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## Lecture 6

# Isotopes and Unstable Isotopes 

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Isotopes: are atoms of the same element that have different masses due to the differences in the number of neutrons they contain.
N : the number of neutrons, Z : the number of protons, A : Mass number ( $\mathrm{N}+\mathrm{Z}$ ).

Isotope geochemistry is an aspect of geology based upon study of the relative and absolute concentrations of the elements and their isotopes in the Earth. Variations in the abundance of these isotopes, typically measured with an isotope ratio mass spectrometer or an accelerator mass spectrometer, can reveal information about the age of a rock or the source of air or water.



The field of isotope geochemistry is divided into two branches: stable and radiogenic isotopes.

- Unstable (Radioactive ) Isotopes:
one having an unstable nucleus and which emits characteristic radiation during its decay to a stable form.
-Stable isotopes:
an isotope of an element that shows no tendency to undergo radioactive breakdown.


## Why we Study Isotopes?

1. Dating, using radioactive isotopes is the only way we have of quantitatively measuring geologic time.
2. We can also measure rates of change of processes as diverse as the building of mountain belts and the evolution rate of snails.
3. We can use isotopes to determine the source of elements in a particular phase (e.g., is particular granite derived from melting mantle or crustal material?).
4. We can use isotopes to tell us what temperature a particular system reached.

## Radioactive isotope:

$$
\begin{aligned}
& \text { number of neutrons }
\end{aligned}
$$

Figure 1: Rb-Sr decay

In this example of beta decay we see the transformation of ${ }^{87} \mathbf{R b}$ to ${ }^{87} \mathrm{Sr}$. We can write this as;
${ }^{87} \mathbf{R b}===>\beta^{-}+{ }^{87} \mathrm{Sr}$
i.e., within the ${ }^{87} \mathbf{R b}$ a neutron has been converted into a proton and an electron (a beta particle) has been expelled from the nucleus to give an ${ }^{87} \mathrm{Sr}$ atom.

## Principles of Radioactive Dating

Over time the amount of the daughter (radiogenic) isotope in a system increases and the amount of the parent (radioactive) isotope decreases as it decays away. If the rate of radioactive decay is known we can use the increase in the amount of radiogenic isotopes to measure time.

Parent
$\longrightarrow$
Daughter

The basic decay equation in radiogenic isotope geochemistry is
$D=D_{0}+N\left(e^{\lambda t}-1\right)$
Where;
$D$ is the total number of daughter atoms in sample
$D_{0}$ is number of daughter atoms in sample at time it formed.
$N$ is the number of parent atoms and
$\lambda$ is the decay constant
We frequently refer to the half life ( $\mathrm{t}_{1 / 2}$ ) of radioactive isotopes. The half life of a radioactive isotope is the time it takes for the number of parent isotopes to decay away to half their original value.
For ${ }^{87} \mathrm{Rb}$, the decay constant is $1.42 \times 10^{-11} \mathrm{y}^{-1}$, hence, $\left(\mathrm{t}_{1 / 2}=\ln 2 / \lambda\right)$ $\mathrm{t}_{1 / 2}{ }^{87} \mathrm{Rb}=4.88 \times 10^{10}$ years. In other words after $4.88 \times 10^{10}$ years a system will contain half as many atoms of ${ }^{87} \mathrm{Rb}$ as it started off with.

In terms of our Rb-Sr isotope system this equation becomes; ${ }^{87} \mathrm{Sr}={ }^{87} \mathrm{Sr}_{0}+{ }^{87} \mathrm{Rb}\left(\mathrm{e}^{\lambda \mathrm{t}}-1\right)$
In practice, it is a lot easier to measure the ratio of isotopes in a sample of rock or a mineral, rather than their absolute abundances. So we measure the ratio of the radioactive parent and radiogenic daughter to a non-radiogenic or radioactive isotope of the daughter element. For the $\mathrm{Rb}-\mathrm{Sr}$ isotope system we use ${ }^{86} \mathrm{Sr}$. So the expression above becomes;
${ }^{87} \mathrm{Sr} /{ }^{86} \mathrm{Sr}={ }^{87} \mathrm{Sr} /{ }^{86} \mathrm{Sr}_{0}+{ }^{87} \mathrm{Rb} /{ }^{86} \mathrm{Sr}\left(\mathrm{e}^{\lambda \mathrm{t}}-1\right)$
We actually measure the present day ${ }^{87} \mathrm{Sr} /{ }^{86} \mathrm{Sr}$ ratio of our sample by mass spectrometer and we can determine concentrations of Rb and Sr by various techniques.
The decay constant of ${ }^{87} \mathrm{Rb}$ is very accurately known so the only unknown in the equation above is the initial Sr isotope ratio, $\left({ }^{87} \mathrm{Sr} /{ }^{86} \mathrm{Sr}\right)_{0}$. Once we have this, we can calculate the age of our system (given by t).

For an igneous rock which formed from isotopically homogeneous magma we assume or know the following;

1) All the minerals crystallized from magma at same time and have the same initial ${ }^{87} \mathrm{Sr} /{ }^{86} \mathrm{Sr}$.
2) Rb and Sr have different geochemical properties, so some minerals preferentially incorporate $\mathbf{R b}$ and others incorporate Sr (e.g., Sr generally follows Ca and Rb follows K. So, micas tend to have higher $\mathbf{R b} / \mathbf{S r}$ than plagioclase). This leads to different $\mathbf{R b} / \mathbf{S r}$ ratios in different minerals.
3) So after some time has passed the mineral phases with the highest $\mathrm{Rb} / \mathrm{Sr}$ ratios will have the highest ${ }^{87} \mathrm{Sr} /{ }^{86} \mathrm{Sr}$ ratios.

* In this case we have two minerals that crystallized from a melt. They both start off with the same ${ }^{87} \mathrm{Sr} /{ }^{86} \mathrm{Sr}$ ratio, but one has a higher ${ }^{87} \mathrm{Rb} /{ }^{86} \mathrm{Sr}$ ratio. After some time has passed, their ${ }^{87} \mathrm{Rb} /{ }^{86} \mathrm{Sr}$ ratios will decrease and their ${ }^{87} \mathrm{Sr} /{ }^{86} \mathrm{Sr}$ ratios will increase as the ${ }^{87} \mathrm{Rb}$ decays to ${ }^{87} \mathrm{Sr}$.

We can visualize this process;


Figure 2: Process of radioactive decay
has the general form of $y=b+m x$, where;
$y={ }^{87} \mathrm{Sr} /{ }^{86} \mathrm{Sr} \mathrm{b}={ }^{87} \mathrm{Sr} /{ }^{86} \mathrm{Sr}_{\mathrm{o}}=$ intercept
$e^{\lambda t}-1=$ slope
$x={ }^{87} \mathrm{Rb} /{ }^{86} \mathrm{~S} r$


Figure 3: Isochron

The straight line that gives the slope on the diagram is termed an isochron, as it connects points that have the same age.
We now have ${ }^{87} \mathrm{Sr} /{ }^{86} \mathrm{Sr}_{\mathrm{o}}$ from the intercept of the isochron, and we have $\mathrm{e}^{\lambda \mathrm{t}}-1$ from the slope.

We want to get the age of our samples, so we need to solve this expression for $t$, the age.
slope $=e^{\lambda t}-1$
$($ slope +1$)=e^{\lambda t}$
$\ln ($ slope +1$)=\lambda t$
$t=[\ln ($ slope +1$)] / \lambda$

$$
{ }^{87} \mathrm{Sr} /{ }^{86} \mathrm{Sr}={ }^{87} \mathrm{Sr} /{ }^{86} \mathrm{Sr}_{0}+{ }^{87} \mathrm{Rb} /{ }^{86} \mathrm{Sr}\left(\mathrm{e}^{\lambda \mathrm{t}}-1\right)
$$

$$
{ }^{87} \mathrm{Sr} /{ }^{86} \mathrm{Sr} \quad-{ }^{87} \mathrm{Sr} /{ }^{86} \mathrm{Sr}_{0}
$$

$$
{ }^{87} \mathrm{Rb} /{ }^{86} \mathrm{Sr}
$$

Problem / The following data were measured on whole rock Basalt samples from Santa Bárbara. Use linear regression to calculate the age and initial ${ }^{87} \mathrm{Sr} /{ }^{86} \mathrm{Sr}$ for this Basalt. If you know that the decay constant for 87 Rb is 1.42 x10-11.

| Sample | ${ }^{87} \mathbf{R b} /{ }^{86} \mathrm{Sr}$ | ${ }^{87} \mathbf{S r} /{ }^{/ 6} \mathrm{Sr}$ |
| :--- | :--- | :--- |
| 1 | 2.104 | 0.72361 |
| 2 | 1.731 | 0.72046 |
| 3 | 2.179 | 0.72410 |
| 4 | 1.738 | 0.72205 |
| 5 | 1.987 | 0.72272 |
| 6 | 1.926 | 0.72221 |

Ex./ Four Samples of whole rock from granite have the following ${ }^{87} \mathbf{S r} /{ }^{86} \mathbf{S r}$ ratios and ${ }^{87} \mathbf{R b}$ and ${ }^{86} \mathrm{Sr}$ concentrations. If you know that decay constant for ${ }^{87} \mathbf{R b}$ is 1.42 $x 10^{-11}$. What is the age of this rock?

| Sample no. | ${ }^{\mathbf{8 7}} \mathbf{S r} /{ }^{86} \mathbf{S r}$ | ${ }^{\mathbf{8 7}} \mathbf{R b} \mathbf{~ p p m}$ | ${ }^{\mathbf{8 6}} \mathbf{S r} \mathbf{~ p p m}$ |
| :---: | :---: | :---: | :---: |
| 1 | 0.7316 | 43.1 | 17.7 |
| 2 | 0.8841 | 74.8 | 3.32 |
| 3 | 0.8309 | 70.4 | 4.48 |
| 4 | 0.9487 | 68.9 | 2.26 |

Problem / The following data were measured on whole rock gneiss samples from the Bighom Mountains of Wyoming. Use linear regression to calculate the age and initial ${ }^{87} \mathrm{Sr}{ }^{86} \mathrm{Sr}$ for this gneiss.

| Sample | ${ }^{87} \mathbf{R b}{ }^{86} \mathbf{S r}$ | ${ }^{87} \mathbf{S r} \boldsymbol{r}^{86} \mathbf{S r}$ |
| :--- | :--- | :--- |
| 1 | 0.1475 | 0.7073 |
| 2 | 0.2231 | 0.7106 |
| 3 | 0.8096 | 0.7344 |
| 4 | 1.1084 | 0.7456 |
| 5 | 1.4995 | 0.7607 |
| 6 | 1.8825 | 0.7793 |

Problem / The following data were measured on whole rock gneiss samples from the Bighom Mountains of Wyoming. Use linear regression to calculate the age and initial $87 \mathrm{Sr} / 86 \mathrm{Sr}$ for this gneiss.

| Sample | $87 \mathrm{Rb} / 86 \mathrm{Sr}$ |  | $87 \mathrm{Sr} / 86 \mathrm{Sr}$ |
| :--- | :--- | :--- | :--- |
| 1 | 0.1475 | 0.7073 |  |
| 2 | 0.2231 | 0.7106 |  |
| 3 | 0.8096 | 0.7344 |  |
| 4 | 1.1084 | 0.7456 |  |
| 5 | 1.4995 | 0.7607 |  |
| 6 | 1.8825 | 0.7793 |  |

```
Q1) Found 87Rb/86Sr
    2.435028249
    22.53012048
    15.71428571
    30.48672566
initial 0.711 from the isochron
landa 1.42 * 10-11
87Sr/86Sr = 87Sr/86Sr0 + 87Rb/86Sr (e\lambdat-1)
The age of the samples
    1-593
    2-546
    3-535
    4-538
1 gigaannum =1billion years,
```

So the natural logarithm of $e$ is equal to one.
$\ln (e)=\log _{e}(e)=1$
What the natural logarithm of the e constant (Euler's constant)?

