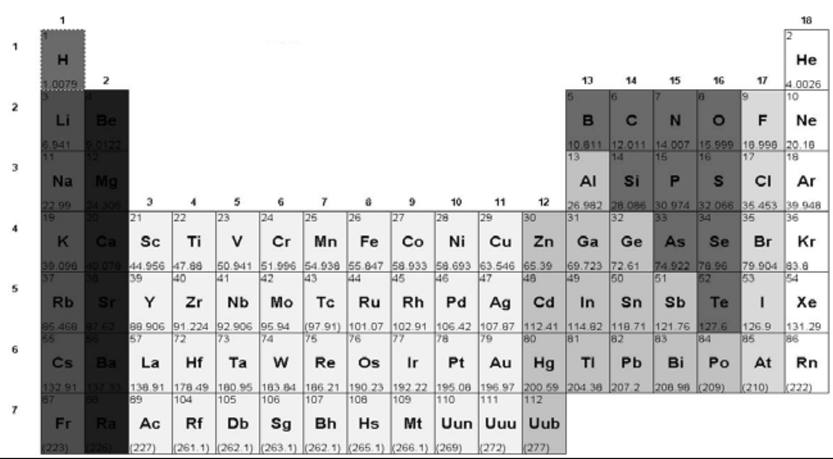
Lecture 17 Isotopes in Petrology

Wednesday, March 25, 2005

Isotopes

Same atomic number, different mass (variable number of neutrons)

General notation for a nuclide: ${}^{14}_{6}C$



Isotopes

Same Z, different A (variable # of neutrons)

General notation for a nuclide: ${}^{14}_{6}C$

As n varies → different isotopes of an element

${}^{12}C$ ${}^{13}C$ ${}^{14}C$

Radioactive Isotopes

- Unstable isotopes decay to other nuclides
- The rate of decay is constant, and not affected by P, T, X…
- Parent nuclide = radioactive nuclide that decays
- Daughter nuclide(s) are the radiogenic *atomic* products

Isotopic variations between rocks, etc. due to:

1. Mass fractionation (as for stable isotopes)

   Only effective for light isotopes: H He C O S

Isotopic variations between rocks, etc. due to:

1. Mass fractionation (as for stable isotopes)
2. Daughters produced in varying proportions resulting from previous event of chemical fractionation

   $^{40}K \rightarrow {}^{40}Ar$ by radioactive decay

   Basalt → rhyolite by FX (a *chemical* fractionation process)

   Rhyolite has more K than basalt

   $^{40}K \rightarrow$ more ^{40}Ar over time in rhyolite than in basalt

   $^{40}Ar/^{39}Ar$ ratio will be different in each

Isotopic variations between rocks, etc. due to:

1. Mass fractionation (as for stable isotopes)
2. Daughters produced in varying proportions resulting from previous event of chemical fractionation
3. Time

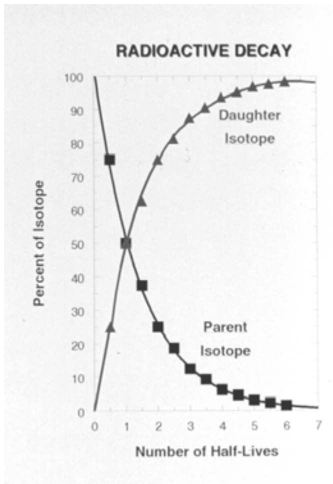
   The longer $^{40}K \rightarrow ^{40}Ar$ decay takes place, the greater the difference between the basalt and rhyolite will be

RADIOMETRIC AGE DETERMINATION

GEOCHRONOLOGY – an absolute method (about 1% accuracy for measuring the ages of rocks, based on the radioactive decay of an unstable parent isotope to a stable daughter isotope

Radioactive Parent Isotope	Stable Daughter Isotope	Half-Life Years
^{40}K	^{40}Ar	1.31×10^9
^{87}Rb	^{87}Sr	4.88×10^9
^{235}U	^{207}Pb	4.51×10^9
^{14}C	^{14}N	5,730

(Half-life is the time in years for a radioactive isotope to decay to half its initial amount)
Precise measurements of the abundances of the parent and daughter isotopes give the age at which a rock formed.



The basic equations for radioactive decay are:-

$$\boxed{N = N_0 e^{-8t}}$$

or

$$\boxed{D = N(e^{8t}-1)}$$

Where:-
N_0 = initial amount of parent isotope
N = amount remaining of parent isotope
D = amount of daughter isotope
8 = decay constant = 0.693/half-life
t = elapsed time since rock formed

[Note - the sum of the parent and daughter isotopes is always the same]
$N_0 = N + D$

Consider the ^{14}C dating method:-

$$\text{Age}(t) = \ln(N_0/N) \times \text{half-life}/0.693$$

Half-life = 5,730 years
$N_0 = {}^{14}C = 13.56$ (a constant because it is the activity of ^{14}C in the atmosphere)
Therefore to determine the age of charcoal all we need to measure is the amount of ^{14}C remaining in the charcoal.

If the activity of the remaining ^{14}C is 3.1, then:-

$$\text{Age}(t) = \ln(13.56/3.1) \times 5730/0.693$$
$$\text{Age}(t) = 12{,}200 \text{ years}$$

Another example:-

The radioactive isotope ^{235}U decays to the stable daughter isotope ^{207}Pb with a half-life of 713 million years. If you analyze a rock in the laboratory and find it contains 50 parts ^{235}U and 750 parts ^{207}Pb, What is the age of the rock? Note - you are assuming that there was no ^{207}Pb initially present in the rock, and that neither isotope has been lost from the rock over time.

Age(t) = $\ln(N_0/N)$ x half-life/0.693
Age(t) = ln(800/50) x 713 x 10^6/0.693
Age(t) = ln(16) x 1,028,860,029
Age(t) = 2,7726 x 1,028,860,029
Age(t) = 2, 852,617,316
<u>Age(t) = 2,853 million years</u>

More realistic case:-

$$D = N(e^{\lambda t} -1)$$

We can calculate the age of a sample (t) if we know:

- D the amount of the daughter nuclide produced
- N the amount of the original parent nuclide remaining
- λ the decay constant for the system in question

Sr-Rb System

- $^{87}Rb \rightarrow {}^{87}Sr$ + a beta particle ($\lambda = 1.42 \times 10^{-11}\ a^{-1}$)
- Rb behaves like K $\rightarrow$ micas and alkali feldspar
- Sr behaves like Ca $\rightarrow$ plagioclase and apatite (but not clinopyroxene)
- $^{88}Sr : {}^{87}Sr : {}^{86}Sr : {}^{84}Sr$ ave. sample = 10 : 0.7 : 1 : 0.07
- ^{86}Sr is a stable isotope, and not created by breakdown of any other parent

$$D = N(e^{\lambda t} - 1)$$

$$^{87}Sr = (^{87}Sr)_o + (^{87}Rb)(e^{\lambda t} - 1)$$

$$\lambda = 1.4 \times 10^{-11}\ a^{-1}$$

$(^{87}Sr)_o$ is the initial ^{87}Sr present at the time of formation

Recast age equation by dividing through by stable ^{86}Sr

$$^{87}Sr/^{86}Sr = (^{87}Sr/^{86}Sr)_o + (^{87}Rb/^{86}Sr)(e^{\lambda t} - 1)$$

$$\lambda = 1.4 \times 10^{-11}\ a^{-1}$$

For values of λt less than 0.1: $e^{\lambda t} - 1 \cong \lambda t$

Thus equation reduces to:

$$^{87}Sr/^{86}Sr = (^{87}Sr/^{86}Sr)_o + (^{87}Rb/^{86}Sr)\lambda t$$

$$y \quad = \quad b \quad + \quad x \quad m$$

= equation for a line in $^{87}Sr/^{86}Sr$ vs. $^{87}Rb/^{86}Sr$ plot

Isochron Technique

Requires 3 or more cogenetic samples with a range of Rb/Sr

Could be:

- 3 cogenetic rocks derived from a single source by partial melting, FX, etc.

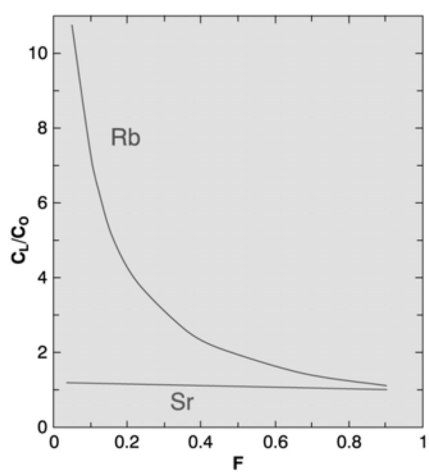


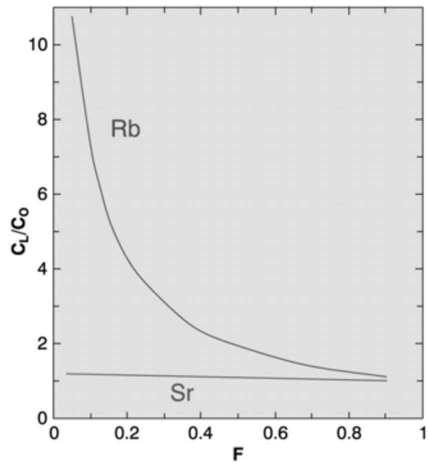
Figure 9-3. Change in the concentration of Rb and Sr in the melt derived by progressive batch melting of a basaltic rock consisting of plagioclase, augite, and olivine. From Winter (2001) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

Isochron Technique

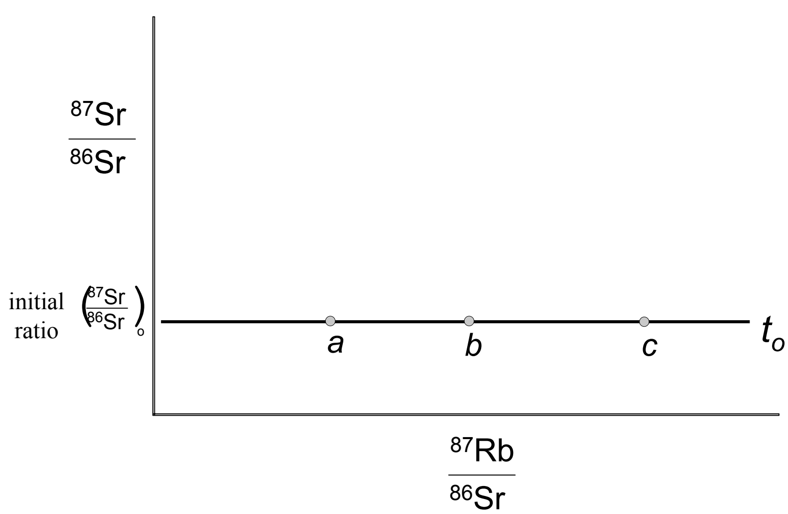
Requires 3 or more cogenetic samples with a range of Rb/Sr

Could be:

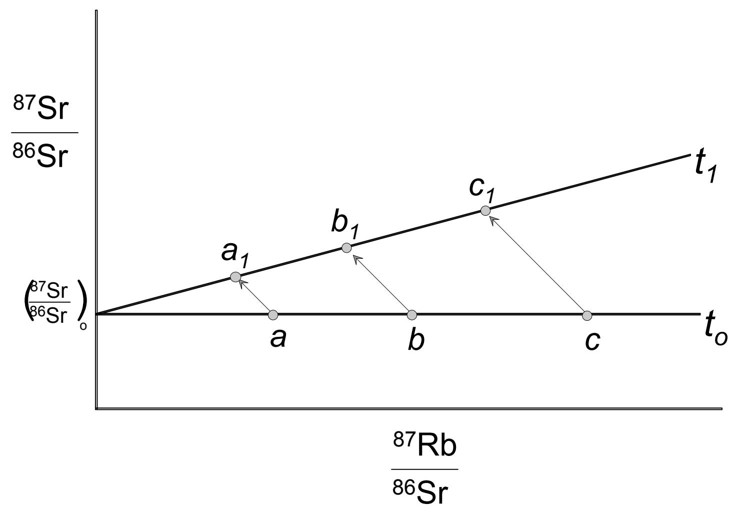
- 3 cogenetic rocks derived from a single source by partial melting, FX, etc.
- 3 coexisting minerals with different Rb/Sr ratios in a single rock



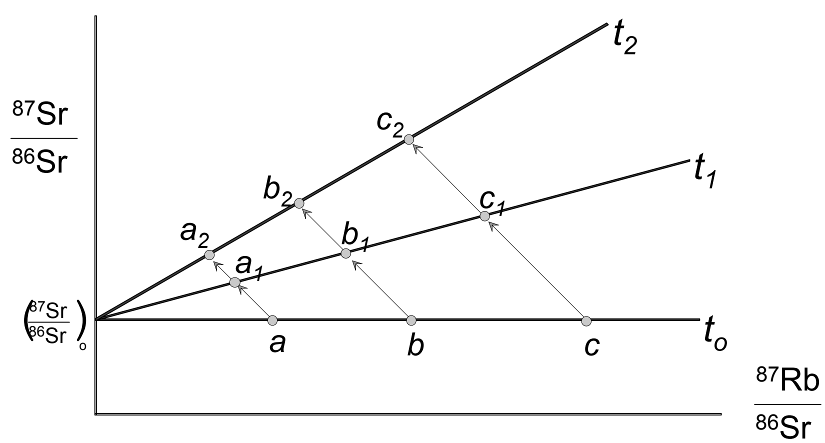
Begin with 3 rocks plotting at a b c at time t_o



After some time increment ($t_0 \rightarrow t_1$) each sample loses some ^{87}Rb and gains an equivalent amount of ^{87}Sr



At time t_2 each rock system has evolved → new line
Again still linear and steeper line



Isochron technique produces 2 valuable things:

1. The age of the rocks (from the slope = λt)
2. $(^{87}Sr/^{86}Sr)_o$ = the initial value of $^{87}Sr/^{86}Sr$

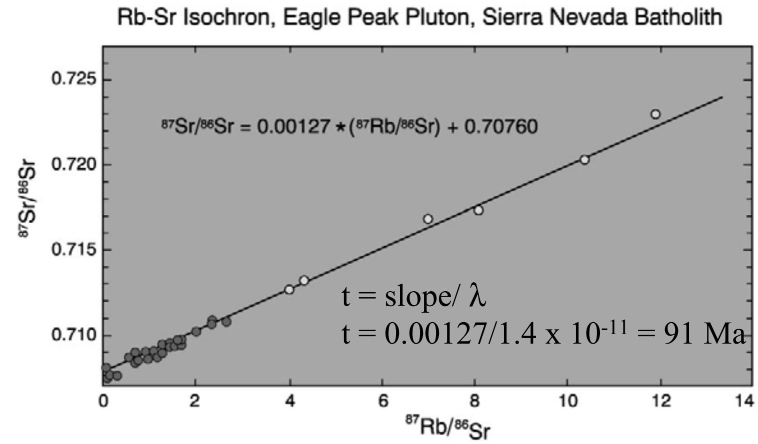


Figure 9-9. Rb-Sr isochron for the Eagle Peak Pluton, central Sierra Nevada Batholith, California, USA. Filled circles are whole-rock analyses, open circles are hornblende separates. The regression equation for the data is also given. After Hill et al. (1988). Amer. J. Sci., 288-A, 213-241.

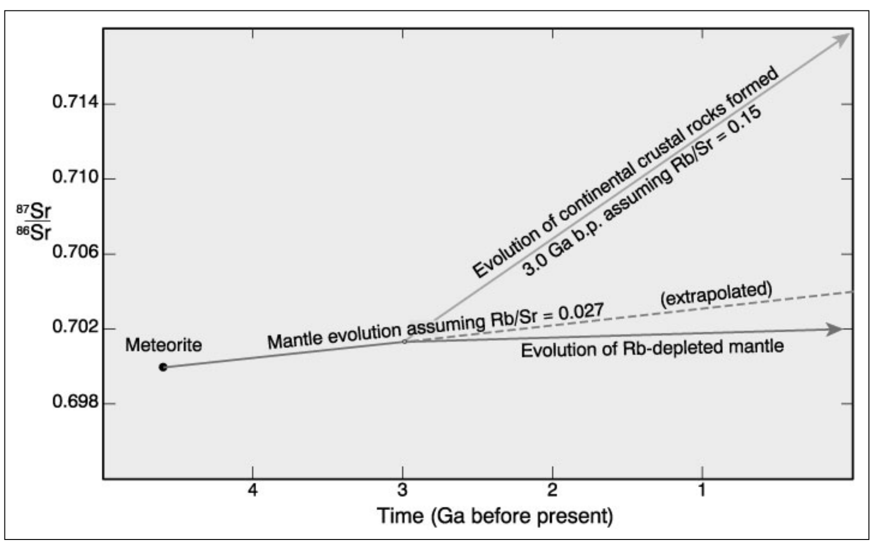
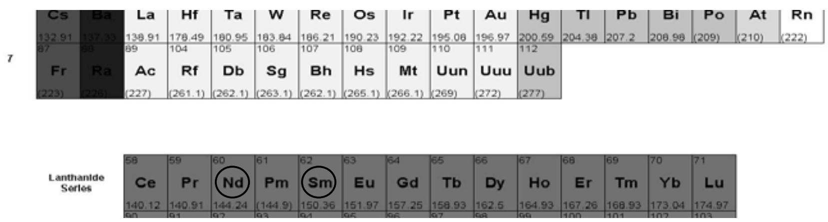


Figure 9-13. Estimated Rb and Sr isotopic evolution of the Earth's upper mantle, assuming a large-scale melting event producing granitic-type continental rocks at 3.0 Ga b.p After Wilson (1989). Igneous Petrogenesis. Unwin Hyman/Kluwer.

The Sm-Nd System

- Both Sm and Nd are LREE
  - Incompatible elements fractionate → melts
  - Nd has lower Z → larger → liquids > does Sm



^{147}Sm → ^{143}Nd by alpha decay

$\lambda = 6.54 \times 10^{-13}\ a^{-1}$ (half life 106 Ga)

- Decay equation derived by reference to the non-radiogenic ^{144}Nd
  - $$^{143}Nd/^{144}Nd = (^{143}Nd/^{144}Nd)_o + (^{147}Sm/^{144}Nd)\lambda t$$

Evolution curve is opposite to Rb - Sr

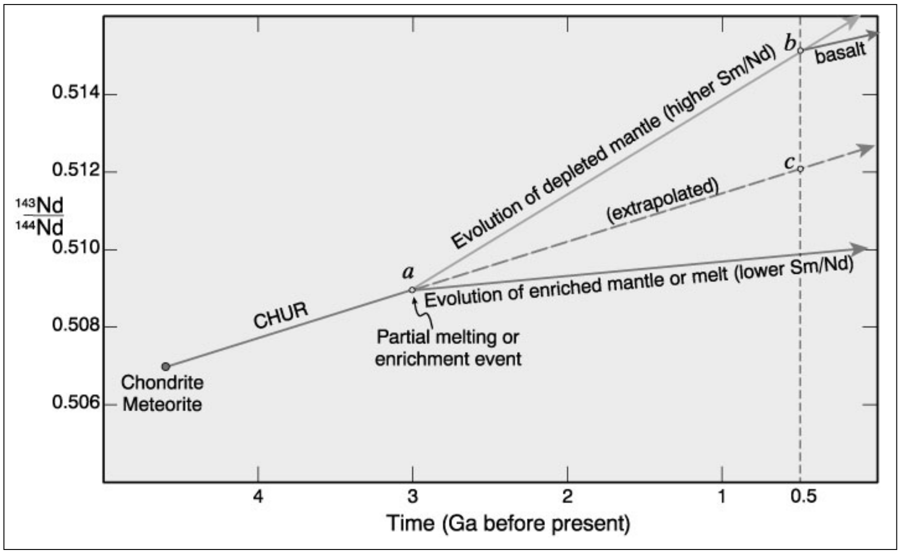
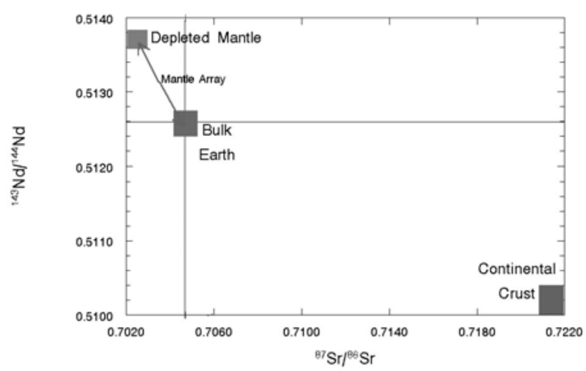


Figure 9-15. Estimated Nd isotopic evolution of the Earth's upper mantle, assuming a large-scale melting or enrichment event at 3.0 Ga b.p. After Wilson (1989). Igneous Petrogenesis. Unwin Hyman/Kluwer.



- The earth is made up of reservoirs with distinct isotopic ratios
- Melting of those reservoirs produces magmas with isotopic ratios that are characteristic of their source reservoirs