

Elements of Geochronology

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Geochronology

Geochronology is the science of determining the age of rocks, fossils, and sediments using signatures inherent in the rocks themselves. *Absolute geochronology* can be accomplished through radioactive isotopes, whereas *relative geochronology* is provided by tools such as palaeomagnetism and stable isotope ratios.

Chronostratigraphy is the branch of stratigraphy that studies the age of rock strata in relation to *time*. Chronostratigraphic units are defined as encompassing all rocks formed within certain time spans of Earth history regardless of their compositions or properties.

Tools

- Radioactive elements have a proven constant decay rate
- Radioactive elements have a proven constant half-life
- Necessarily, a datable material must come from a closed system, containing both the parent isotopes and their decay products

Radioactive element is one that decays so that its atoms transform into atoms of another element at a constant rate. The rate can be measured in the lab and can be specified in years.

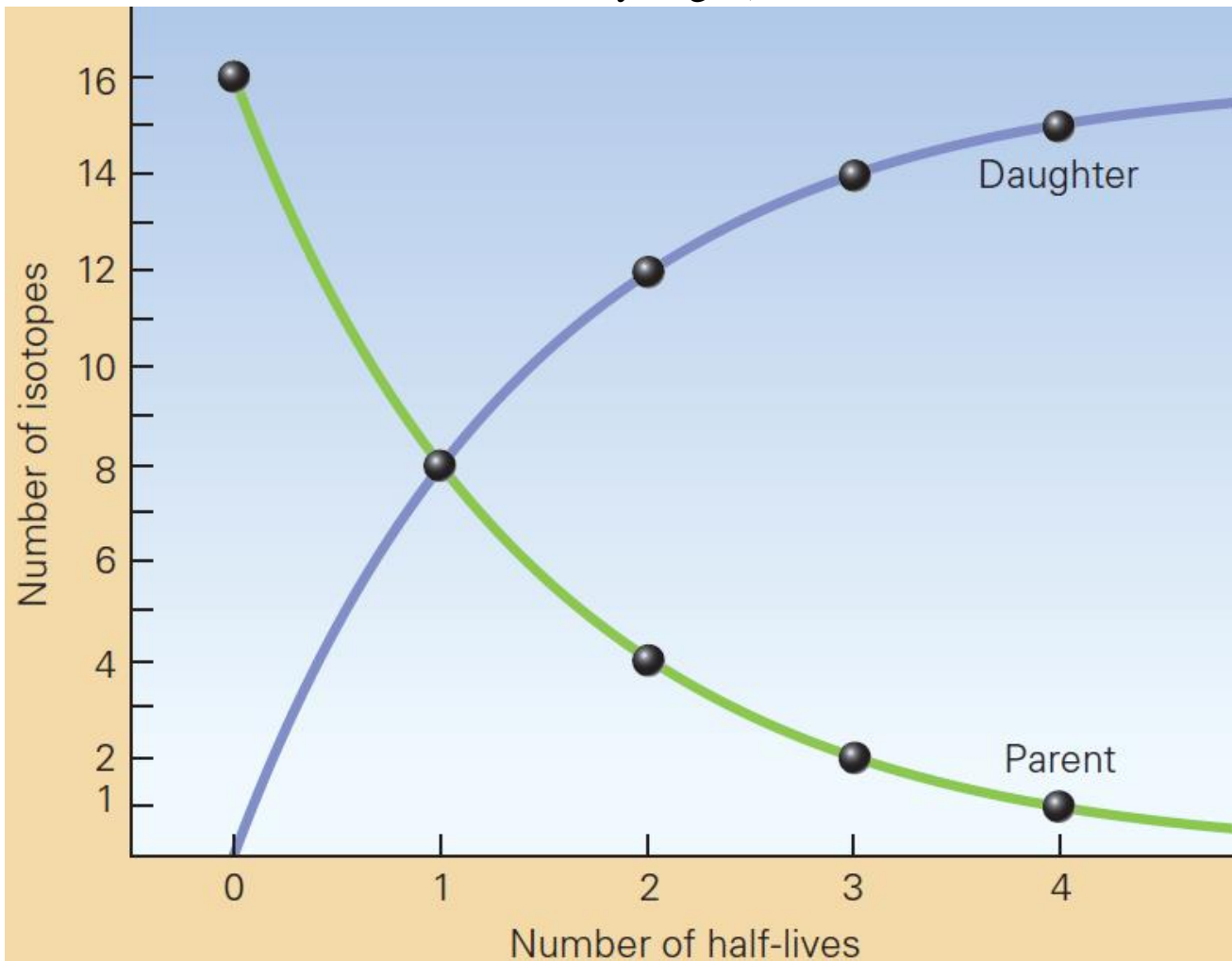
In the 1950s, geologists first developed techniques for using measurements of radioactive elements to calculate the ages of rocks. Geologists originally referred to this process of determining the numerical age of rocks as *radiometric dating*; more recently, it has come to be known as *isotopic dating*.

Isotope: The element having the same atomic number but a different atomic weight.

Example: All uranium atoms have 92 protons, but the uranium-238 isotope (abbreviated ^{238}U) has an atomic weight of 238 and thus has 146 neutrons, whereas the ^{235}U isotope has an atomic weight of 235 and thus has 143 neutrons. many elements have two or more isotopes. Of these, some are *stable*, but some are not. The *unstable* isotopes, by definition, are called *radioactive isotopes*.

Unstable isotopes undergo a change called *radioactive decay*, which converts them into a different element. Radioactive decay can take place by a variety of reactions, but regardless of the details, all these reactions change the atomic number of the nucleus and, therefore, the identity of the element. The isotope that undergoes decay as the *parent isotope* and the decay product as the *daughter isotope*.

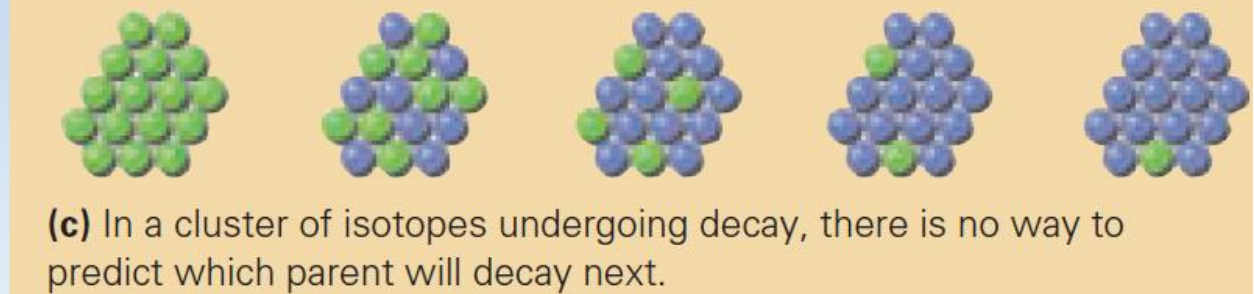
We can measure how long it takes for half of a group of parent isotopes to decay. This time is called the **half-life** of the isotope. Imagine a crystal containing 16 radioactive parent isotopes. (Note that in a real crystal, the number of atoms would be immensely larger.)



(a) This graph shows how the number of parent isotopes decreases and the number of daughter isotopes increases as time passes. The rate of change decreases with time.



(b) The ratio of parent-to-daughter isotopes changes with the passage of each successive half-life.



(c) In a cluster of isotopes undergoing decay, there is no way to predict which parent will decay next.

After one half-life, 8 isotopes have decayed, so the crystal now contains 8 parent and 8 daughter isotopes. After a second half-life, 4 of the remaining parent isotopes have decayed, so the crystal contains 4 parent and 12 daughter isotopes. And after a third half-life, 2 more parent isotopes have decayed, so the crystal contains 2 parent and 14 daughter isotopes. For a given decay reaction, the half-life is a constant, measured in years.

Isotopic Dating Technique

The following steps are used in the dating technique.

- *Collecting the rocks:* Geologists collect unweathered rocks for dating, for the chemical reactions that happen during weathering may remove parent or daughter isotopes. If, for example, weathering allows daughter elements to escape, then the isotopic clock becomes inaccurate.
- *Separating the minerals:* Once a good sample of fresh rock has been collected, the sample is crushed and the appropriate minerals are separated from the debris.
- *Extracting parent and daughter isotopes:* To separate out the parent and daughter isotopes from minerals, geologists use several techniques, including dissolving the minerals in acid or evaporating portions of them with a laser. This stage must take place in a *clean lab*, a special facility with ultra-filtered air and water, to avoid contaminating the samples with stray isotopes.
- *Analyzing the parent-daughter ratio:* Geologists pass the isotopes through a mass spectrometer, a sophisticated instrument that uses a strong magnet to separate isotopes from one another according to their respective weights. The instrument can count the number of atoms of specific isotopes separately.

At the end of the laboratory process, geologists can define the ratio of parent-to-daughter isotopes in a mineral and from this ratio determine the age of the mineral.

Isotopic Dating Technique

The table lists several radioactive parent to stable daughter transformations that can be used to determine the formation ages of Earth materials. The rate at which such parent: daughter ratios decrease depends on the rate of decay, which is given by the **decay constant** (λ), the proportion of the remaining radioactive atoms that will decay per unit of time.

Decay series	Decay process	Decay constant (λ)	Half-life	Applicable dating range
$^{14}\text{C} \rightarrow ^{14}\text{N}$	Beta decay	$1.29 \times 10^{-4}/\text{year}$	5.37 Ka	<60 Ka
$^{40}\text{K} \rightarrow ^{40}\text{A}$	Electron capture	$4.69 \times 10^{-10}/\text{year}$	1.25 Ga	500 Ka to >4.5 Ga
$^{87}\text{Rb} \rightarrow ^{87}\text{Sr}$	Beta decay	$1.42 \times 10^{-11}/\text{year}$	48.8 Ga	10 Ma to >4.5 Ga
$^{147}\text{Sm} \rightarrow ^{143}\text{Nd}$	Alpha decay	$6.54 \times 10^{-12}/\text{year}$	106 Ga	200 Ma to >4.15 Ga
$^{232}\text{Th} \rightarrow ^{208}\text{Pb}$	Beta and alpha decays	$4.95 \times 10^{-11}/\text{year}$	14.0 Ga	10 Ma to >4.5 Ga
$^{235}\text{U} \rightarrow ^{207}\text{Pb}$	Beta and alpha decays	$9.85 \times 10^{-10}/\text{year}$	704 Ma	10 Ma to >4.5 Ga
$^{238}\text{U} \rightarrow ^{206}\text{Pb}$	Beta and alpha decays	$1.55 \times 10^{-10}/\text{year}$	4.47 Ga	10 Ma to >4.5 Ga

Generally, the age of any sample may be calculated from the following equation:

$$t = (1/\lambda) \ln (d/p + 1)$$

where t = age (in years), λ = the decay constant, d = number of stable daughter atoms and p = number of radioactive parent atoms.

Uranium-Lead Dating

Uranium (U) occurs in two radioactive isotopes, both of which decay in steps to different stable isotopes of lead (Pb). The closely related actinide element thorium (Th) decays in a similar fashion to yet another stable isotope of lead. The essential information on the radioactive and stable isotopes involved for these three decay series ($^{238}\text{U} \rightarrow ^{206}\text{Pb}$, $^{235}\text{U} \rightarrow ^{207}\text{Pb}$ and $^{232}\text{Th} \rightarrow ^{208}\text{Pb}$) is summarized in the table.

Decay Series	Decay Process	Decay Constant	Half-Life	Applicable Dating Range
$^{232}\text{Th} \rightarrow ^{208}\text{Pb}$	Beta and Alpha Decay	$4.95 \times 10^{-11}/\text{year}$	14.0 Ga	10 Ma to >4.5 Ga
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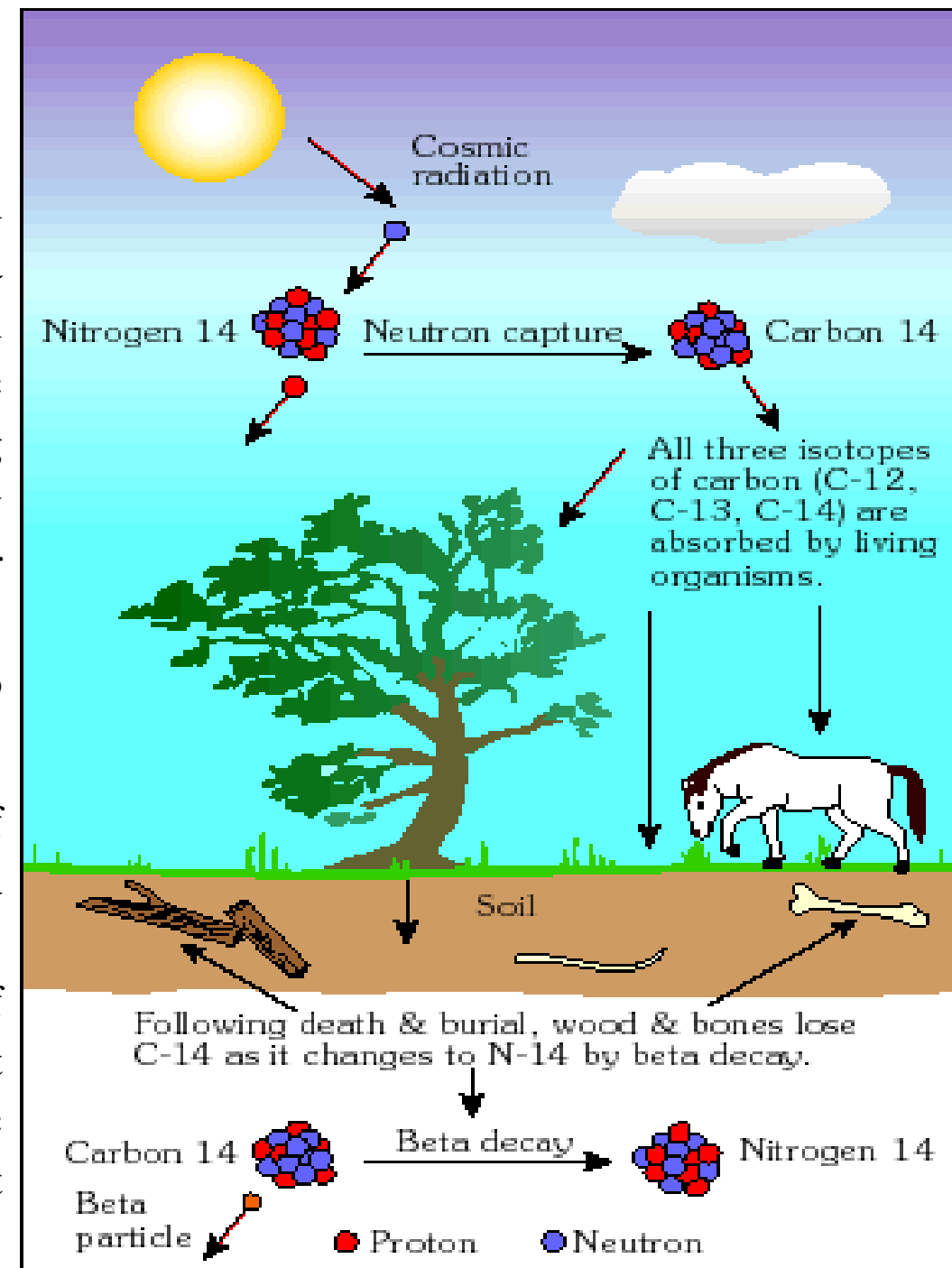
Of the three decay series, the most commonly used is $^{238}\text{U} \rightarrow ^{206}\text{Pb}$. This is because ^{238}U is much more abundant than the other two radioactive isotopes and thus easier to measure accurately. Typically, heavy minerals, such as zircon, sphene and/or monazite, are used for analyses because they contain substantial actinides, are relatively easy to separate and resist chemical alteration.

One advantage of these decay series is that the measurement of multiple, closely related isotopes permits ages to be checked against each other and provides robust sample ages when both methods yield a closely similar age.

Carbon-14 Dating

Carbon-14 dating tells us the ages of organic materials—such as wood, cotton fibers, charcoal, flesh, bones, and shells—that contain carbon originally extracted from the atmosphere by photosynthesis. ^{14}C , a radioactive isotope of carbon, forms naturally in the atmosphere when cosmic rays (charged particles from space) bombard atmospheric nitrogen-14 (^{14}N) atoms. When plants consume carbon dioxide during photosynthesis, or when animals consume plants, they ingest a tiny amount of ^{14}C along with ^{12}C , the more common isotope of carbon. After an organism dies and can no longer exchange carbon with the atmosphere, the ^{14}C in its body begins to decay back to ^{14}N . Thus, the ratio of ^{14}C to ^{12}C changes at a rate determined by the half-life of ^{14}C .

^{14}C dating can be used to determine the age of prehistoric fire pits or of organic debris in sediment. ^{14}C has a short half-life (5730 years) and therefore, cannot be used to date anything older than about 70,000 years. But this range makes it a useful tool for geologists to study sediments of the last ice age (Pleistocene) and for archaeologists studying ancient cultures or prehistoric peoples. Again, since rocks do not contain organic carbon, and may be significantly older than 70,000 years, we cannot determine the age of rocks by using the ^{14}C dating method.



Questions to Consider

1. Contrast numerical age with relative age.
2. Describe the principles that allow us to determine the relative ages of geologic events.
3. What does the process of radioactive decay entail?
4. How do geologists obtain an isotopic date?

Suggested Readings: Earth – Portrait of a Planet by Stephen Marshak
Earth Materials by Kevin Hefferan and John O'Brien