1988
Optically stimulated luminescence	0–300 ka	quartz silt	Aitken, 1998
Cosmogenic			
In situ ^{10}Be, ^{2}6Al	3–4 Ma	quartz	Lal, 1988, Nishiizumi, 1991
He, Ne	Unlimited	olivene, quartz	Cerling and Craig, 1994
^{36}Cl	0–4 Ma		Phillips et al., 1986
Chemical			
Tephrochronology	0–several Ma	volcanic ash	Westgate and Gorton, 1981; Sarna-Wojicki et al., 1991
Amino acid recemization	0–300 ka; range temperature dependent	carbonate shell	Bada et al., 1970; Bada, 1972; Wehmiller et al., 1988
Paleomagnetic			
Identification of reversals	>700 ka	fine sediments, volcanic flows	Cox et al., 1964; 1964
Secular variations	0–700 ka	fine sediments	Creer, 1962; 1967; Lund, 1996
Biological			
Dendrochronology	10 ka, depending upon existence of a local master chronology	wood	Fritts, 1976; Jacoby et al., 1988; Yamaguchi and Hoblitt, 1995

table from Burbank and Anderson, 2001

Tree Ring Dating Basics

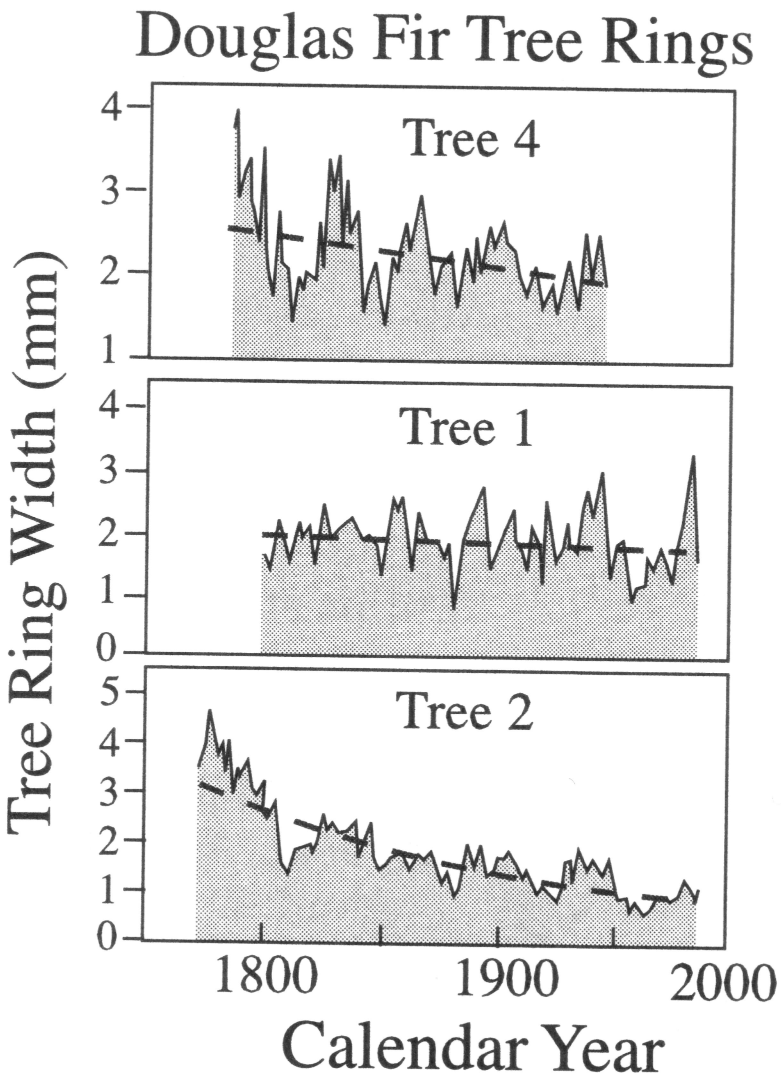
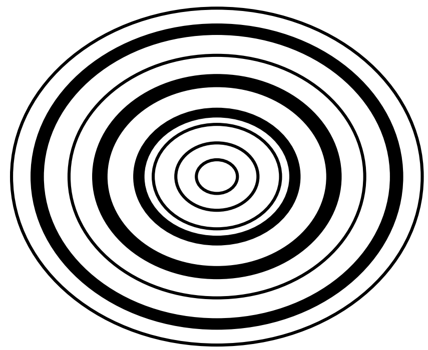


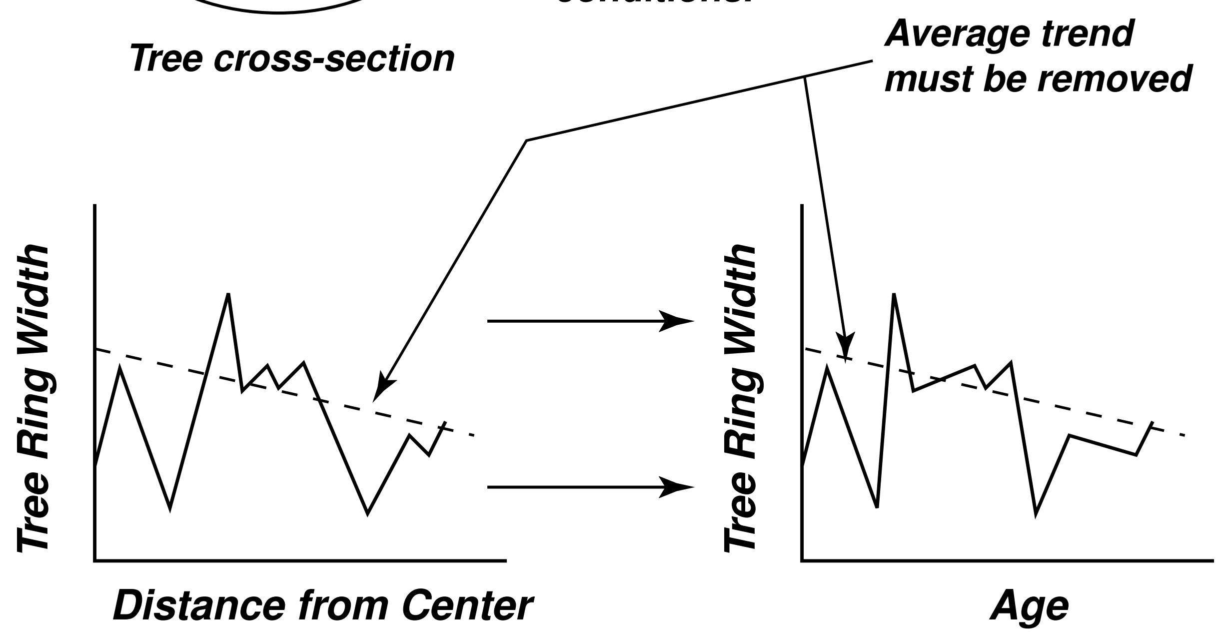
figure from Burbank and Anderson, 2001 after Yamaguchi, 1995



Tree cross-section

- If tree is alive, just count back in time based on the ring thicknesses.

**** Tree ring width may decrease as the tree gets older-- these trends must be subtracted out of the time-series. Also, width of rings depends on species and environmental conditions.***



Tree Ring Dating

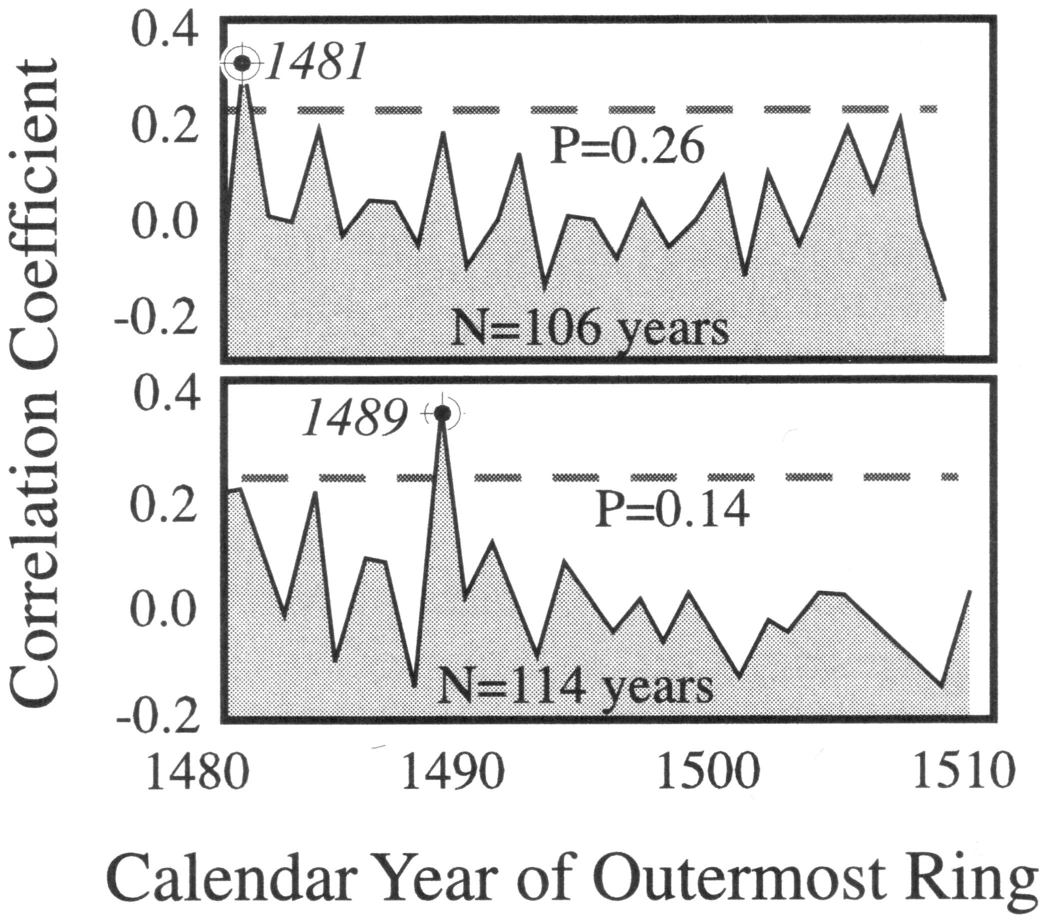
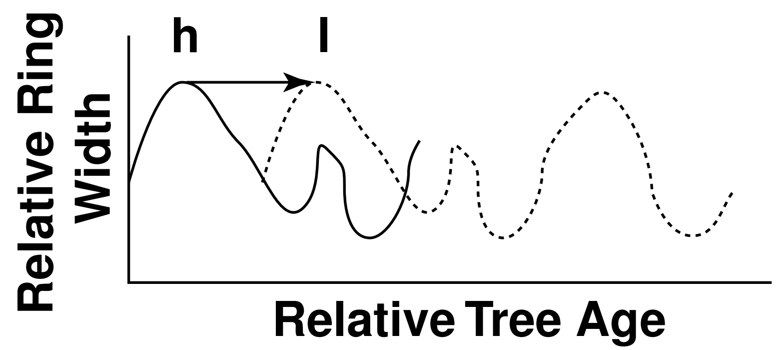


figure from Burbank and Anderson, 2001 after Yamaguchi, 1995

- To extend record farther back in time, dead trees are analyzed whose age overlaps with living record. Matches in ages are found, and "composite" tree ring record may be extrapolated back in time:



l = low correlation; h = high correlation
*** Limit to extrapolation ~10 kyr from Bristlecone Pines.**

- Method provides very accurate age control for recent (< 10 kyr) features.

Radiocarbon Dating

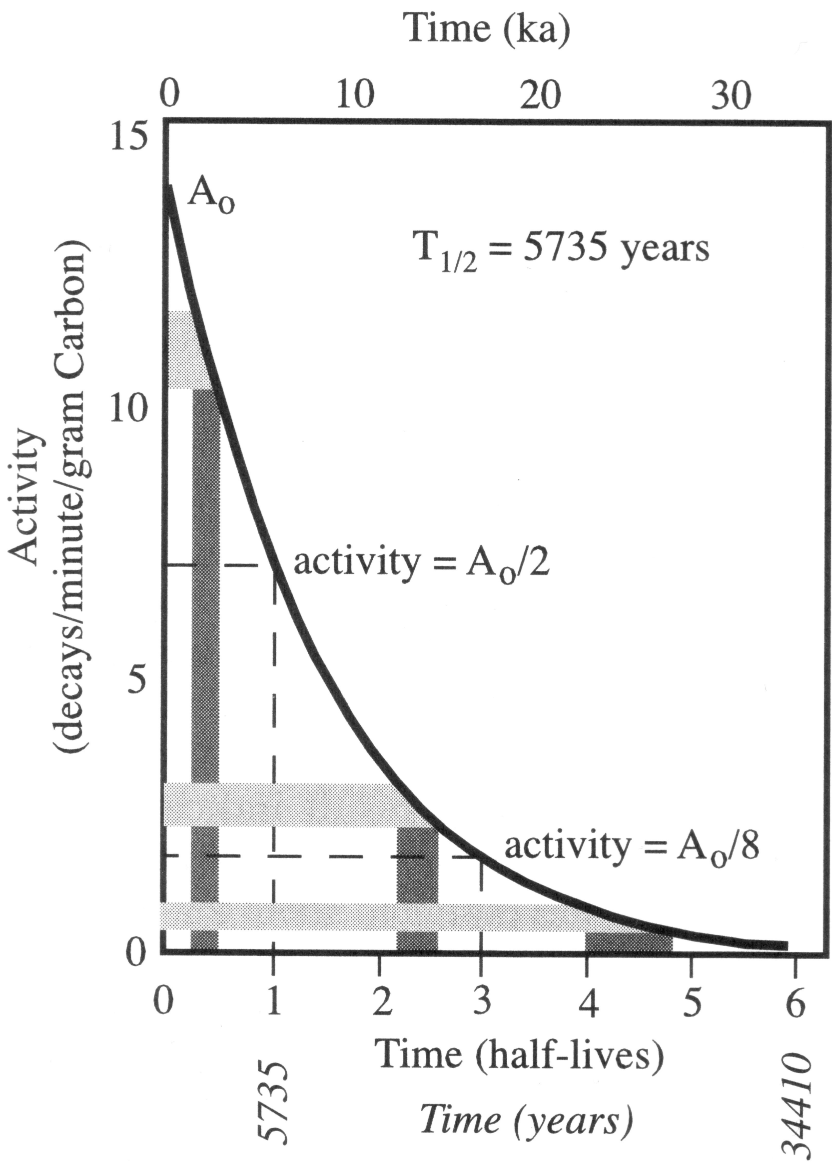


figure from Burbank and Anderson, 2001 after Olsson, 1968

- While alive, organisms incorporate roughly the atmospheric ratio of $^{14}C/^{12}C$. However, when they die, the ratio declines as 14C decays to 14N.

- By measuring $^{14}C/^{12}C$ ratio, one can estimate the time since the organism died. Where it has been incorporated into the stratigraphic record, age of unit may be inferred (although it is assumed that the organism died at approximately the same time the stratum was deposited).

- Must know: initial $^{14}C/^{12}C$ ratio, decay rate of 14C, and measured $^{14}C/^{12}C$ ratio.

*** Useful only over about 7 half-lives (or 50 ka).**

*** Measurement methods for $^{14}C/^{12}C$ ratio: 1) β-emission and 2) AMS.**

Problems with Radiocarbon Dating

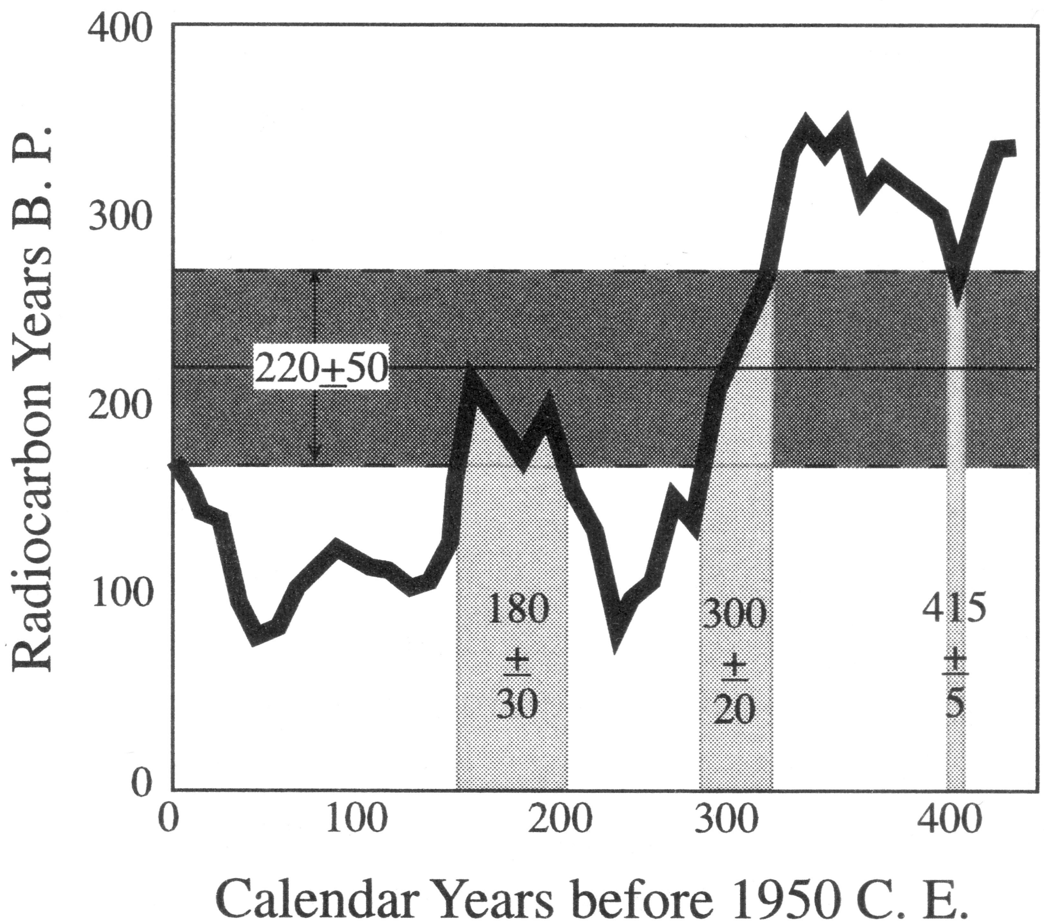


figure from Burbank and Anderson, 2001 after Porter, 1981

- Atmospheric 14C/12C ratio has apparently fluctuated through time

**** This change in the starting conditions can affect the ages inferred from measured 14C/12C ratios.***

- Calibration of the method is necessary. Tree ring method has been used to create a radiocarbon calibration curve that maps radiocarbon ages into calendar years.

U-Th Series Dating

** Method is based on the spontaneous decay of ^{238}U, ^{235}U, and ^{232}Th to Pb isotopes.*

** Not dependent on atmospheric ratios or cosmic ray flux, so it is reliable without calibration.*

** Must take place in a closed system, whereby either the parent or its daughters cannot be leaked out of the system. Most systems do not satisfy this condition. Tests can be made to determine if the system is closed or not.*

U-Th Decay Chain

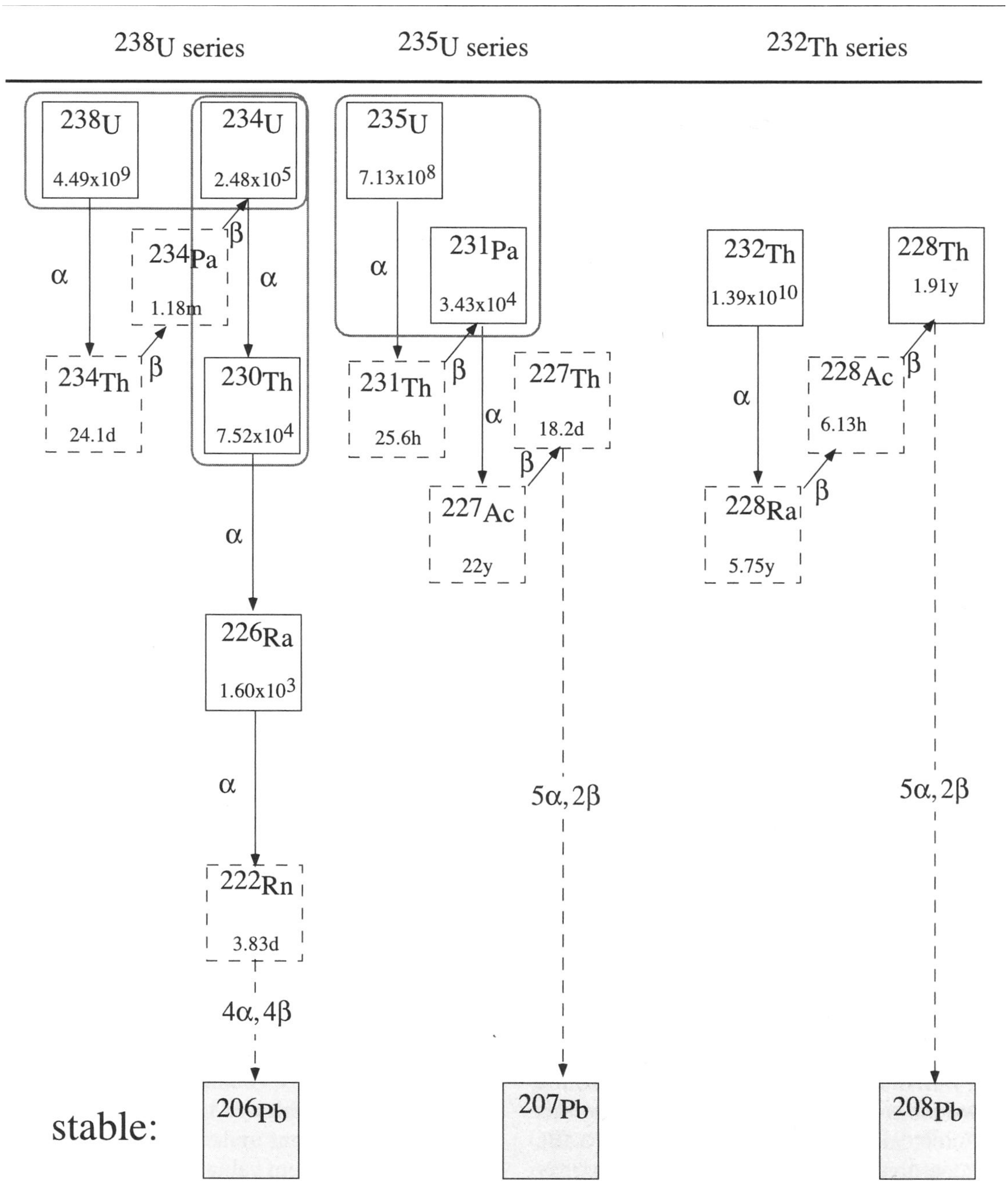
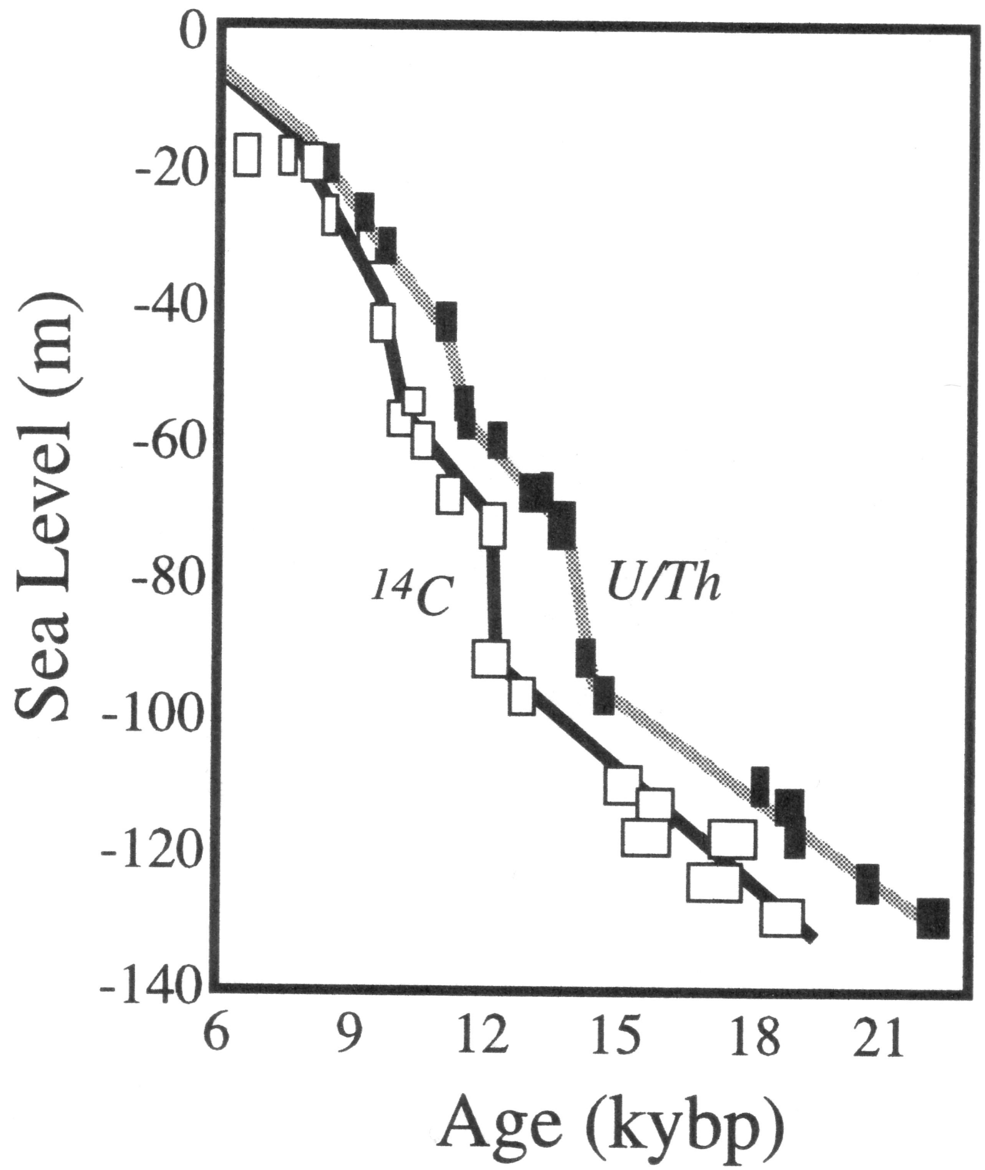


figure from Burbank and Anderson, 2001

U-Th and Radiocarbon Comparison

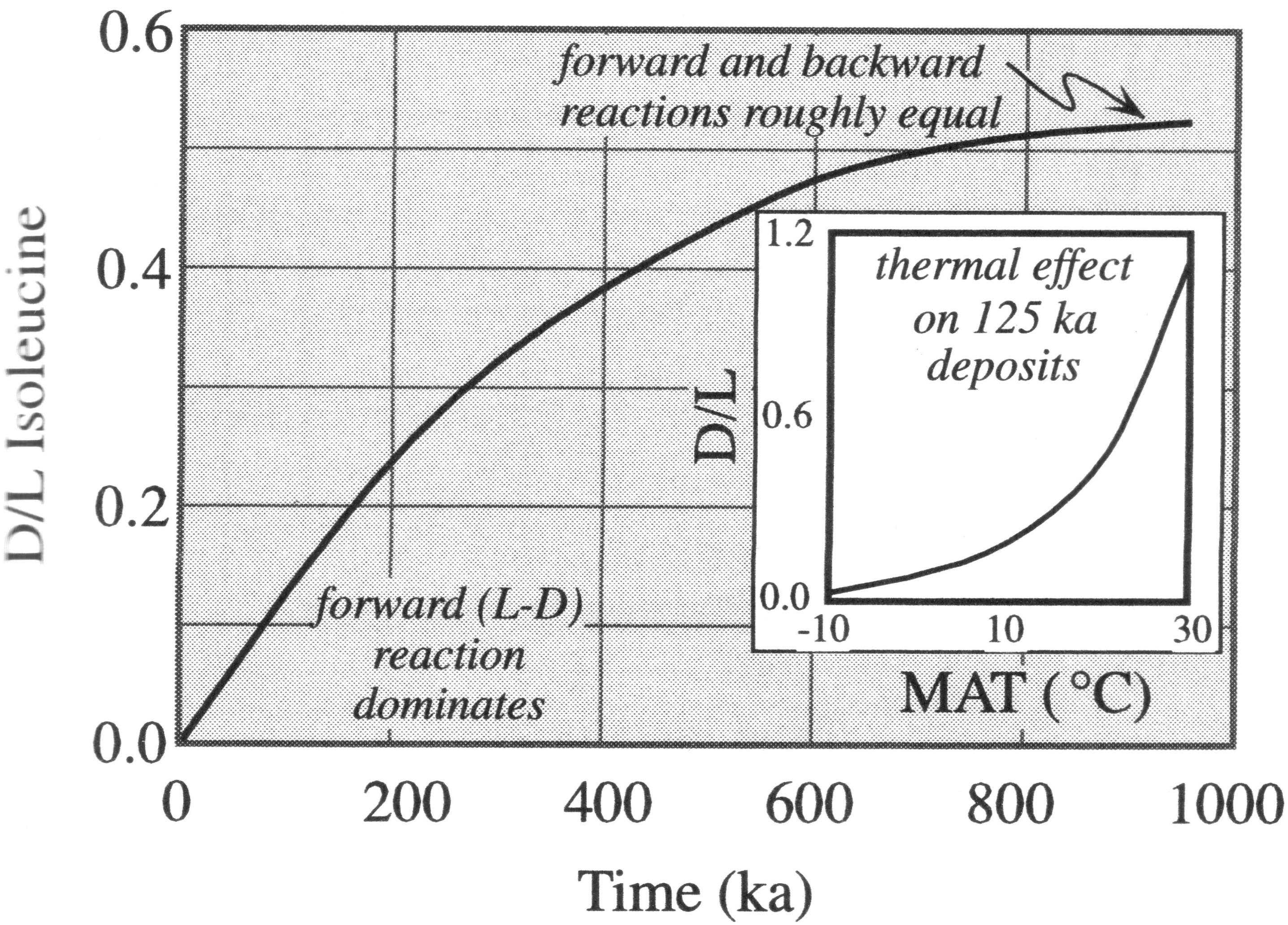


- U-Th dates from corals may be used to calibrate radiocarbon ages past 10 ka.

** Calibration suggests that radiocarbon ages older than 10 ka may be systematically younger than calendar ages.*

figure from Burbank and Anderson, 2001 after Bard et al., 1990

Amino Acid Racemization



- Two orientations of amino acid molecules: "D" for dextro (right-handed) and "L" for levo (left-handed).

- Organisms only use L-configurations of amino acids; however, upon death, "L" amino acids may transform into "D" amino acids. Thus, we can date death.

*** Reaction rates highly dependent on temperature and acid type.**

figure from Burbank and Anderson, 2001 after Kaufman and Miller, 1992 and Hearty and Miller, 1987

Luminescence Dating

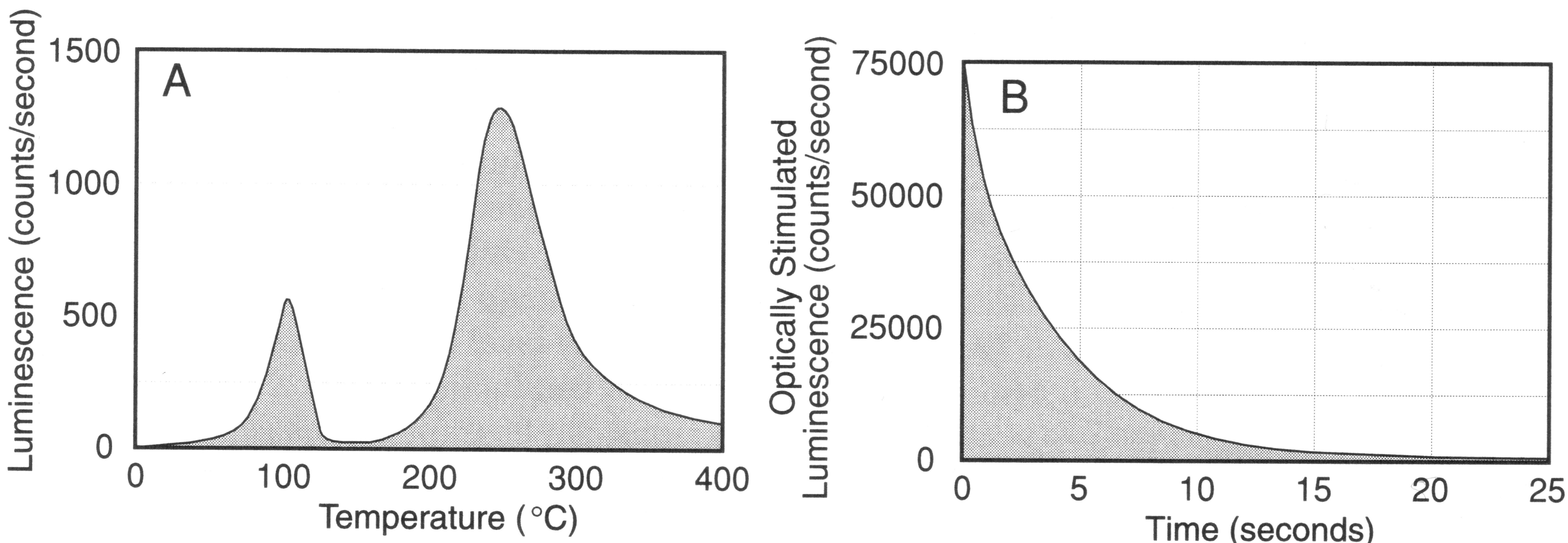
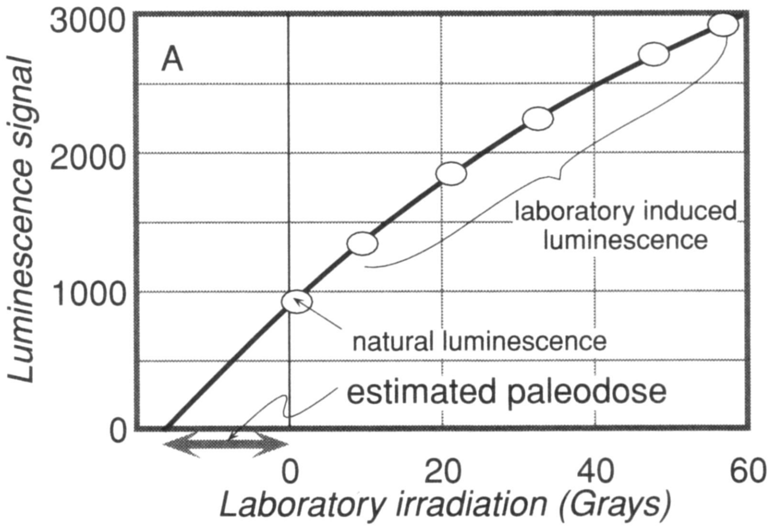


figure from Burbank and Anderson, 2001 after Duller, 1996

- When energy is trapped in certain crystals (most notably quartz and feldspar), some electrons move from the lower-energy band (valence band) to a higher-energy band (conduction band). Energy comes from radioactive decay of atoms in material surrounding a target crystal. Some electrons can be trapped between these two bands and made to drop back to valence band when energy is added, releasing a photon. By knowing the amount of atoms that have decayed (yielding a dose rate) and measuring the number of atoms trapped in the metastable state between the valence and conduction bands, an age can be calculated.

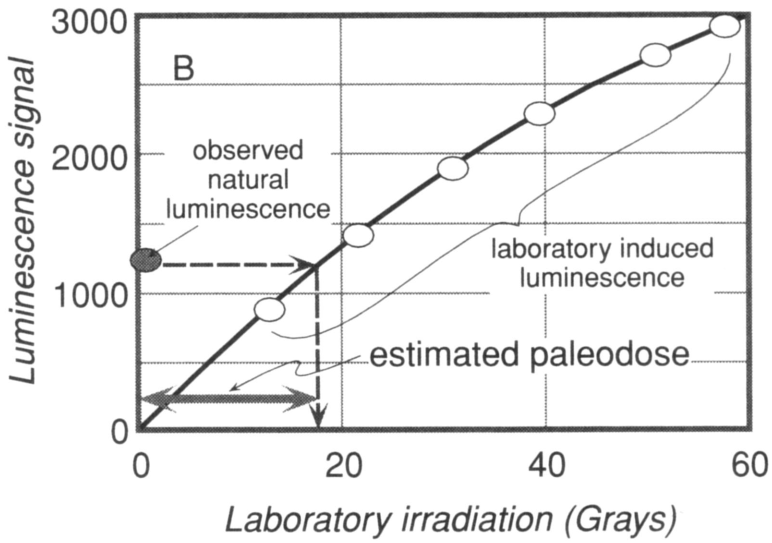
*** Thermoluminescence uses heat to release photons to measure paleodose. Optically-stimulated luminescence uses light of a particular wavelength to measure excitation.**

Different Methods to Determine Paleodose



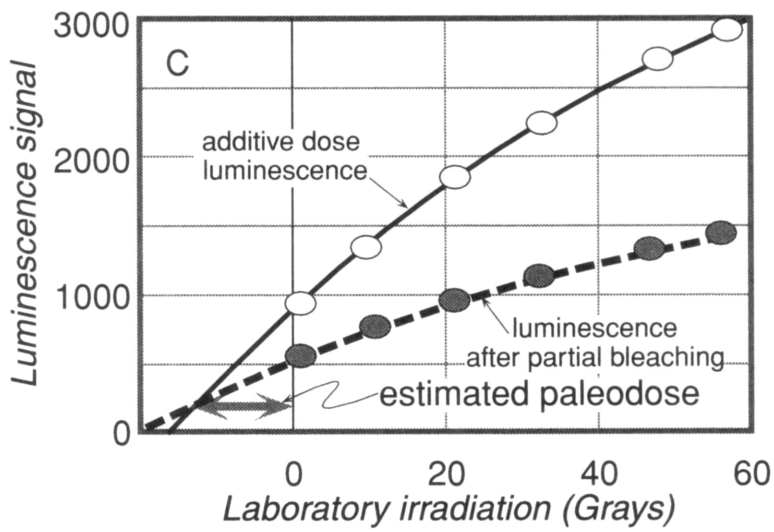
Additive dose method

- Samples are irradiated in the laboratory, luminosity is plotted as a function of irradiation, and paleodose is inferred.



Regenerative method

- Two sets of samples are used. First, natural luminosity of samples is measured. Then, energy state is reset by high radiation dose. Continuous irradiation establishes paleodose.



Partial Bleach method

- Two sets of samples are used. Samples are irradiated in the laboratory, luminosity is plotted as a function of irradiation, and paleodose is inferred. Second group is partially bleached by addition of irradiation. Procedure is repeated to infer .

figure from Burbank and Anderson, 2001 after Duller, 1996

Fission Track (Lattice Damage) Methods

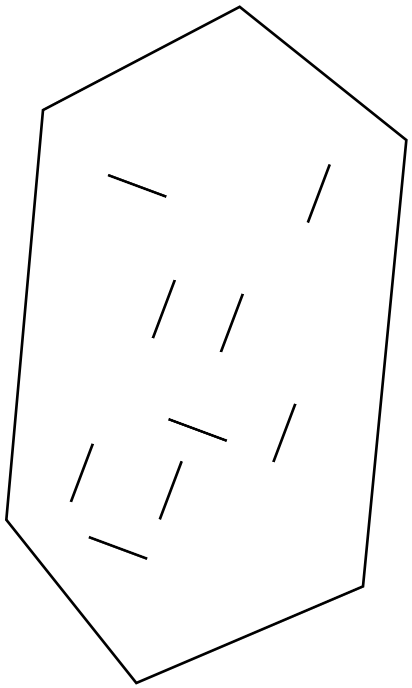
- Fission track methods are based on the observation that when fission of large atoms occurs and liberates energy the fission products tear the crystal lattice of a mineral as the high-energy particles fly away.

- The damage tracks record a fission event, so by knowing the concentration of the parent product in the mineral, its half-life, and the number of fission events, an age can be determined.

- Minerals will "heal" these tracks if the temperature is high enough. The temperature at which total healing occurs varies with the mineral, its composition, and the rate at which the mineral cools.

- Therefore, "hot" minerals formed at the same time as "cold" minerals will have fewer tracks. The tracks in this case record the time at which the mineral cooled below its healing temp.

Apatite Fission Track (AFT)



- Closing temperature between 80-120 ^{o}C.

- To determine uranium content of apatite, an external detector (usually a mica plate) is put onto the crystal and it is irradiated with neutrons. Number of induced fission events whose tracks penetrate the apatite surface is recorded by mica detector.

- Prior to irradiation, sample is etched to highlight spontaneous fission tracks. After irradiation, mica is etched to reveal induced tracks.

** Problems: human and statistical counting errors, errors in measurement of neutron flux from reactor, and uncertain ^{238}U decay constant.*

*** To circumvent these problems, they are lumped into a calibration factor and a sample of known age (by independent methods) is counted to calibrate method for a particular person. Frequent recalibration is necessary.*

U-Th-He Fission Track Dating

- Method is based on the retention of He in the crystal lattice of apatite below ~80^{o}C. Above this temperature, He leaks out of the crystal lattice.

- By measuring parent and daughter products, the time at which the apatite passed through its cooling temperature may be inferred. From this, exhumation rates in the shallow crust may also be inferred.

- Smaller crystal sizes have lower closure temperatures than larger crystals. Therefore, by analyzing crystals of various sizes, a detailed shallow exhumation history may be inferred.

Cosmogenic Radionuclide Dating

- Method provides a means of dating the exposure of a surface to the atmosphere.

- Cosmic rays bombard the surface of the earth, producing exotic isotopes. By measuring the concentration of these in situ isotopes and knowing the production of these isotopes from cosmogenic bombardment, an exposure age may be computed.

Production of CRNs

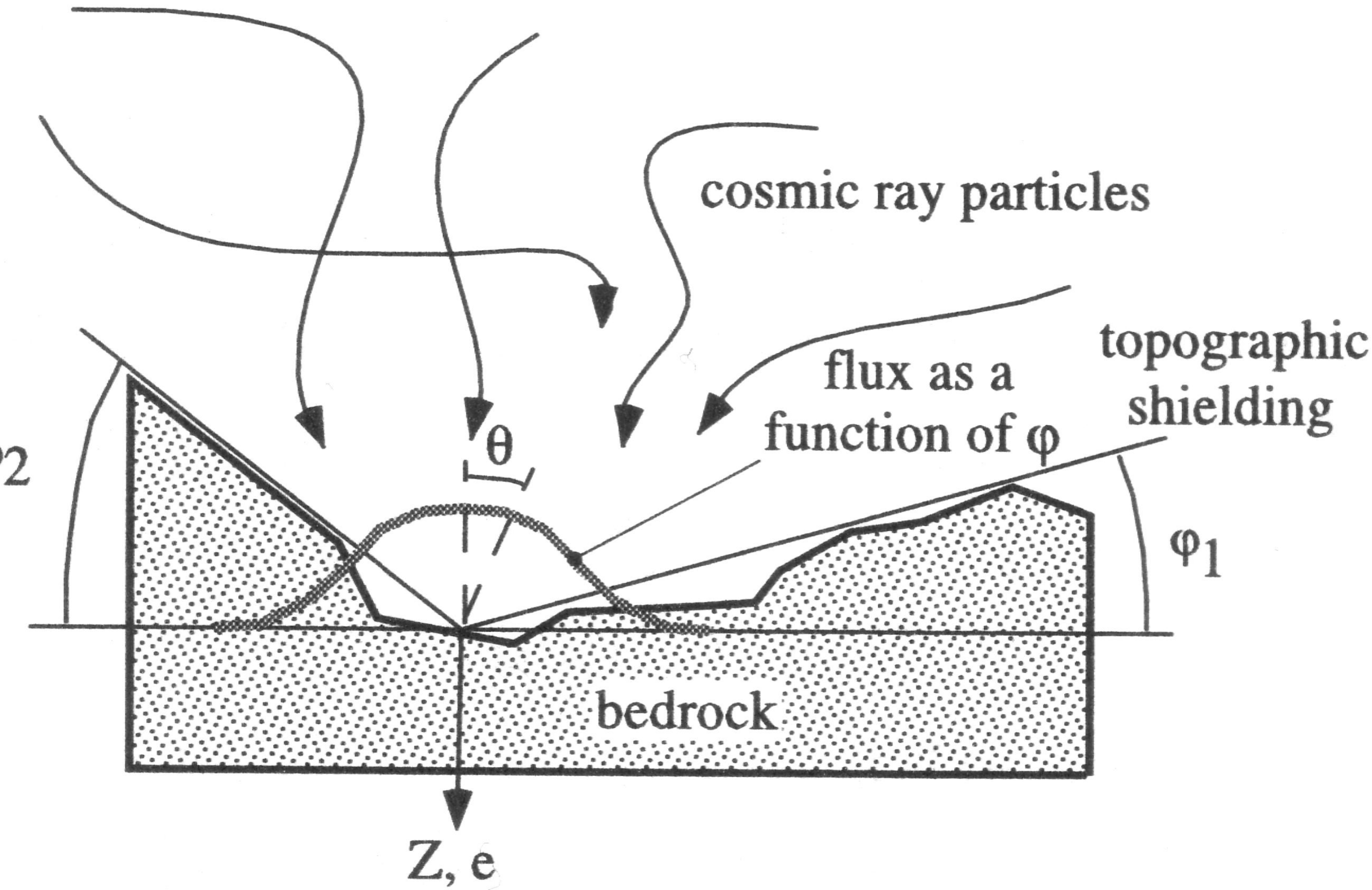


figure taken from Burbank and Anderson, 2001

- Cosmic rays are focused by the geomagnetic field towards the poles and travel through the atmosphere, producing "garden variety" isotopes. Those isotopes reaching the surface produce in situ CRNs (in the rocks themselves) by colliding with target atoms, producing isotopes.

*** Production rates dependent on latitude, elevation, geomagnetic field intensity, and the isotope and amount of target atoms.**

In Situ Cosmogenic Production Rates

	^{14}C	^{10}Be	^{26}Al	^{36}Cl
P_o	21.0	5.81	34.9	4 - 9
λ	$1.2x10^{-4}$	$4.62x10^{-7}$	$9.9x10^{-7}$	$4.81x10^{-7}$
$1/\lambda$	8276	$2.16x10^{6}$	$1.01x10^{6}$	$2.1x10^{6}$
$t_{1/2}$	5735	$1.5x10^{6}$	$0.7x10^{6}$	$0.3x10^{6}$

table taken from Burbank and Anderson, 2001

Production Rates with Depth

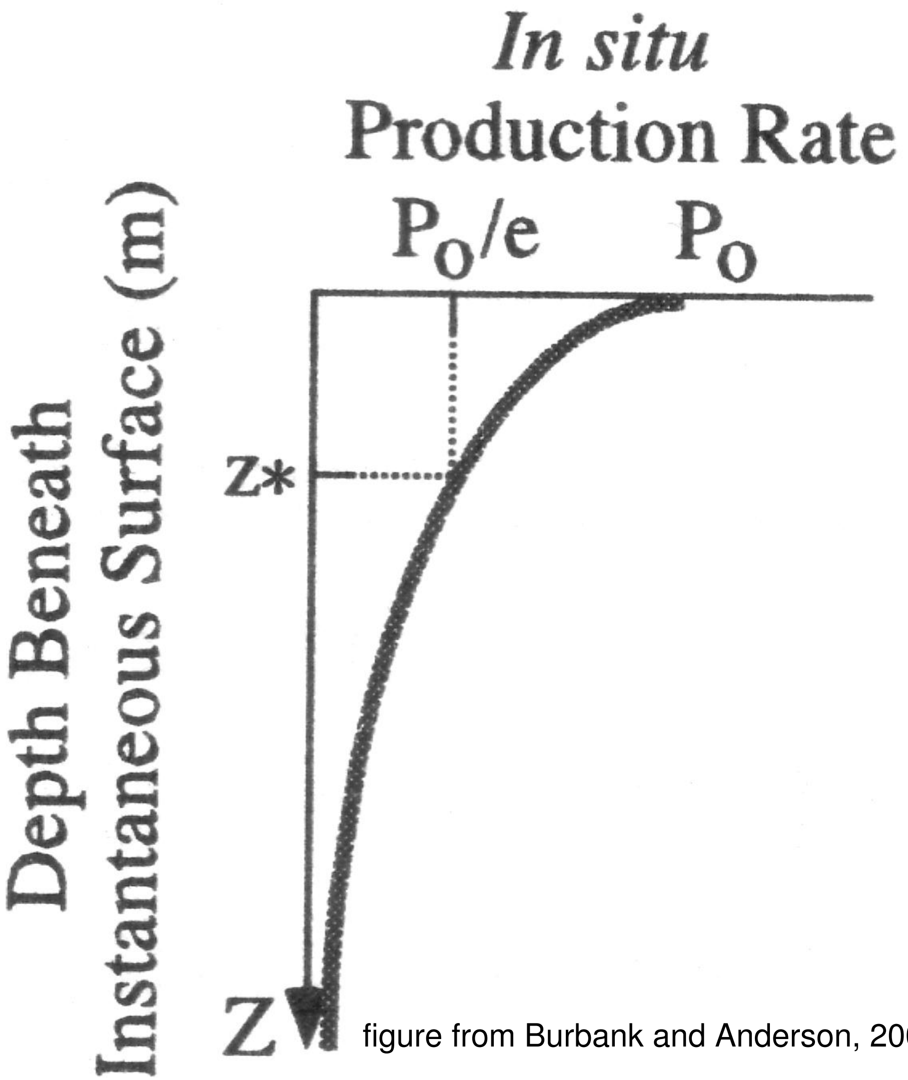


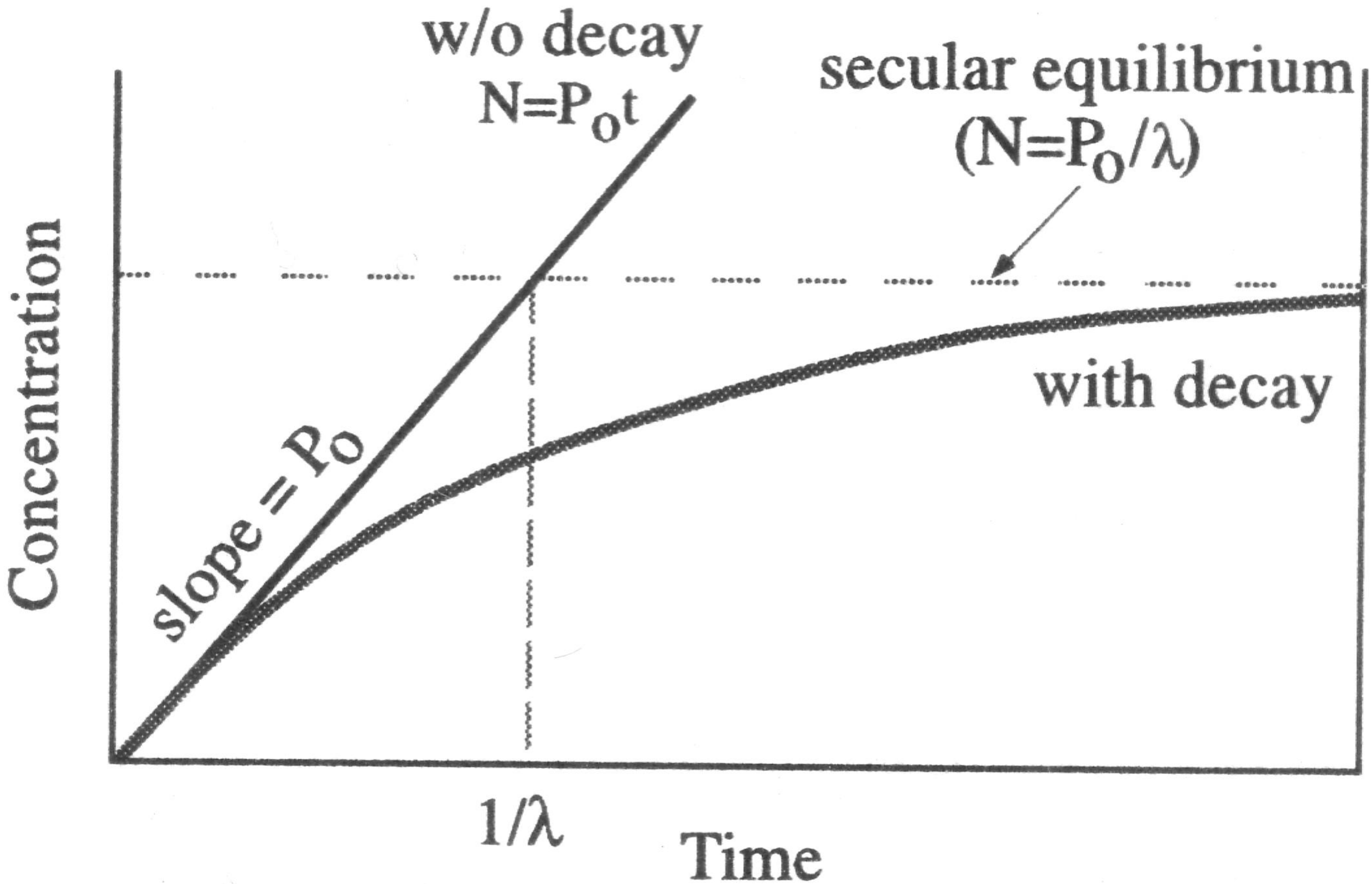
figure from Burbank and Anderson, 2001

- As cosmic rays interact with solids below the surface, their energy converts target atoms to isotopes. Because less cosmic rays penetrate the solids with depth, the production rate declines as a function of depth.

$$P(z) = P_o e^{-z/z^*}$$

** If depth samples are taken, exposure age can be better resolved.*

Cosmogenic Exposure Age- No Erosion



Cosmogenically Determined Erosion Rates

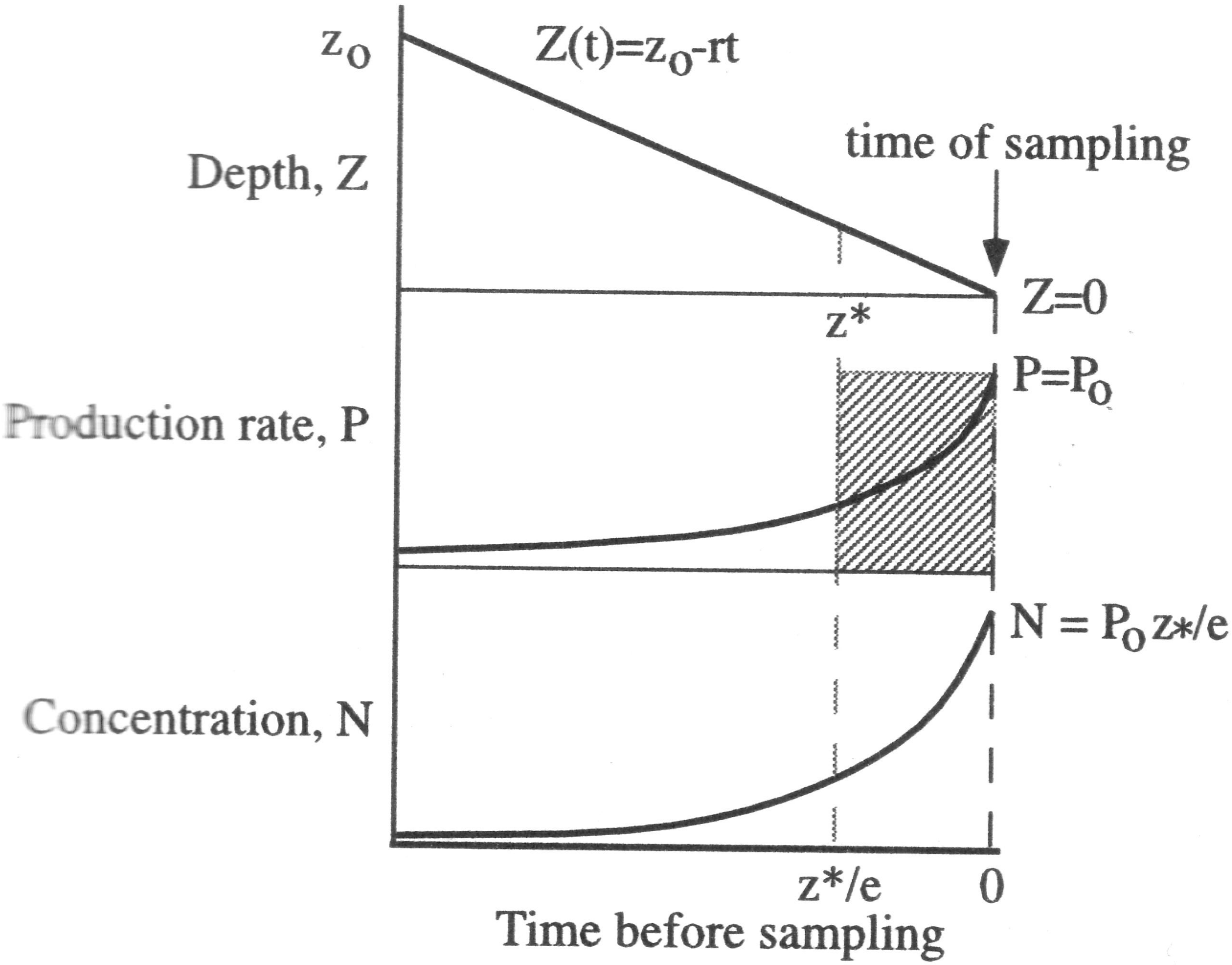


figure from Burbank and Anderson, 2001

- Slower erosion rates leave rock exposed to cosmic rays longer-- higher concentrations than slower rates.

- By assuming steady erosion, concentration of isotopes at surface may serve as an indicator of erosion rate.

Problems with Interpreting CRN Dates

- Production rate varies with geomagnetic latitude and field intensity. The geomagnetic intensity (and hence production rate) may change significantly over the life of the sample.

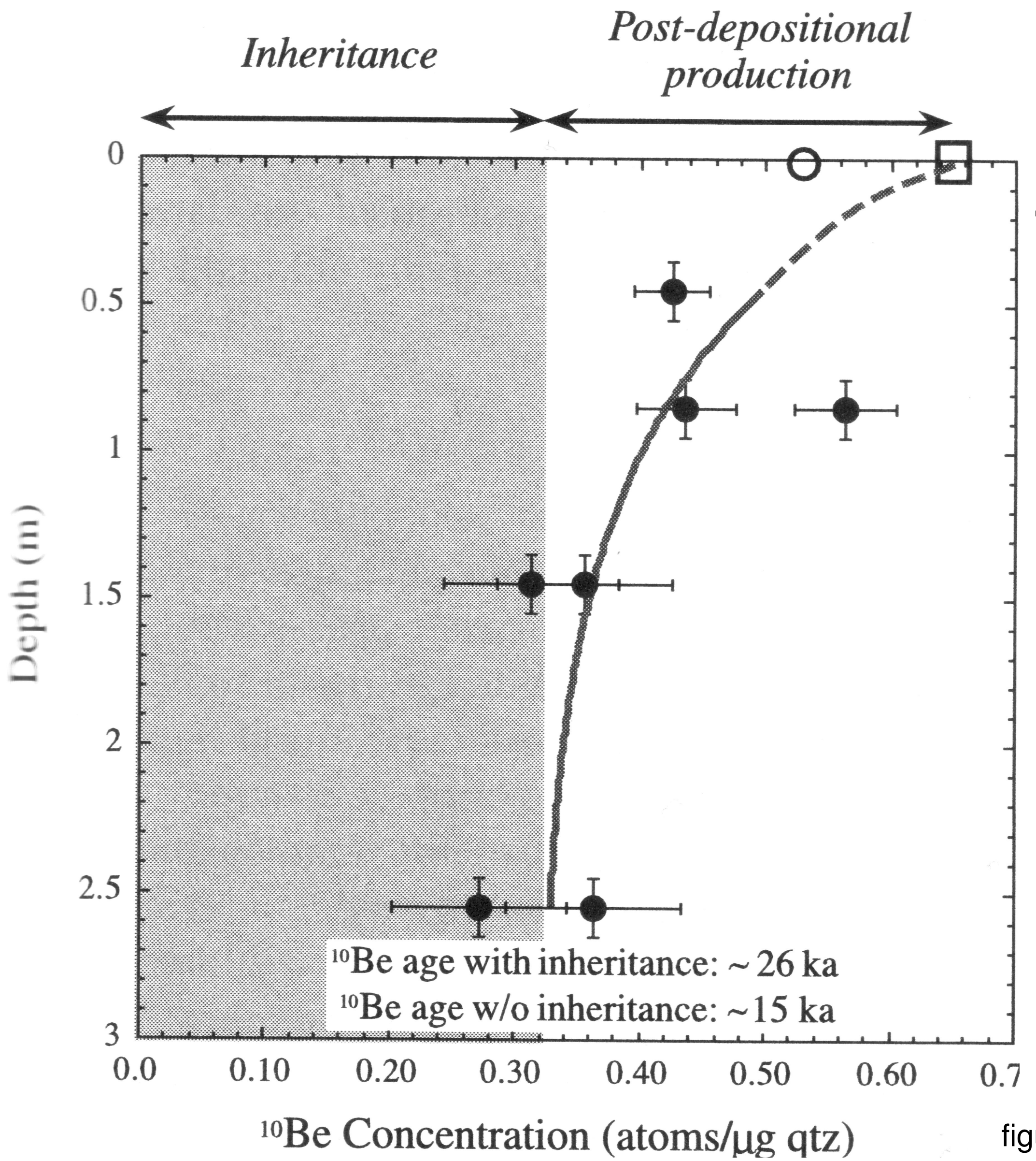
- Production rate calibrations are few.

- Geomorphic history of sample must be VERY well constrained:

**** Age represents combination of clast exposure on a surface, the clast exposure prior to deposition, and the amount and rate of erosion of the surface.***

**** More complicated exposure histories may be interpreted with v dating, but the exposure and burial episodes must be somewhat constrained a priori.***

How can we estimate prior exposure?

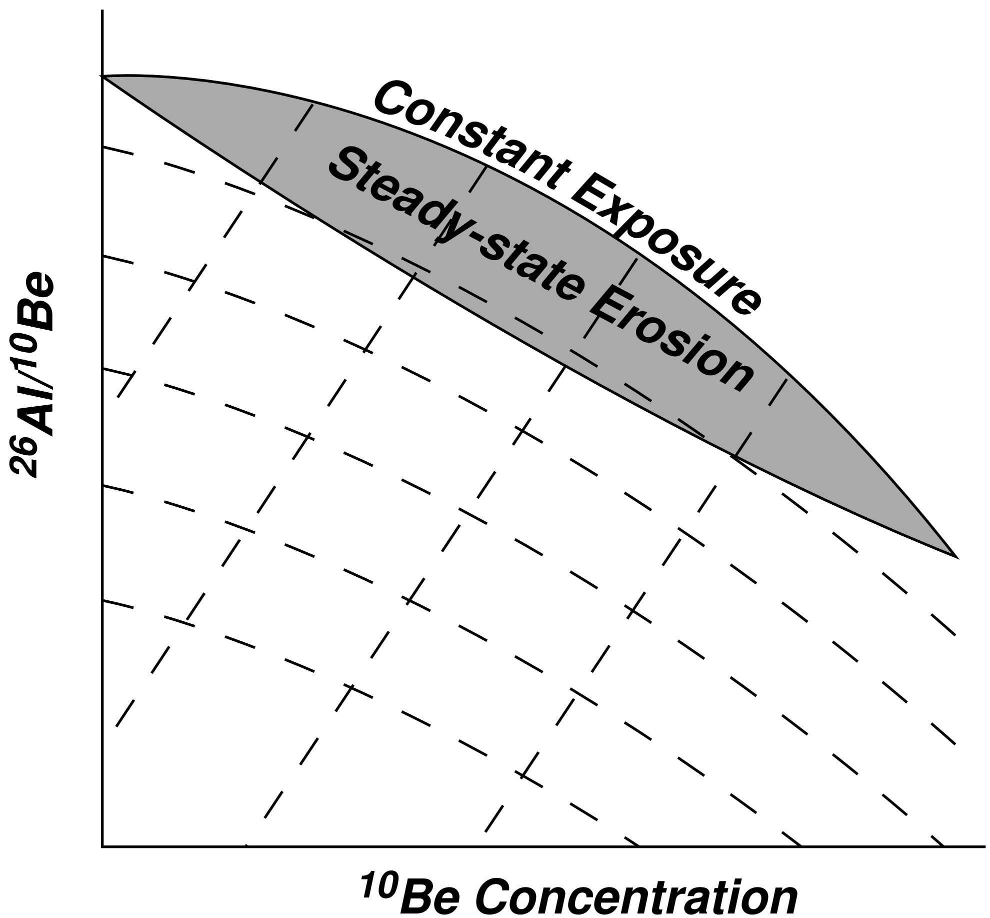


- Because production rate decreases quickly with depth, by taking a series of samples with depth, the prior exposure may be determined. Samples > 3m deep likely have few CRNs produced in situ after deposition, so CRN concentrations represent prior exposure.

*** Must assume that all samples in column have identical prior exposure.**

figure from Burbank and Anderson, 2001

How might one determine if samples have a complex erosion and burial history?



- Use two different CRNs with different production and decay rates!

**** While samples are exposed, ratio of production rates remains constant.***

**** With shielding, one of the isotopes will decay faster than the other, changing the ratio of the two isotopes.***

**** As samples approach secular equilibrium, ratio of two isotopes declines.***

Important Points:

- Absolute ages of geomorphic features or attributes of these features (cooling rates) may be inferred from a variety of methods:

** Tree Rings*
** Radiocarbon Dating*
** U-Th Series Dating*
** Amino Acid Racemization*
** Luminescence Dating*
** Fission Track Dating*
** Cosmogenic Radionuclide Dating.*

** The mineralogic/biologic constituents necessary for each method must be present.*

Important Points:

- Cosmogenic Radionuclide Dating has potential to directly date exposure of surfaces. Interpretation of ages remains problematic:

- It is unclear how production rates change over time. Calibration by independent methods is necessary.

- Age represents convolution of prior exposure, exposure, and erosion.

-Multiple isotopes may be used to help sort out erosion and burial history of a sample.

Next Class:

Stress, Strain, Deformation, and Kinematics