RADIOMETRIC DATING AND NUMERICAL CALIBRATION OF THE TIME SCALE

I. INTRODUCTION

A. Numerical Dating Techniques

1. Numerical dating is the process of applying techniques of physics and chemistry to rock sequences to establish an absolute "numerical age" for the time of formation.

a. The idea behind numerical dating in to establish the absolute (numerical) time in the past (before present time) in which a particular geologic event occurred or formed

(1) Deposition of a sedimentary unit
(2) Eruption of a volcanic lava or pyroclastic unit
(3) Emplacement and cooling (solidification) of a plutonic magma
(4) Heating and deformation of a metamorphic rock suite

b. Numerical dating is based on established rates of physical and/or chemical processes that operate in silicate minerals and rocks, and/or organic-bearing sedimentary rocks (i.e. those containing carbon-based molecules)

(1) Rates of process = process per unit time

(2) Fundamental laboratory and empirical observations of time-related chemical and physical phenomena must be established.

(a) Materials of the process classified as

i) reactant
ii) product

(b) Time and/or rate of conversion of reactants to products must be established

(c) Once conversion rate is known:

i) Comparison of amount (mass) or ratio of reactants to products can be solved mathematically to establish absolute time of process

(3) Time of process = numerical age of material from time at which process/reaction began to time of analytical observation (present)

c. Characteristics of a good "rock clock"

(1) system must store process information at a known rate

(2) rock system must behave as a closed system (with no leakage of processes or products)

(3) rates of process and time of occurrence must have useful age or time period over which they occur

(a) e.g. a process that involves a rate of 10 b.y. would be of little value because the oldest numerical age of the earth has been established at 4.5 b.y.

d. Overview of techniques

(1) Radiochronology: based on process of spontaneous radioactive decay of unstable isotopes contained within crystal structure of minerals.

(2) Carbon-14 Dating: variation of radiochronologic technique applied to Carbon-bearing deposits (implies connection to organic processes)

2. Calibration of the Geologic Time Scale

a. Absolute or numerical dating used in combination with basic stratigraphic principles (superposition, cross-cutting relations, inclusions, etc)

(1) Placing numerical/"absolute" ages on the Relative Geologic Time Scale

(2) Especially significant for differentiating geologic events in the Precambrian where other methods of stratigraphic analysis are not applicable (i.e. crystalline "non-layered" rocks with little fossil record)

B. Historical Perspectives of Numerical Dating

1. 1897- Lord Kelvin: 19th century British Physicist

a. Assumed a rate of cooling for a presumed molten earth

(1) calculated age of earth = 20-40 million years

2. 1899- Geologist John Joly

a. examined the salinity of ocean water

b. assumed (estimated) an annual rate of delivery of salts to oceans by rivers

(1) considering the initial salinity = 0

c. determined an age of oceans of about 90 m.y.

3. Radiochronology/Radioactive Decay

a. 1896- Henri Becquerel, French physicist

(1) accidentally discovered Uranium spontaneously emits rays that cause fogging of photographic plates in total darkness

(a) named property of Uranium as "radioactivity"

b. 1905-1910- B.B. Boltwood, Chemist at Yale University

(1) presented theory that uranium radioactively decays to form lead

(2) chemically analyses uranium minerals from around world determined that:

- (a) older uranium rocks contained more lead than younger ones
- (b) Assumed crude decay rates for Uranium
  - i) estimated age of 340 million years for Carboniferous Rocks
  - ii) estimated 1640 million years for Precambrian Rocks

c. Ernest Rutherford - 1905- Physicist from New Zealand

- (1) experimented with radioactivity and suggested that given a constant radioactive decay rate, the ratios of products and reactants could yield the age of a mineral

d. 1910-Present

- (1) advances and refinement of techniques have take place
  - (a) mass spectrometers refined for use in differentiating isotopes of elements on the basis of atomic weight and mass
  - (b) Advanced experimental studies of radioactive decay and decay rate constants

II. PRINCIPLES OF RADIOMETRIC DATING

A. Basics of Radioactivity

1. Isotopes: variations of a given element

   a. contain same no. of protons (which define the element)
   b. contain differing nos. of neutrons

   - (1) variation in no. of neutrons results in variation in atomic weight of isotope
     - (a) e.g. Carbon 12 and Carbon 14 (isotopes of Carbon)
       - i) atomic no. of C = 6
         - a) Carbon 12 = 6 neutrons
         - b) Carbon 14 = 8 neutrons

2. Radioactive Isotopes

   a. Isotope Instability: some isotopes of elements are electrostatically unstable in nature and undergo spontaneous radioactive decay-----transition to a more stable form

   - (1) Delicate Electrostatic Balance
     - (a) Charge Balance: all atoms must be balanced with respect to positive proton charge and negative electron charge
       - i) like charges repel
       - ii) opposite charges attract
     - (b) The neutron as the referee

i) The neutron, although of zero net charge, acts as a referee in the charge balancing act between positives and negatives.

ii) Neutron/Proton ratio important in determining atomic stability and dictating tendency for radioactive decay

a) n/p ratio stable to 1.5 at ^{209}Bi

b) As protons (atomic no.) increases beyond this point in the periodic table, the repulsive forces between protons in the nucleus also increases

c) At higher atomic nos., it is necessary to stabilize the inter-proton repulsive force by addition of extra neutrons and effectively increasing the distance between protons.

d) Caveat: too many additional neutrons will also render the atom unstable and spontaneous radioactive decay occurs

e) Radioactive decay occurs to yield a more favorable n/p ratio for a given element

f) However, at atomic numbers greater than Bi 209 are unstable regardless of n/p ratio, and hence tend towards spontaneous radioactive decay.

g) n/p ratios relatively stable between 1 and 1.5, all n/p ratios outside these limits are extremely unstable and undergo radioactive decay

h) although some isotopes within n/p 1-1.5 are also unstable

(2) Unstable Nuclei

(a) if particular nucleus is unstable, will undergo radioactive decay to produce a new nucleus

i) If product is not stable ==== further decay to another form of nucleus

3. More Terminology

a. Nuclide: general term for radioactive atoms and elements

b. Parent Nuclide: original unstable element present before radioactive decay

c. Daughter Nuclide: product resulting from radioactive decay (stabilization) of parent nuclide

d. Decay Series: Parent decays into daughter product which in turn may be unstable and undergoes a second decay step, occurs repetitively until stable end product exists

4. Types of Spontaneous Radioactive Decay (Alpha, Beta, and Gamma: Alpha and Beta = particulate radioactivity; Gamma = electromagnetic "wave" radioactivity)

a. Alpha Decay: Unstable isotope emits alpha particles to increase stability

(1) Alpha Particle = Helium Nucleus = 2 protons + 2 neutrons (atomic weight of 4) (alpha particle has n/p ratio = 1)

(a) decay common in elements with atomic numbers > 83

(b) Alpha decay causes decrease in no. of protons in nucleus

i) Hence, tends to > n/p ratio

ii) e.g. Decay Series U 235 to Th 231

Uranium 235: Atomic No. = 92; 92 protons + 143 neutrons (n/p=1.554)

Thorium 231: Atomic No. = 90; 90 protons + 141 neutrons (n/p=1.567)

Alpha Particle = 2 protons + 2 neutrons

U 235 ----- alpha particle + TH 231

** Hence U 235 loses 2 protons + 2 neutrons to form daughter product TH231

b. Beta Decay: Unstable isotope emits beta particles to increase stability

(1) Process 1: If n/p ration is too high (unstable) then n/p ratio is decreased by conversion of a neutron to a proton within the nucleus

(a) Neutron = Proton + Electron = (1+) + (1-) = 0

(b) "B- decay" = (Neutron - Electron) = Proton + Free Electron

i) The Free Electron = B- particle

ii) The Neutron is converted to a proton by loss of an electron

iii) E.g. Decay of Indium 116 (In 116) to Tin 116

In 116 = Atomic No. 49 = 49 protons + 67 neutrons (n/p = 1.367)

Sn 116 = Atomic No. 50 = 50 protons + 66 neutrons (n/p=1.320)

In 116 ----- (B-) + Sn 116

**In beta decay process one neutron is converted to a proton with a release of a free electron or Beta negative particle (since an electron has no atomic mass, the atomic weight of the Parent and Daughter products remains unchanged, only the atomic number changes)

(2) Process 2: if n/p ratio is too low to be stable

(a) B+ decay: proton loses "positron" as free B+ particle, and converts to a neutron

Sb (116/51) ---- (B+) + Sn (116/50)
(n/p=1.275) (n/p=1.32)

(b) Electron Capture: proton captures an electron to form a neutron

Au (195/79) + (e-) ------ Pt (195/78)
(n/p=1.468) (n/p=1.5)

c. Gamma Decay

(1) While alpha and beta decay involves transformation of the nucleus in terms of particle emission...

(2) Gamma "rays" = electromagnetic radiation which behaves according to wave theory as opposed to particle theory

(a) Gamma rays = electromagnetic radiation commonly given off as a by-product of alpha and beta decay processes

i) e.g. Co (60/27) ----- Ni (60/28) + (B-) + (2 gamma)

(b) However, gamma rays may also be emitted by spontaneous gamma decay without alpha or beta emissions

(c) X-rays = gamma rays emitted following Beta-form electron capture

i) captured electron leaves a space in valence energy shells, shifting of remaining electrons to lower shells results in release of energy or gamma "X-rays".

(3) Radiation Hazard:

(a) Particulate radiation (alpha, beta) may be stopped by physical barriers (skin, clothing, wood/plaster walls)

(b) Electromagnetic Radiation (gamma) is much more penetrative and difficult to obstruct

i) gamma radioactivity is much more dangerous to cell tissue

B. Decay Rates and Time

1. Radioactive decay: occurs at a geometric rate

   a. Proportion of daughter atoms to parent atoms remains constant

2. Decay Constant (element/isotope specific)
   a. For given element, experimentally determined probability of decay

3. Half-life ($T_{1/2}$)

   a. Amount of time required for one half of the parent element to radioactively decay into the daughter product

   b. Relationship of half-life to decay constant:

      (1) $T_{1/2}$ = (0.69315/decay constant)

4. Laboratory Experimentation

   a. Half-life and Decay constants experimentally determined under laboratory conditions, can be applied historically to rock record via Law of Uniformitarianism

   b. Known Decay constants and half-life values:

Parent Isotope	Daughter Product	Decay Process	Half-life (Yrs)	Decay Constants
K-40	Ar-40	Electron Capture	1.25×10^{9}	5.54×10^{-10}
U-238	Pb-206	Decay Series	4.47×10^{9}	1.55×10^{-10}
U-235	Pb-207	Decay Series	7.04×10^{8}	9.85×10^{-10}
Th-232	Pb-208	Decay Series	1.40×10^{10}	4.95×10^{-11}
Rb-87	Sr-87	B- Decay	4.88×10^{10}	1.42×10^{-11}
C-14	N-14	B- Decay	5.73×10^{3}	1.21×10^{-4}

   c. Various isotopes of various elements have half-lives ranging from seconds to billions of years

C. Analytical Technique

1. Half-lives determined by specially designed laboratory counters, measures rate of radioactive decay.

2. Knowing the half-life (decay rate) the age of mineral bearing the given element can be determined:

   a. All minerals contain some radioactive isotopes to varying degrees as impurities included in the crystal structure

   b. Rock Analysis Technique

      (1) Determine amount of given parent nuclide and daughter nuclide present in mineral structure of rock sample

         (a) Isotopes identified using mass

spectrometer

i) Spectrometer or electromagnetic-emitting device that segregates isotopes of a sample on the basis of mass and atomic weight

(2) Determine proportion of Parent to Daughter Products in sample

(a) formulate percent parent remaining

i) Assuming a closed system, with zero daughter isotope present at the time of mineral formation:

$$\%\text{Parent Remaining} = \frac{\text{Mass Parent}}{\text{Mass Parent + Daughter}}$$

E.g. 100% Parent = Time Zero (i.e. no radioactive decay)

% Parent Remaining will exponentially decrease with time according the half-life geometric decay series

(3) Determine Age of Sample

(a) Governing Equations:

$N = N_o e^{-*t}$ Where

N = No. of parent atoms at time t
t = time elapsed since time 0 (time of formation)
* = decay constant
e = mathematical constant = 2.718

$* = \ln(2)/T_{1/2} = 0.69314/T_{1/2}$ Where

ln = log normal
$T_{1/2}$= half-life of parent nuclide

Replacing * of the first equation with equation 2, taking the ln of both sides of the equation, and rearranging:

$$t = -\frac{T_{1/2}}{0.69314}\ln(N/No)$$

t = age of rock
N/No = ratio of no. of present parent atoms to original

E.g. Calculate the age of a mineral using U-235 decaying to Pb-207. From summary table above, the half-life = 7.04 x 10^8 yrs. Based on mass spectroscopy analysis, N = 440,000 atoms of U-235, and that No = 1,200,000 atoms of U-235 (assuming that there was no Pb-207 in the sample at to).

Solving the equation above should yield t = 1.019 x 10^9 yrs Try It!!

D. Reliability and Sources of Uncertainty

1. Uncertainty and sources of error

a. Mineralogic/Isotopic systems were not "closed" throughout the history of the mineral

(1) Daughter loss through radiogenic leakage

(a) perhaps very prevalent with K-Ar dating

i) Ar = noble gas, under tectonic deformation/heating, stress and fracturing of mineral at crystalline structure level could result in leakage of Ar gas, thus yielding anomalous age values

a) Will result in anomalous "young" age

b. Base assumption that no daughter nuclide was present at the time of formation of the mineral

(1) what if there was? .... anomalous age determination

c. Experimental Error

(1) approximation of half-lives and decay constants
(a) accuracy known to be within 1-2%

(2) Calibration errors with mass spectrometer
(a) will influence isotopic ratio values

(3) Human-Instrument-Experimental Variation

d. Statistical Representation of Error

(1) A no. of replicate sample runs are completed and corresponding ages calculated

(2) Precision estimate of data

(a) e.g. t = 300 M.Y. +/- 15 M.Y.

i) i.e. the data could fall in a range of 30 M.Y. about the t estimate

(b) Precision Estimate = standard deviation of values determined from numerous replicated analyses.

III. COMMONLY USED ISOTOPIC SYSTEMS AND METHODOLOGY

A. Principal Methods of Radiometric Age Determination

Parent Nuclide	Daughter Nuclide	Half-Life (Yrs)	Useful Date Range (Yrs)	Materials Dated
Carbon-14	Nitrogen-14	5730	~40,000	Wood, Peat, $CaCO_3$ shells Charcoal
Protactinium-231	Actinium-227	33,000	<150,000	Deep sea sediment, aragonite corals
Thorium-230	Radium-226	77,000	<250,000	Deep sea sediment, aragonite corals
Uranium-238	Lead-206	4,510 million	>5 million	Monazite, zircon, uraninite
Uranium-238	Fission Tracks	-----	~65,000	volc. glass, zircon, apatite
Uranium-235	Lead-207	713 million	>60,000	Monazite, zircon, uraninite

Potassium-40	Argon-40	1,300 million	>100,000	Muscovite, biotite, hornblende, glauconite, sanidine, whole volc. rock
Rubidium-87	Strontium-87	47,000 million	>5 million	Muscovite, biotite, lepidodite, microcline, glauconite, whole metamorphic rock

B. K-Ar Method

1. Utilitarian Method

a. K abundant in earth's crust (2.6 Wt. % of total volume)
b. Relatively ubiquitous in occurrence in rock record
c. K-40 to A-40 decay sequence may be used to date wide range of rocks from Pleistocene through Archeozoic

2. Decay Process

a. K-40 decay

(1) 89% B- decay to produce Calcium-40
(2) 11 % electron capture decay to produce Ar-40

3. Advantages

a. Ar-40 is noble gas, rarely present in natural occurrence in igneous rocks (i.e. primarily derived through K-40 decay)

b. Ar-40 = non-reactive inert gas, hence simple and easy to identify analytically

(1) can be detected to very low concentrations

(2) Useful for young rocks within 100,000 yrs old

4. Disadvantages

a. leakage of radiogenic argon by diffusion processes, out of mineral crystal structure (diffusion = process of chemical transfer along concentration gradients)

(1) would yield anomalously young age dates (Ar-40 underestimated)

(2) Causes

(a) slow cooling of igneous rocks above "blocking temperature" (see below) for prolonged periods of time

(b) tectonic micro-fracturing of crystal lattice

(c) Metamorphic re-heating of mineral with gas escape

5. Applications

a. Dating of Lava flows, ashes and quickly cooled plutonic rocks

- b. Glauconite Mineralization in Marine Sediments
  - (1) Glauconite = K-Fe-Al-Silicate
    - (a) forms on sea floor under quiet marine conditions
    - (b) K-40 incorporated into glauconite mineral structure during growth at primary stage of mineral development

C. U-Pb Methods

- 1. Mode of Occurrence
  - a. Uranium found in 3 naturally occurring states
    - (1) U-238, U-235 and U-234
  - b. Uranium-bearing minerals include Uraninite, Monzanite and Zircon
- 2. Decay Process
  - a. Uranium Decay Series: Uranium decays into lead via 5 relatively short-lived intermediate daughter products
    - (1) U-238 Series
      - (a) 8 alpha decay steps + 6 Beta Decay Steps
      - (b) Intermediate daughter products:
        - i) Thorium, Palladium, Radium, Radon, and Polonium
      - (c) Final Daughter Product - Lead 206 (stable)
    - (2) U-235 Series
      - (a) "Actinium Series"
      - (b) 7 alpha decay steps
      - (c) 4 beta decay steps
      - (d) Final Product = Lead 207 (stable)
    - (3) Thorium-232 = intermediate daughter product of Uranium decay
      - (a) Th-232 decays to Lead 208
- 3. Precautionary Relationships
  - a. Most if not all Uranium-bearing minerals contain some primary lead included at the time of formation
    - (1) Must determine primary vs. daughter product lead
      - (a) Common lead contains proportion of lead 204, which is not a decay product, hence must have been present at time of mineral formation
        - i) determine content of lead 204, and in turn can estimate proportion of primary Pb-207 and Pb-208, to correct determination of daughter

products

    - b. Secondary Loss of Lead Daughter Product
        - (1) Cause
            - (a) Thermal Re-heating associated with metamorphism or igneous intrusion

- 4. Advantages
    - a. Multiple Uranium isotope decay series provides means of cross-checking age determinations independently

- 5. Applications
    - a. Igneous uranium-bearing minerals
    - b. Uranium-bearing calcite shell material
    - c. Uranium-bearing travertine precipitates

D. Th-230 Method

- 1. Used in dating recent, unconsolidated marine sediments
- 2. Th-230 intermediary daughter nuclide of U-238 decay
    - a. Th-230 in turn decays to Radium-226
        - (1) $T_{1/2}$ = 83,000 yrs
    - b. Th-230 readily absorbed into layer lattice of marine clay minerals
- 3. Systematic down-core variation in Th-230/Ra-226 content has been successfully used to date deep sea sediment cores.

E. Rb-Sr Method

- 1. Mode of Occurrence
    - a. Rb-85 and Rb-87 commonly occurring
        - (1) Rb-87 = 25% of all rubidium
    - b. Rb-87 found in wide variety of minerals
        - (1) k-spar, mica, pyroxene, amphibole, olive, clays
- 2. Decay Process
    - a. Rb-87 undergoes B- decay to form Sr-87 daughter nuclide
- 3. Applications
    - a. Igneous intrusives: granites, pegmatites and mafics
    - b. Metamorphic Rocks: effective in Precambrian
- 4. Precautions
    - a. common Rb-bearing minerals also contain common (primary) strontium
        - (1) Sr-86 and Sr-87: found in relatively constant ratios
    - b. Must I.d. primary Sr-87 on basis of accompanying Sr-86 in sample
        - (1) Subtract primary Sr-87 from radiogenic Sr-87 daughter nuclide
            - (a) Proportion of radiogenic to primary > with > age

(b) therefore, error decreases with > age of rock

F. Radiocarbon Dating

1. Introduction

a. Carbon dating based on organically-derived compounds (isotopes above derived from purely inorganic processes)

b. Applications: wood, charcoal, seeds, cloth, paper, peat, bones, shells, cave deposits (calcium carbonate)

2. Decay Process

a. Carbon Isotopes

(1) C-12 and C-13 (stable isotopes)
(2) C-14 (radioactive)

b. C-14 Process

(1) Origin:

(a) derived from N-14 in upper atmosphere
(b) N-14 + cosmic electromagnetic radiation ---- C14

i) N-14 + Neutron ---- Proton + C-14

(c) C-14 once formed, in turn incorporated into atmospheric carbon dioxide, and in turn, incorporated into C-based compounds of plants, animals, and calcium carbonate deposits.

(2) Reverse Decay

(a) C-14 transforms to N-14 through B-decay

i) C-14 ---- N-14 + B-

c. Isotopic Equilibrium of C-14 Reservoir

(1) C-14 is continually being produced in the atmosphere, equilibrium exists between C-14 and other forms of carbon in atmosphere, hydrosphere and biosphere

(a) C-14 content of atmosphere has fluctuated with time in response to change in flux of cosmic ray input (solar activity and/or magnetic field variations)

3. Dating Method

a. Radiocarbon dates are determined by detecting the amount of C-14 remaining in dead organic material

b. The original amount of C-14 is determined based on estimations of atmospheric equilibrium of the C-12/C-14 ratio

(1) Method does not examine N-14, it readily escapes to the atmosphere (this is different

than the "daughter" based comparisons presented above)

c. C-14 half-life = 5730 +/- 40 years

d. C-14 Dating becomes problem in older deposits due to short half-life

(1) C-14 currently detectable to 10 half-lives (i.e ~ 40,000 Yrs B.P.)

G. Other Related Dating Methods

1. Fission Track Dating

a. Based on observation of radiation damage to the mineral crystal structure during radioactive decay.

(1) Fission = spontaneous splitting of atoms into sub-atomic particles
(2) U-238 commonly undergoes spontaneous fission and is commonly found as a trace element in volcanic glass, zircon, and apatite

(a) Fission-Tracks = structural damage to the crystal structure of the mineral as fission products shoot through solid during radioactive and particle emission

i) Can be readily identified in the mineral with an electron microscope

ii) Can be readily identified with a standard petrographic microscope if sample is etched with a strong acid to enhance the tracks

b. Age dating technique

(1) with > time, > density and number of fission tracks

(a) By counting tracks and comparisons with standards, can derive age of mineral grain

(b) "Annealing" temperature of tracks: If mineral is raised to higher temperature, tracks may become healed and undetectable in crystal structure

(c) Date = time since mineral passed through last annealing temperature phase

IV. TECHNIQUES FOR RADIOMETRIC DATING AND TIME CALIBRATION OF ROCK RECORD

A. Igneous and Metamorphic Rocks

1. Igneous and Metamorphic Rocks readily amenable to radiometric dating techniques

a. The minerals form "in-situ" as primary components of the igneous crystallization process.

b. Radioactive isotopes "lock-in" minerals at the time of crystallization, begin decay process and daughter nuclide formation.

- c. A variety of minerals and isotopes may be found in same sample: readily amenable to "cross-checking" age date by more than one technique.

2. Setting the Isotopic Clock (Thermal Activity)

    - a. "Blocking Temperature" or "Diffusion Threshold"

        - (1) Temperature of cooling, below which mineral structure is solidified and "closed" with respect to isotopic system.

            - (a) above which, parent/daughter nuclides are mobile into and out of the mineral system

            - (b) i.e. a critical cooling temperature must be reached before the egg timer is chemically turned on.

3. Metamorphism and Heating: Re-setting the Isotopic Clock

    - a. Re-heating of rock and/or mineral by metamorphic or igneous processes, could raise the temperature of the minerals above the blocking temperature or diffusion threshold

        - (1) Net result: escape of daughter product... effectively wiping the slate clean and resetting the "clock"

B. Sedimentary Rock Record

1. Problematic Aspects of Radiometric Dating and Sedimentary Rocks

    - a. Sedimentary Rocks represent in large part, clastic debris that is weathered and eroded from "parent" crystalline rocks, or re-cycled sedimentary rocks.

    - b. Hence, the mineralogy of sedimentary rocks is not a primary product, but a secondary product of the weathering, erosion, transportation process.

    - c. Hence, radiometric dating of minerals in clastic sedimentary rocks will yield the date of crystallization of the mineral in the crystalline source terrain, <u>not</u> the time of deposition of the sedimentary rock.

2. Indirect Applications of Radiometric Dating to Sedimentary Rocks

    - a. Interbedded Volcanic Lavas, Ashes, and Pyroclastics

        - (1) Lava flows and ashes can be incorporated as interbeds within contemporaneous sedimentary deposits

        - (2) Provide readily datable marker bed to calibrate ages of sedimentary strata in close proximity (above and below) to the marker

            - (a) Whole-rock K-Ar dating

(b) K-Ar and Rb-Sr dating of volcanic minerals

(3) Calibrating fossil-bearing sedimentary sequences with volcanic marker beds, provides a numerical age to fossils, which can then be used for refined biostratigraphy

b. Bracketed Ages: Cross-cutting Relations with Igneous and Metamorphic Rocks

(1) Radiometric dating of intrusives coupled with cross-cutting relations can "bracket" the time during which a sedimentary deposit could have formed.

(a) Bracketed ages can be useful in defining minimum rates of processes

3. Direct Applications: Radiochronology of Sedimentary Rocks

a. Radiocarbon: Carbon-14 Method and Recent Sediments
b. Thorium Radiochronology Deep Sea Seds. (see discussion above)
c. K-Ar or Rb-Sr dating of in-situ formed glauconite from sedimentary deposits

SUMMARY: Types of Rocks Most Useful for Geochronology / Radiometric Dating of Sedimentary Sequences

Type of Rock	**Stratigraphic Relationship**	**Reliability of Age Data**
Volcanic Lava/ash	Interbedded with "contemporaneous sedimentary Rocks	Yield associated of Sed. rocks in contact
Plutonic Igneous Rocks	Intrude/cross-cut sed. rocks Lie unconformably below sed. rocks	Minimum ages of intruded rx Maximum ages of intruded rx
Meta-sedimentary Rocks	Datable sequences in themselves Lie unconformably below sed. rocks	Minimum ages of meta-seds Maximum ages of overlying rx
Sediments with woody organics		Yield actual ages of Sed. Rx
Sediments with authigenic minerals (in-situ glauconite)		Yield minimum ages of Sed. Rx