Tools and methods
Geochronology

Methods relying on the decay of naturally occurring radiogenic isotopes:

<table>
<thead>
<tr>
<th>Parent isotope</th>
<th>Daughter isotope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potassium-40</td>
<td>Argon-40</td>
</tr>
<tr>
<td>Rubidium-87</td>
<td>Strontium-87</td>
</tr>
<tr>
<td>Uranium-235</td>
<td>Lead-207</td>
</tr>
<tr>
<td>Uranium-238</td>
<td>Lead-206</td>
</tr>
<tr>
<td>Thorium-232</td>
<td>Lead-208</td>
</tr>
</tbody>
</table>
Radioactivity

Natural and artificial radioactivity

Natural radioactivity

Isotopes that have been here since the earth formed: 238U, 235U, 232Th, 40K

Isotopes produced by cosmic rays from the sun, i.e cosmogenic radionuclides: 14C, 10Be, 36Cl

Synthetic radioisotopes

Made in nuclear reactors when atoms are split (fission).
Produced using cyclotrons, linear accelerators...

\[ _{19}^{39}K \text{ (n, p)} _{18}^{39}Ar \]
The dawn of radiometric dating

“U-Pb” method

• Boltwood studied radioactive elements and found that Pb was always present in uranium and thorium ores. Pb must be the final product of the radioactive decay.

• In 1907, he reasoned that since he knew the rate at which uranium breaks down (its half-life), he could use the proportion of lead in the uranium ores (chemical dating, isotopes not discovered yet) as a meter or clock.

• His observations and calculations put Earth's age at 2.2 billion years.
He accumulation method

- Based on the fact that $^{235}\text{U}$, $^{238}\text{U}$ and $^{232}\text{Th}$ emit 7, 8 and 6 $\alpha$-particles, resp. in their decay to Pb

- U and Th concentration can be determined chemically and the current rate of He production can be calculated

- The sample is heated to release He and the *helium-retention age* is calculated
Radioactive decay half-lifes, $T_{1/2}$

- if it is possible to determine the ratio of the PARENT and DAUGHTER atoms, it is then possible to determine how long ago the decay process started \(\rightarrow\) age determination
Radioactive decay
half-lifes, $T_{1/2}$

![Graph showing radioactive decay](graph.png)

- **newly formed mineral**
  - $20\% : 0\%$

- **Time units (1 unit = 1 half-life)**
  - $0$, $1$, $2$, $3$, $4$, $5$

- **Proportion of parent atoms remaining**
  - 100, 80, 60, 40, 20, 0

- **Graph notes**
  - ● = parent atoms
  - ● = daughter atoms
Radiometric dating
Radiometric dating

Method is restricted to minerals which:

- Still contain some of the parent nuclei
- Allowed for no gain or loss of D or P as time passed
- Initially contained no D (or $D_0$ must be known)
Radioactive decay

- Rate of decay is proportional to the number of decaying nuclei

\[ \frac{dN}{dt} = -\lambda N \]

- Integrate to find the change in \( N \) with time

\[ \frac{dN}{N} = -\lambda \cdot dt \]

\( \lambda = \text{decay constant} \)
Radioactive decay

• Integrate:

\[
\int_{N_0}^{N(t)} \frac{1}{N} \, dN = -\int_0^t \lambda \, dt
\]

• Find \( N(t) \):

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

Parent-Daughter system:

\[
D = D_0 + N(e^{\lambda t} - 1)
\]
Radioactive decay and age equation

Parent—daughter system:
\[ D = N_0 - N \]
\[ D \text{ – Number of daughter atoms, today} \]
\[ N \text{ – Number of parent atoms, today} \]
\[ N_0 \text{ – Number of parent atoms, initially present} \]

\[ N = N_0 \cdot e^{-\lambda \cdot t} \quad \text{or} \quad N_0 = N \cdot \frac{1}{e^{-\lambda t}} = Ne^{\lambda t} \]

\[ N_0 = D + N, \text{ hence: } D + N = Ne^{\lambda t}, \text{ or } D = N e^{\lambda t} - N, \text{ or } D = N(e^{\lambda t} - 1) \]

\[ t = \frac{1}{\lambda} \ln \left(1 + \frac{D}{N}\right) \]

This is the mathematical expression that relates radioactive decay to geologic time!!

If some daughter nuclides, \( D_0 \), are there initially: \( D = D_0 + N(e^{\lambda t} - 1) \)
Parent-Daughter system

**Diagram A:**
- Y-axis: Proportion of parent atoms ($N_p$) remaining (percent).
- X-axis: Time units.
- Graph shows the decay of parent atoms over time.

**Diagram B:**
- Y-axis: Proportion of daughter atoms ($N_d$) (percent).
- X-axis: Time units.
- Graph shows the growth of daughter atoms over time.

**Decay of parent atoms**
- Initially, 100% of parent atoms are present.
- Over time, the proportion decreases exponentially.

**Growth of daughter atoms**
- Initially, 0% of daughter atoms are present.
- Over time, the proportion increases exponentially.
Decay of radionuclide (N) to stable radiogenic daughter (D*)

\[ N = N_0 e^{-\lambda t} \]
\[ D^* = N_0 - N \]
\[ D^* = N_0 - N_0 e^{-\lambda t} \]
\[ D^* = N_0 (1 - e^{-\lambda t}) \]

Auflösen nach t:

\[ t = \ln\left(1 + \frac{D^*}{N_0}\right)/\lambda \]
Rb–Sr system

Number of protons

<table>
<thead>
<tr>
<th>38</th>
<th>37</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sr</td>
<td>Sr</td>
</tr>
<tr>
<td>87</td>
<td>88</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>48</th>
<th>49</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>Rb</td>
<td>87</td>
</tr>
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<td>87</td>
<td></td>
</tr>
</tbody>
</table>

Number of neutrons

Isotope abundance

Sample A

Sample B

Sample C

T$_{1/2}$ = 4.8 x 10$^{10}$ years
Rb–Sr system

\[ \frac{^{87}\text{Sr}}{^{86}\text{Sr}} = \left(\frac{^{87}\text{Sr}}{^{86}\text{Sr}}\right)_0 + \frac{^{87}\text{Rb}}{^{86}\text{Sr}} (e^{\lambda t} - 1) \]

\[ y = b + x \cdot m \]

\[ m = (e^{\lambda t} - 1) \]

\[ T = \ln(m + 1)/\lambda \]
Decay Series

Radioactive decay and growth in a three-component series

N₁: half-life = 1 hour
N₂: half-life = 5 hours
N₃: stable
Decay Series

Decay of a long-lived parent $N_1$ to a short lived daughter $N_2$
(similar to U-Pb decay-chain)

Radiochemical equilibrium is established after several half-lifes of $N_2$
Neutron Activation

Increase of activity of a product nuclide produced by a nuclear irradiation reaction

similar to $^{39}$Ar produced from $^{39}$K: $^{39}$K (n, p) $^{39}$Ar

Irradiation was terminated after three half-lives and the activity then decreased at a rate determined by the half-life of the produced radionuclide.
Assumptions inherent in radiometric dating

Prior to sample formation, material was free to move – molten

A radioactive nuclide parent (N) will ultimately decay to a daughter species (D)

Measurement of the D/P ratio and knowledge of the $t_{1/2}$ of the parent will give an estimate of the age of the sample

$$\text{age} = \frac{\ln(1 + D/N)}{\lambda}$$
Assumptions inherent in radiometric dating

Method is restricted to minerals which:

• Still contain some of the parent nuclei

• Allowed for no gain or loss of D or N as time passed

• Initially contained no D (or $D_0$ must be known)
Assumptions inherent in radiometric dating

The values of N and D have changed only as a result of radioactive decay, i.e., the system is closed chemically.

The isotopic composition of the parent was not altered by fractionation at the time of formation of the rock.

The decay constant is known accurately.

The “isochron” is not a mixing line.

The analytical data are accurate.