

## Week Three

### Radiometric Dating

**Background:** Geologists have to be able to age rocks. They need to do this in order to establish the sequence of events responsible for that rock and ultimately, the entire geological history of an area. There are several ways that geologists can age rocks and you were introduced to some of these in the lectures last week. Principles such as **Superposition**, **Cross-cutting Relationships** and **Original Horizontality** allow you to establish a relative sequence of geological events and hence, give what we refer to as a **relative date**. For example, if an igneous dike cuts across a sandstone, the dike must be younger than the sandstone. Paleontologists use fossils to age rocks. A limestone containing the bryozoan *Archimedes*, which you last saw in lab 1, would be Mississippian in age. By establishing the fossil content of a rock, paleontologists can generally put an age on it. But once again this is a relative date rather than an **absolute date**. Paleontologists cannot look at a fossil in a rock and say that that rock is 175.5 million years old, unless there has been some independent and absolute dating technique used to establish that age. The most common absolute dating technique used by geologists is **radiometric dating** (also called **radioisotopic dating**). The origins of radiometric dating can be traced back to early 20<sup>th</sup> century laboratories in Europe and North America. Physicists began to realize that some **isotopes** of elements were unstable and over time, broke down to other elements (called **daughter atoms**) and particles (**radioactivity**). This **decay** was consistent for a particular isotope and totally independent of any outside variables. Earnest Rutherford, a New Zealand-born Canadian Physicist in Montreal, was the first scientist to realize that radioactive decay could be used to establish the age of materials. All you needed to know was the **half life** of the radioactive isotope ( $t_{1/2}$ ), its **rate of decay** ( $\lambda$ ) and the following additional variables: (1) the number of **parent atoms** present in the rock when it formed ( $N_0$ ), (2) the number of daughter

---

Microscopic views of porphyritic felsic rocks that are suitable for radiometric dating. Each field of view is 4 mm across. Figure from Williams, H., et al., 1954. Petrography, W.H. Freeman and Co. San Francisco, 406p.

atoms present in the rock when it first formed ( $D_0$ ), (3) the number of parent atoms in the rock today ( $N$ ), and (4) the number of daughter atoms in the rock today ( $D$ ). Before we get to the **age formula** that relates these variables together, let's first consider  $t_{1/2}$  and  $\lambda$ . An isotope's half life is defined as the amount of time required for half of the parent isotope to decay to its daughter isotope. These data have been firmly established (see Table 3-1). The rate of decay of each unstable isotope is different but is always determined by the following formula:

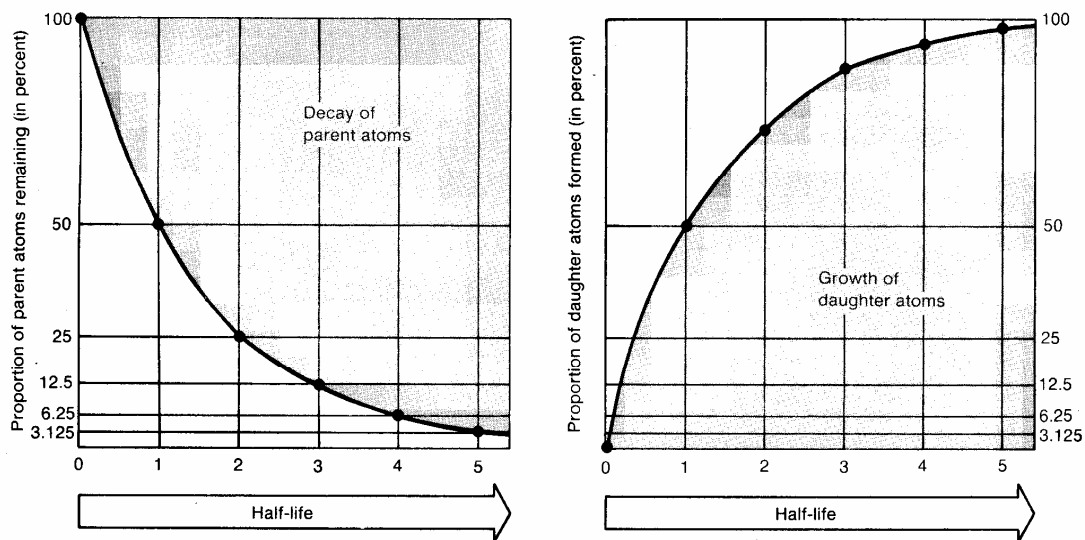
$$[1] \quad \lambda = \frac{0.693}{t_{1/2}}$$

It ends up being a very small number because the half life of most unstable elements is usually a very big number. Radioactive decay is **exponential**. Exactly one half of the amount of radioactive isotope present in a rock decays after each half life. The amount of daughter isotope *increases* in the same exponential way (Figure 3-1). The half life of  $^{235}\text{U}$  is 713 MA (million years), so after 713 MA, only 50% of the original  $^{235}\text{U}$  in a rock would still be present (50% of the original uranium would alter to  $^{207}\text{Pb}$ ). After another 713 MA, 50% of that  $^{235}\text{U}$  would decay leaving only 25% of the original amount (75%  $^{207}\text{Pb}$ ). After another 713 MA, only 12.5% of the  $^{235}\text{U}$  would be left (50% of 50% of 50%). Get the picture? Since the Earth formed approximately 4.6 GA (billion years) ago, about six  $^{235}\text{U}$  half lives have passed. Therefore only 1.6% of the original  $^{235}\text{U}$  still exists on our planet. In contrast, we still have about 50% of the original  $^{238}\text{U}$  that formed back when the Earth was condensing from the solar nebula. Its half life is as long as the Earth is old (4.5 GA).

Anyway, let's get back to the age relationship. The following formula was established to relate the number of parent atoms to rock age and is the basic formula by which radiometric dating works:

$$[2] \quad N = N_0 e^{-\lambda t}$$

Relationships like this can be intimidating at first because they involve mathematical components that we don't deal with on a daily basis. However, even if you are a math-phobe like most geologists, you have to agree that it doesn't look *all that bad* as far as mathematical formulas go. Can a few variables and constants plugged into a scientific calculator really give you the age of rocks? Ultimately the answer is yes, but there is quite a lot of work that needs to be done to derive those few variables and

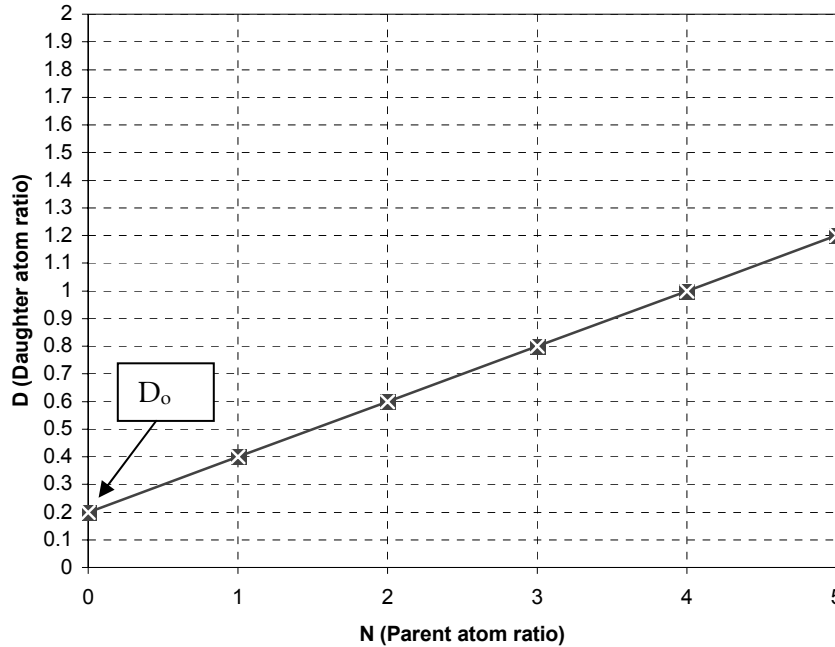


**Figure 3-1:** Radioactive decay of parent atoms and subsequent increase of daughter atoms compared to isotope half life. From Brice, J.C. et al., 1993. *Laboratory Studies in Earth History*. Wm. C. Brown, 242 pp.

constants.  $N$  and  $D$  (the number of parent and daughter atoms, respectively, in the rock today) are easily measured with a mass spectrophotometer. With a mass spec., you put your samples in, you get numbers out. But  $N_0$  and  $D_0$  (the number of parent atoms and daughter atoms, respectively, in the rock when it first formed) are tricky to determine\*. After all, no one was around when the rock formed, so both of these variables have to be estimated. Luckily there is a relatively simple way to do this. If you take 3 or more samples from a rock that you know *formed from the same magma at the same time*, you can determine  $N_0$  and  $D_0$  through a simple graphing procedure using  $N$  and  $D$  data (the variables that you can easily measure in rocks today). All of the samples will have different ratios of parent and daughter atoms, but they should all plot along a single line if they were formed at the same time (refer to Figure 3-2). Using extrapolation, it is possible to determine how much original daughter material was in the rock when it first formed. Figure 3-2 plots  $N$  versus  $D$  data for a series of analyses.  $D$  is plotted on the Y axis of the graph.

\* Isotopic data are not normally reported as actual counts of atoms as the definition implies. These data are instead reported as ratios and are evaluated relative to another similar, but stable isotope. For example, when rocks are dated using  $^{87}\text{Rb}$  -  $^{87}\text{Sr}$ ,  $N_0$  and  $N$  data are reported as  $^{87}\text{Rb}/^{86}\text{Sr}$  and  $D_0$  and  $D$  data are reported as  $^{87}\text{Sr}/^{86}\text{Sr}$  ( $^{86}\text{Sr}$  is stable). This also negates any units, which would otherwise be a pain in the butt.

### Isochron Diagram



*Figure 3-2: An isochron diagram used to establish  $D_0$ . See the text for details*

Where the line crosses the Y axis (i.e., when  $N = 0$ ) corresponds to  $D_0$ . For the example given,  $D_0$  is 0.2000. This type of graph is called an **isochron diagram** and is a necessary first step when attempting to date rocks.

The dating formula that was given earlier is the basic template for dating rocks, but it is difficult to use as written. Instead, we use the following relationship (be calm, it's not as bad as it looks):

$$[3] \quad \text{Rock age} = \frac{1}{\lambda} \times \ln\left[\frac{(D_0 - D)}{N} + 1\right]$$

Here's an example of the formula in use. Suppose you found a granite with datable minerals in it like uranite (a uranium-bearing mineral). You opt to use the  $^{238}\text{U} - ^{206}\text{Pb}$  dating method. The data you got from the lab was as follows:  $D = 0.1100$ ;  $N = 0.1200$ . You determined earlier that  $D_0 = 0.2000$ .

1) The first step is to determine the decay constant for  $^{238}\text{U}$ :

$$\lambda = 0.693 \div 4,500,000,000 \\ = 1.54 \times 10^{-10}$$

2) Now it is a simple matter of plugging in all of these data:

$$\text{Rock age} = 1 \div 1.54 \times 10^{-10} \times \ln[((0.2000 - 0.1100) \div 0.1200) + 1] \\ = 3,630,000,000 \text{ years}$$

So the rock is roughly 3.6 billion years old (3.6 Ga). Not bad huh?

Any way, this lab is all about radiometric dating and the stuff you can do with it. You will have an opportunity to obtain dates on rocks, evaluate sequences of events and apply these data to relevant geological questions. The skills you learn here will help you to understand some of the arguments and ideas that we will discuss about earth history later in the class. They might even make you like mathematics (when hell freezes over).

**Table 3-1:** Table of radioactive isotopes of use for radiometric dating, their daughter products, approximate half lives and applications.

Parent Isotope	Daughter Isotope	Half Life (years)	Datable Material(s)
$^{14}\text{C}$ (Carbon-14)	$^{14}\text{N}$ (Nitrogen-14)	5,730	Wood, shells and organic material
$^{235}\text{U}$ (Uranium-235)	$^{207}\text{Pb}$ (Lead-207)	713,000,000	Metamorphic, igneous rocks, Zircon, U-bearing minerals
$^{40}\text{K}$ (Potassium-40)	$^{40}\text{Ar}$ (Argon-40)	1,310,000,000	Metamorphic, igneous & sedimentary rocks; feldspar-bearing minerals
$^{238}\text{U}$ (Uranium-238)	$^{206}\text{Pb}$ (Lead-206)	4,500,000,000	Metamorphic, igneous rocks, Zircon, U-bearing minerals
$^{232}\text{Th}$ (Thorium-232)	$^{208}\text{Pb}$ (Lead-208)	13,890,000,000	Metamorphic, igneous rocks, Zircon, U-bearing minerals
$^{87}\text{Rb}$ (Rubidium-87)	$^{87}\text{Sr}$ (Strontium-87)	48,800,000,000	Various igneous & metamorphic rocks and minerals
$^{147}\text{Sm}$ (Samarium-147)	$^{143}\text{Nd}$ (Neodymium-143)	106,000,000,000	Very old igneous rocks, REE bearing minerals



Notes

Name: \_\_\_\_\_

Grade \_\_\_\_\_/100 + 3 bonus points

### GY 112 Lab Assignment 3 Radiometric Dating

**Note:** You will need a calculator with a **ln** function key. If you have taken a calculus class at South, you probably have one. If not, see the instructor or borrow one from fellow classmate.

**Part A: Determining decay constants**

1) Determine the rate of decay ( $\lambda$ ) for the following radioactive isotopes using formula [1].

**(worth 2 points each; total 12 points)**

Radioactive Isotope	$t_{1/2}$ (years)	$\lambda$
$^{14}\text{C}$ (Carbon-14)	5,730	
$^{235}\text{U}$ (Uranium-235)	713,000,000	
$^{40}\text{K}$ (Potassium-40)	1,310,000,000	
$^{238}\text{U}$ (Uranium-238)	4,500,000,000	$1.54 \times 10^{-10}$
$^{232}\text{Th}$ (Thorium-232)	13,890,000,000	
$^{87}\text{Rb}$ (Rubidium-87)	48,800,000,000	
$^{147}\text{Sm}$ (Samarium-147)	106,000,000,000	

2) What percentage of  $^{14}\text{C}$  would remain in a rock after 5 half lives have passed?

\_\_\_\_\_ % of original amount **[3 points]**

3) What percentage of  $^{147}\text{Sm}$  would remain in a rock after 5 half lives have passed?

\_\_\_\_\_ % of original amount **[3 points]**

4) How much time would have passed after 5 half lives of  $^{14}\text{C}$ ?

\_\_\_\_\_ **[3 points]**

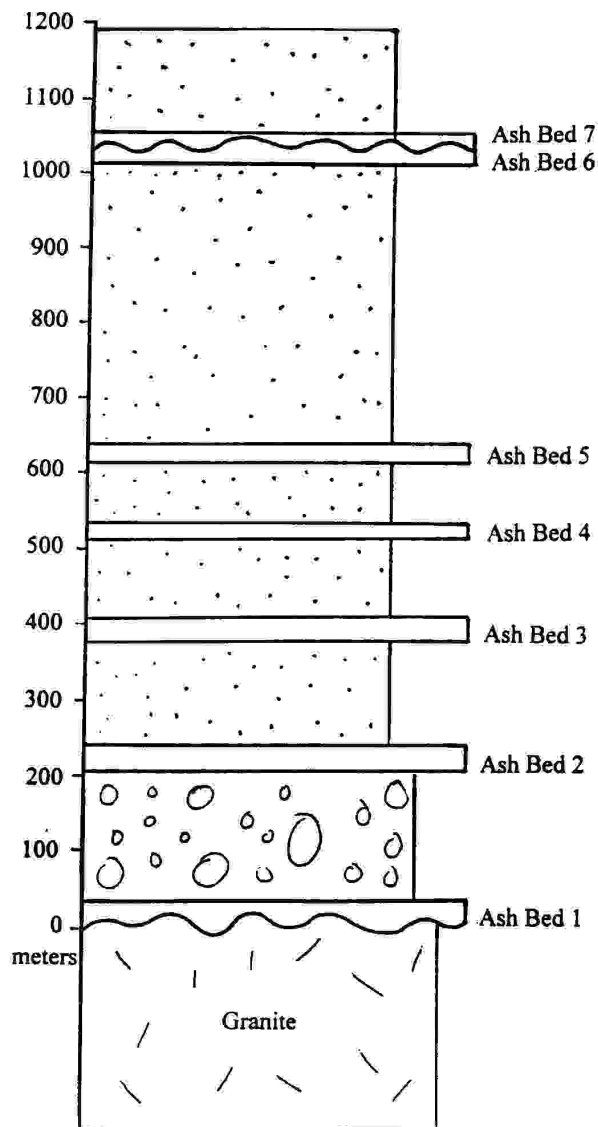
5) How much time would have passed after 5 half lives of  $^{147}\text{Sm}$ ?

\_\_\_\_\_ **[3 points]**

### Part B: Determining radiometric dates on stratigraphic sections

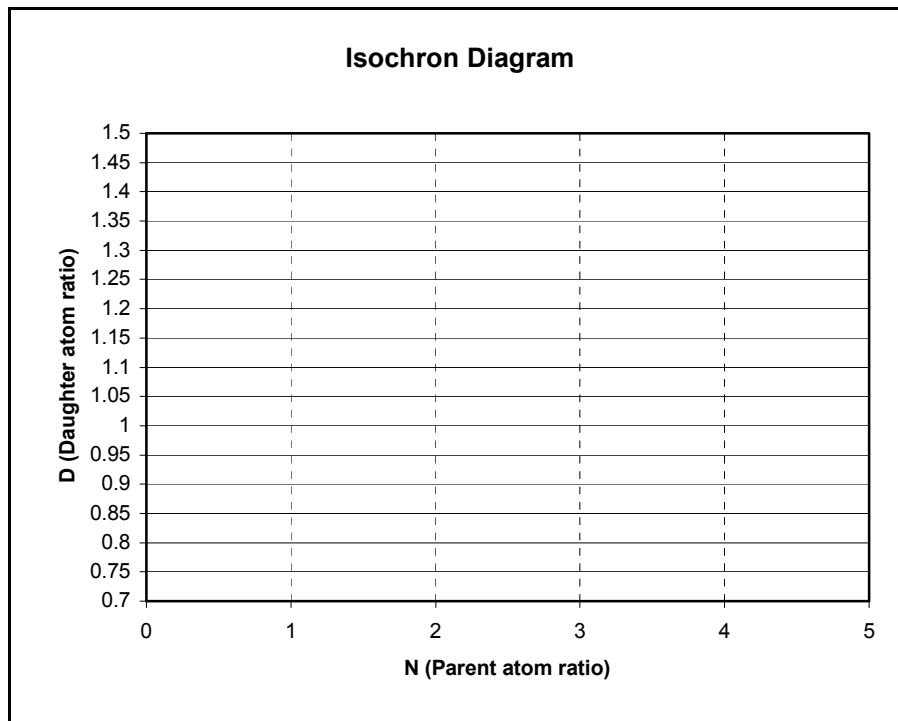
The following diagram is a schematic stratigraphic section that summarizes the thickness and order of fictitious rocks exposed in a fictitious mountain. You will see stratigraphic sections several times in this class as they are the most effective way of illustrating vertical rock associations. All of the questions in this exercise refer to this section.

After studying the section, you observed 7 volcanic ash beds and determined that they are suitable for radiometric dating. They contain high concentrations of zircon ( $ZrSiO_4$ ), a mineral that contains U as a trace element. You opt to date each of the beds using the  $^{235}U/^{207}Pb$  method.



1) You need to determine  $D_0$  for the ash beds. Since they have the same overall composition, you are going to assume that all 7 ash beds have the same value of  $D_0$  (This is not absolutely correct, but an okay assumption for a GY 112 class). You arrange to have 3 samples of ash bed 1 analyzed for  $^{235}\text{U}$  and  $^{207}\text{Pb}$ . The following data came back from the lab:

$N (^{235}\text{U}/^{237}\text{U})$	$D (^{207}\text{Pb}/^{237}\text{U})$
3.005	1.002
4.789	1.150
1.211	0.8505



Using the figure above, determine  $D_0$  \_\_\_\_\_ [6 points]

2) The analyses that you requested have just returned from the laboratory and comprise part of the table below. Using the methodology outlined in the example exercise at the start of this lab, determine the age of each of the ash beds **[35 points]**

Ash Bed	N ( $^{235}\text{U}/^{237}\text{U}$ )	D ( $^{207}\text{Pb}/^{237}\text{U}$ )	Age (years)
1	0.1352	0.4879	
2	0.1822	0.4199	
3	0.2286	0.3630	
4	0.0494	0.6751	
5	0.0430	0.6919	
6	0.1867	0.5523	
7	0.3522	0.4361	

2) A granite unconformably underlies the layered rock sequence that contains the ash beds.

What kind of unconformity is it? \_\_\_\_\_ **[2 points]**

3) You also date the granite dated using  $^{238}\text{U}/^{206}\text{Pb}$ . The relevant data are below. What age do you get? **[5 points]**

Method	D <sub>0</sub>	N	D	Age (years)
U/Pb	0.8563	1.386	0.4959	
K/Ar				<b>1.410 x 10<sup>9</sup> (1.41 Ga)</b>

4) Several years ago, the same granite was dated using  $^{40}\text{K}/^{40}\text{Ar}$  and the date obtained was 1.41 GA (see table above). This is not the same as the date you should get. Why? It is NOT because of any error in either method. This is an interpretation question so THINK about it before you seek help. (Hint: Consider the physical states of the daughter isotopes. How does argon (Ar) differ from lead (Pb)?)

---



---



---



---



---



---



---

**[5 points]**

5) Given the  $^{40}\text{K}/^{40}\text{Ar}$  age of the granite and the age of the first ash bed which overlies the granite, how much is the time gap represented by the first unconformity?

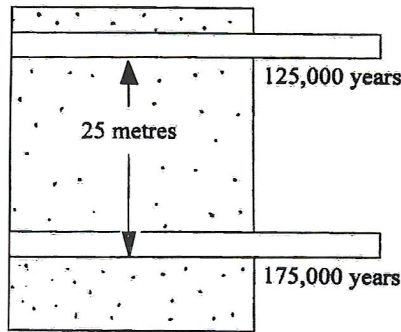
\_\_\_\_\_ [3 points]

6) How much is the time gap represented by the second unconformity

\_\_\_\_\_ [3 points]

**Part C: Applications**

Here is a neat application of absolute dating that geologists find invaluable. If you can date layers within a sedimentary sequence, you can determine the rate of sedimentation between those layers. As an example, consider the following sketch:



It shows two ash beds within a stratigraphic section that have both been dated. There is 50,000 years between them and they are 25 meters apart (vertically). This means that 25 meters of sediment were deposited within 50,000 years. The sedimentation rate can be worked out very easily:

$$\text{Rate} = 25 \text{ meters} \div 50,000 \text{ years} = 0.0005 \text{ m/year.}$$

Geologists would rewrite this as 0.5 mm/year.

1) Refer back to the stratigraphic section you looked at previously. Determine the sedimentation rate between:

the base of ash bed 1 to the base of ash bed 2: \_\_\_\_\_ mm/year

the base of ash bed 3 to the base of ash bed 4: \_\_\_\_\_ mm/year

the base of ash bed 4 to the base of ash bed 5: \_\_\_\_\_ mm/year

the base of ash bed 5 to the base of ash bed 6: \_\_\_\_\_ mm/year

[3 points each; 12 points total]

Name: _____
-------------

2) How has the rate of sedimentation changed from the bottom of the sedimentary section (ash bed 1) to the top (ash bed 6)?

---

---

---

---

---

---

[5 points]

**Bonus exercise:** An amateur paleontologist walks into your office with a bone claiming that it came from a dinosaur that he uncovered in his backyard. You get the bone analyzed for  $^{14}\text{C}$  and get the following data:  $D=0.3234$ ;  $N=0.0233$ . Is it from a dinosaur? Why or why not?

---

---

---

---

---

---

[3 bonus points]