Radiometric Dating – Tutorial Script

How do we determine the age of a rock, a shell, or a meteorite? Radiometric dating.

First step: we need to identify a radioactive parent material that is present in our rock and that decays into daughter material at a rate that ensures enough of both parent and daughter in the rock to measure them. There are a number of parent-daughter radioactive-decay pairs, and each pair has a different decay rate, known as a half-life. Half-life is the amount of time it takes for ½ of the original parent radioactive material to decay into daughter product.

For example: Carbon-14 decays to Nitrogen-14 with a half-life of 5700 years. The numbers—14 – indicate particular **isotopes** of these atoms. For example, all atoms with 6 protons are carbon atoms (all Nitrogen atoms have 7 protons). However, each atom can have varying amounts of neutrons, and we call all those permutations (the same atom, but different number of neutrons, **istotopes**). Carbon-14 is a carbon isotope with 6 protons and 8 neutrons (total 14). Carbon-12 is a carbon isotope with 6 protons and 6 neutrons (total 12). Carbon-13 is a carbon isotope with 6 protons and 7 neutrons (total 13).

Pause now.

Any naturally occurring substance with carbon in it will have about 99% Carbon-12, 1.1% Carbon-13, and some trace amounts of the radioactive Carbon-14 isotopes. What makes Carbon-14 and Nitrogen-14 a very good isotope pair is that most substances that contain carbon in a structure (such as shells made of $CaCO_3$) do not also have nitrogen in them. So any nitrogen-14 we see in the material will have come from the decay process.

For Carbon-14, every 5700 years, ½ of the original Carbon-14 has decayed to Nitrogen-14. After one half-life, assuming there was no Nitrogen-14 to begin with in a rock sample, the ratio of the two should be 1:1 – equal. After two half-lives, the ½ that remained of parent after the first half life is now halved again. Half of a half is ¼. The remaining ¾ is daughter, and the ratio of Parent to Daughter is 1:3. Another half-life, and we halve the ¼. There's now 1/8 parent and 7/8 daughter, and the ratio is 1:7 and so on. At this point, 3 half-lives have passed, and the time is 5700 x 3 or 17,100 years. A shell that was buried 17,100 years ago would have a Carbon -14/Nitrogen-14 ratio of 1:7. If we are trying to use the Carbon-14/Nitrogen-14 radioactive decay pair to date a rock that's 100 million years old, there likely will not be enough parent left to measure, and that would not be a good choice!

Pause now.

In addition to the Carbon-14/Nitrogen-14 pair being useful only for relatively young rocks, this pair is also useful only if there is carbon in the rock – and specifically carbon that was present in a living organism at some point on Earth's surface. While one half of all meteorites do contain some carbon, they fail on the other two requirements, and so we need to identify another radioactive decay pair. Fortunately, there are a number of other pairs such as: Uranium-238 which decays to Lead-206 and has a half life 4.5 billion years, Uranium -235 which decays to Lead-207 and has a half-life 700 million years, Potassium-40 which decays to Argon-40 and has a half-life of 1.4 billion years).

Second step: we need to ensure the rock or shell or bone fragment has remained a closed system: while parent decays into daughter, there must be no migration of parent or daughter isotopes into or out of the rock, otherwise the ratios we see do not reflect decay over the lifetime of the rock. For example: if a rock has undergone extensive metamorphism at high heats, atoms become mobile within the rock and can migrate in and out. Similarly, if a rock undergoes chemical weathering on its surface, minerals can break down and atoms can migrate in and out.

Pause now.

So how do we date a meteorite? First, we ensure it was a closed system by picking a good sample without any weathering or evidence of melting. Then we place a sample of it in a mass spectrometer to measure the ratio of the particular radioactive decay pair we're studying: in this case Uranium-238 and Lead-206. When asteroids first coalesce they contain plenty of Uranium-238, but no Lead-206. The only way to produce Lead-206 is as a radioactive decay daughter product of Uranium-238. Every 4.5 billion years, ½ of Uranium-238 will decay into Lead-206. So if we open a closed system asteroid that formed 4.6 billion years ago with no Lead-206 at that time and no loss or gain from or to the outside world since, we can use the ratio of the parent and daughter within to determine how long decay has been happening or how old the meteorite is. And what do we find? Almost exactly equal amounts of U-238 to Pb 206! That ratio of 1:1 is possible only if exactly one half life has passed: the meteorite formed about 4.5 billion years ago. Of course in the lab, we get a lot more precise.

What if we used Uranium-235 and Lead-207 to date the same meteorite? What would we find as our ratio? Remember, the half-life for Uranium-235 to Lead-207 is 700 million years. For something that is 4.6 billion years old, that means it would have passed through 6.7 half-lives. Let's look at what that means for the ratio. One half life gives a ratio of ½ parent to ½ daughter or 1:1. Two half lives halve the parent again so we have a ratio of ¼ parent to ¾ daughter or 1:3. Three half lives = 1/8:7/8 or 1:7. Four half-lives = 1/16:15/16 or 1:15. Five half-lives = 1/32:31/32 or 1:31. Six half lives = 1/64:63:64 or a ratio of 1:63. And Seven half lives = 1/128 parent to 127/128 daughter or 1:127. So the ratio we'd expect for something that had experienced 6.7 half-lives is somewhere close to 1:127, close to 7 half-lives.

To be more precise, we use this equation: the fraction of parent remaining = e to the power of (-T/1.443), where T is the number of half lives passed. Since T is 6.7, that means the fraction of parent remaining is 0.00963. The remaining 0.99037 must be daughter. And the ratio is 1:103.

Calculating age using multiple isotope pairs is a method we use to confirm our dates.

Pause now.

For more information and more detail, continue on to the next video in this series.

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<u>Earth Formation Series:</u>
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Radiometric Dating
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