Isotopes

Reading:
Winter, Chapter 9, pp. 167-180

Isotopes

Have the same Z but different A (variable # of neutrons)
General notation for a nuclide: $^{14}_6\text{C}$

Superscript (n) specifies the different isotopes of an element
$^{12}\text{C}$, $^{13}\text{C}$, $^{14}\text{C}$

Stable Isotopes

- Stable means they last nearly forever
- Chemical fractionation is impossible
- Mass fractionation is the only isotopic discrimination possible

Oxygen Isotopes

$^{16}\text{O}$ 99.756% of natural oxygen
$^{17}\text{O}$ 0.039% “
$^{18}\text{O}$ 0.205% “

Concentrations expressed by reference to a standard
The international standard for O isotopes is:
standard mean ocean water (SMOW)

$^{18}\text{O}$ and $^{16}\text{O}$ are the commonly used isotopes and their ratio is expressed as $\delta$:

$$\delta^{(18}\text{O}/^{16}\text{O}) = \frac{^\delta(^{18}\text{O}^{^{/^{16}}\text{O}})_{\text{sample}} - ^\delta(^{18}\text{O}^{^{/^{16}}\text{O}})_{\text{SMOW}}}{^\delta(^{18}\text{O}^{^{/^{16}}\text{O}})_{\text{SMOW}}} \times 1000$$

the result is expressed in per mille (‰)

What is $\delta$ of SMOW?
What is $\delta$ for meteoric water?

Evaporation seawater produces water vapor
  - Light isotopes are enriched in vapor > liquid
  - This is efficient since $\Delta$ mass = 1/8 total mass

$$\delta = \frac{^{18}O/^{16}O_{\text{vapor}} - ^{18}O/^{16}O_{\text{SMOW}}}{^{18}O/^{16}O_{\text{SMOW}}} \times 1000$$

therefore $^{18}O/^{16}O_{\text{vapor}} < ^{18}O/^{16}O_{\text{SMOW}}$

thus $\delta_{\text{cloud}}$ is (-)

Stable isotopes are useful in assessing relative contribution of various reservoirs, each with a distinctive isotopic signature

- O and H isotopes
  - Juvenile vs. meteoric vs. brine water
- $\delta^{18}O$ for mantle rocks $\neq$ surface-reworked sediments
  - Evaluate contamination of mantle-derived magmas by crustal sediments

Radioactive Isotopes

- Unstable isotopes decay to other nuclides
- The rate of decay is constant, and not affected by P, T, X…
- Parent nuclide is the 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)
2. Daughters produced in varying proportions resulting from previous event of chemical fractionation
   - $^{40}K \rightarrow ^{40}Ar$ by radioactive decay
   - Basalt $\rightarrow$ 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
Radioactive Decay

The Law of Radioactive Decay

\[
\frac{dN}{dt} \propto N \quad \text{or} \quad \frac{dN}{dt} = \lambda N
\]

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

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

The K-Ar System

\(^{40}\text{K}\) decays to either \(^{40}\text{Ca}\) or \(^{40}\text{Ar}\)

- \(^{40}\text{Ca}\) is common. Cannot distinguish radiogenic \(^{40}\text{Ca}\) from non-radiogenic \(^{40}\text{Ca}\)
- \(^{40}\text{Ar}\) is an inert gas which can be trapped in many solid phases as it forms in them

The Sr-Rb System

On the rubidium side of the equation:

\[^{87}\text{Rb} \rightarrow {87}\text{Sr} + \text{a beta particle} \quad (\lambda = 1.42 \times 10^{-11} \text{ a}^{-1})\]

Rb behaves like K, it concentrates in micas and alkali feldspar
**Strontium Side**

- Sr behaves like Ca
  - It concentrates in plagioclase and apatite (but not in clinopyroxene)
- $^{88}\text{Sr} : ^{87}\text{Sr} : ^{86}\text{Sr} : ^{84}\text{Sr}$
  - Average sample yields $10 : 0.7 : 1 : 0.07$
- $^{86}\text{Sr}$ is a stable isotope
  - It is not created by breakdown of any other parent

Recast age equation by dividing through by stable $^{88}\text{Sr}$

$$^{87}\text{Sr}/^{86}\text{Sr} = (^{87}\text{Sr}/^{86}\text{Sr})_0 + (^{87}\text{Rb}/^{86}\text{Sr})(e^{\lambda t} - 1)$$

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

For values of $\lambda t$ less than 0.1: $e^{\lambda t} \equiv \lambda t$

Thus eq. 9-15 for $t < 70$ Ga (!!) reduces to:

$$^{87}\text{Sr}/^{86}\text{Sr} = (^{87}\text{Sr}/^{86}\text{Sr})_0 + (^{87}\text{Rb}/^{86}\text{Sr})\lambda t$$

\[ y = b + x \cdot m \]

$= $This is the equation for a line in a $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $^{87}\text{Rb}/^{86}\text{Sr}$ plot

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

**Isochron Technique**

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

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

or

3 coexisting minerals with different K/Ca ratios in a single rock

Begin with 3 rocks plotting at $a$ $b$ $c$ at time $t_0$

At time $t_1$ each rock system has evolved $\rightarrow$ new line

Again still linear and steeper line
Isochron technique produces 2 valuable things:

1. The age of the rocks (from the slope = $\lambda t$)
2. $(^{87}\text{Sr}/^{86}\text{Sr})_0 =$ the initial value of $^{87}\text{Sr}/^{86}\text{Sr}$