ABSOLUTE DATING OF IGNEOUS AND METAMORPHIC ROCKS

INTRODUCTION

Absolute Dating refers to determining the length of time in years that has passed since a rock formed. It is the age of the rock. For igneous rocks, this means the time since the molten material cooled and minerals crystallized. For metamorphic rocks, it refers to the time since metamorphism occurred. Absolute dating can not be easily applied to sedimentary rocks. Clastic sedimentary rocks are composed of aggregates of grains, each of which may have been derived from a rock of a different age. The date that would be indicated for the rock would be the average age of all of the grains tested from the rock. It would tell nothing about when the grains were deposited or lithified into a sedimentary rock. Non-clastic sedimentary rocks generally lack the important radioactive elements that allow the absolute age to be determined.

Absolute dating is possible because of radioactive decay. All atoms of an element have the same number of protons, but may differ in the number of neutrons they contain. Atoms of an element which differ in the number of neutrons are called **isotopes** of the element. Some isotopes are extremely stable, but others appear to contain an intrinsic instability that eventually causes the nucleus of the atom to break apart. **Radioactive decay**, also called **fission**, is the process whereby the nucleus of an atom self-destructs, producing smaller, more stable atoms, sub-atomic particles and heat. **Radioactivity** refers to the powerful ejection of high energy, sub-atomic particles from the atom during fission. These particles are dangerous because they can cause damage as they pass through organic tissue. The atoms that undergo decay are called the **parent** and the new atoms produced are called the **daughters**. Daughters are different elements than the parent because they have a different number of protons in their nuclei. Usually there are several intermediate steps of radioactive decay, each producing an unstable radioactive daughter between the decay of the parent and the final production of a stable daughter. Because of conservation of mass, the combined number of protons and neutrons of the daughters should equal the number of protons and neutrons in the parent.

The rate of radioactive decay is called the **half-life** of an isotope. It is defined as the time required for one-half of the amount of the parent to undergo decay and generate stable daughters. The half-life is the same regardless if considering a small sample or all of that radioactive isotope in the Earth. Because half-life is unaltered by time, temperature, pressure or any other normal process, radioactive decay functions as the ideal clock. If one knows the half-life of the isotope, the amount of parent remaining and the amount of daughter generated by decay, it is a simple matter to determine the age of the rock.

THE SIMPLEST SCENARIO

In the simplest scenario all of the daughter isotope in the rock sample has been generated by the decay of the parent.

Example 1.
U^{235} decays to Pb^{207} and the half-life is 713 million years.
Analysis of a rock sample indicates that the rock contains 6.25 units of U^{235} and 93.75 units of Pb^{207}.
How old is the rock?

1. First determine the original amount of U^{235} that was in the rock when it formed, i.e. before any decay occurred. This will be equal to the amount of U^{235} remaining in the rock, plus the amount of Pb^{207} that was generated by decay.

$$6.25 \text{ units of } U^{235} + 93.75 \text{ units of } Pb^{207} = 100 \text{ units of } U^{235} \text{ originally in the rock}$$

2. Next determine the number of half-lives of decay that occurred before the U and Pb reached their current proportions.

Number of Half-lives	*Initial Amount of Parent at Start of Each Half-life*	*Amount of Parent and Daughter at End of Each Half-life*

1 half-life = 713 million years 100 units of U^{235} --> 50 units of U^{235} + 50 units of Pb^{207}
2 half-lives = 1426 million years *50 units of U^{235} --> 25 units of U^{235} + 75 units of Pb^{207}
3 half-lives = 2139 million years 25 units of U^{235} --> 12.5 units of U^{235} + 87.5 units of Pb^{207}
4 half-lives = 2852 million years 12.5 units of U^{235} --> 6.25 units of U^{235} + 93.75 units of Pb^{207}

* 50 units of U^{235} is what remained after one half-life. 75 units of Pb^{207} is 50 units generated in the first half-life plus 25 units generated in the second half-life.

Four complete half-lives are required to reach the proportions of U^{235} and Pb^{207} found in the rock. Thus, the age of the rock would be about 2.852 billion years old.

A MORE COMPLICATED SCENARIO

The example above assumes that all of the Pb^{207} present in the rock was produced by decay of the U^{235}. Yet, this is rarely true. It is more likely that there was already some Pb^{207} in the rock before any of the U^{235} decayed. Thus, determining the age of a rock is more complicated.

Example 2

U^{235} decays to Pb^{207} and the half-life is 713 million years.
Analysis of a rock sample indicates that the rock contains 18.75 units of U^{235} and 146.25 units of Pb^{207}.
How old is the rock?

1. First determine the amount of Pb^{207} in the rock when it formed, i.e. Pb^{207} not generated by the decay of U^{235}. From the analysis of thousands of rock samples which contain no U^{235}, it is known that lead isotopes occur in the following ratio: 5 Pb^{204}:6 Pb^{205}:3 Pb^{207}. This means that for every 5 units of Pb^{204} there should be 6 units of Pb^{205} and 3 units Pb^{207} in any rock. All Pb^{207} beyond this ratio was added by decay of U^{235}.

Additional analysis of the sample rock reveals that there are 25 units of Pb^{204} and 30 units of Pb^{205}. Given the ratios $5Pb^{204}$:$6Pb^{205}$:$3Pb^{207}$, if there are five times the amount of Pb^{204} (5x5=25) and five times the amount of Pb^{205} (5x6=30), one would expect five times the amount of Pb^{207}, or 15 units of Pb^{207} (5x3=15) already to have been in the rock when it formed. Five times 5 Pb^{204}:6 Pb^{205}:3 Pb^{207} is the same as 25 Pb^{204}:30 Pb^{205}: 15 Pb^{207}

2. After determining the amount of Pb^{207} in the rock when it formed, calculate the amount of Pb^{207} produced by decay. Of the 146.25 units of Pb^{207}, 15 units were already present and so only 131.25 units were generated by decay of U^{235}.

146.25 units of Pb^{207} now in the rock - 15 units of Pb^{207} not from decay = 131.25 units Pb^{207} generated by decay of U^{235}

3. To determine the original amount of U^{235} in the rock, add the amount of U^{235} remaining in the rock to the amount of daughter Pb^{207} produced by decay.

18.75 units of U^{235} + 131.25 units of Pb^{207} = 150 units of U^{235} originally in the rock

4. Finally, determine how many half-lives of decay occurred before the U and Pb reached their current proportions.

Number of Half-lives	*Initial Amount of Parent at Start of Each Half-life*	*Amount of Parent and Daughter at End of Each Half-life*
1 half-life = 713 million years	150 units of U^{235} -->	75 units of U^{235} + 75 units of Pb^{207}
2 half-lives = 1426 million years	75 units of U^{235} -->	37.5 units of U^{235} + 113.5 units of Pb^{207}
3 half-lives = 2139 million years	37.5 units of U^{235} -->	18.75 units of U^{235}+ 131.25 units of Pb^{207}

Three complete half-lives are required to reach the proportions of U^{235} and Pb^{207} found in the rock. Thus, the age of the rock would be 2.139 billion years old.

THE MOST COMPLICATED SCENARIO

An additional complication in determining the absolute age of a rock occurs if the age does not coincide with an even number of half-lives. For example, if the rock in Example 2 had been 1.8 billion years old, the age would not coincide with either two or three half lives. The amount of U^{235} remaining would have been between 37.5 and 18.75 units. It is sometimes necessary to work with fractions of a half-life.

Example 3.
U^{235} decays to Pb^{207} and the half-life is 713 million years.
Analysis of a rock sample indicates that the rock contains 37.5 units of U^{235} and 180.5 units of Pb^{207}.
How old is the rock?

1. First determine how much Pb^{207} was in the rock when it formed and was not generated by the decay of U^{235}. From the analysis of thousands of rock samples which contain no U^{235}, it is known that lead isotopes occur in the following ratio: 5 Pb^{204}:6 Pb^{205}:3 Pb^{207}.

Additional analysis of the rock reveals that there are 30 units of Pb^{204} and 36 units of Pb^{205}. Given the ratio 5Pb^{204}:6Pb^{205}:3Pb^{207}, if there are six times the amount of Pb^{204} and six times the amount of Pb^{205}, one would expect six times the amount of Pb^{207}, or (6 x3=18) 18 units of Pb^{207} already to have been in the rock when it formed. Six times 5 Pb^{204}:6 Pb^{205}:3 Pb^{207} is the same as 30 Pb^{204}:36 Pb^{205}: 18 Pb^{207}

2. To determine the amount of Pb^{207} produced by decay, subtract the 18 units of Pb^{207} that were present in the rock when it formed from the total amount of Pb^{207} now in the rock.

180.5 units of Pb^{207} now in the rock - 18 units of Pb^{207} not from decay = 162.5 units of Pb^{207} generated by decay of U^{235}

3. To determine the original amount of U^{235} in the rock, add the amount of U^{235} remaining to the amount of Pb^{207} generated by decay.

37.5 units of U^{235} + 162.5 units of Pb^{207} = 200 units of U^{235} originally in the rock

4. Finally, determine how many half-lives of decay occurred before the U and Pb reached their current proportions.

Number of Half-lives	*Initial Amount of Parent at Start of Each Half-life*	*Amount of Parent and Daughter at End of Each Half-life*
1 half-life = 713 million years	200 units of U^{235} -->	100 units of U^{235} + 100 units of Pb^{207}
2 half-lives = 1426 million years	100 units of U^{235} -->	50 units of U^{235} + 150 units of Pb^{207}
3 half-lives = 2139 million years	50 units of U^{235} -->	25 units of U^{235} + 175 units of Pb^{207}

The rock must be older than two half-lives (1426 million years), but younger than three half-lives (2139 million years) because there are more than 25 units of U^{235} remaining in the rock, but fewer than 50 units.

The 37.5 units of U^{235} remaining in the rock is midway between 25 units and 50 units. If half of the material decays in a half-life, only a quarter of the material would decay in a half of a half-life. One quarter of 50 is 12.5 and the amount of U^{235} remaining would be (50-12.5 = 37.5) in one half of a half-life (½ of 713 = 356.5 years). So the age of the rock would be two and one-half half lives or 1782.5 million years.

Number of Half-lives	*Initial Amount of Parent the Start of Half-life*	*Amount of Parent and Daughter in the Rock at the End*
1 half-life = 713 million years	200 unit of U^{235} -->	100 units of U^{235} + 100 units of Pb^{207}
2 half-lives = 1426 million years	100 units of U^{235} -->	50 units of U^{235} + 150 units of Pb^{207}
½ half-life = 1782.5 million years	50 units of U^{235} -->	37.5 units of U^{235} + 167.5 units of Pb^{207}

Two and one-half half-lives are required to reach the proportions of U^{235} and Pb^{207} found in the rock. The age of the rock would be 1.7825 billion years old.

A MARGIN OF ERROR

Sometimes, parent or daughter material may be removed from or added to a rock by groundwater. This will result in an erroneous absolute age for the rock. If daughter is lost or parent is gained, the age indicated will be too young. To reach the ratio of parent and daughter in the rock too few half-lives will be indicated. In contrast, if parent is lost or daughter is gained, the age indicated will be too old. Too many half-lives will be indicated by the ratio of parent and daughter.

Not all radioactive materials are as likely to be added or removed in a given set of environmental conditions. Therefore some isotopes will be better indicators of age than others. Unfortunately, it is not always possible to determine which are the more reliable age indicators for a given set of conditions. Thus, age is determined using several radioactive elements. The average age, together with a correction factor, is reported as the age of the rock.

Example 4.

Using the following radioactive isotopes, several different ages were obtained for a rock.

U^{238}--> Pb^{206} indicates the age is 1.8 billion
U^{235}--> Pb^{207} indicates the age is 1.4 billion
Rb^{87}-->Sr^{87} indicates the age is 2.0 billion.

To determine the average age use the maximum and minimum ages determined (1.4 + 2.0)/2 = 1.7 billion years. To determine the error factor, average the difference between the maximum (2.0 billion) and minimum (1.4 billion) ages. (2.0 - 1.4)/2 = .6/2 = .3 billion years

The age of the rock would be reported as 1.7 billion +/- 300 million.

This states that the age could be as old as 2.0 billion or as young as 1.4 billion.