Exercise 2
Relative and absolute dating of geologic events

Introduction
The study of Earth history involves determining the sequence of geologic events over immense spans of time. In most cases the correct order of events can be determined without knowing their actual ages: that is, we simply establish that event B occurred before event C, but after event A. Such dating, in which the occurrence of events is determined relative to one another, is known as relative dating.

Of course it is always useful to know the actual ages of rocks and events, if possible. Actual ages are determined by means of radiometric dating techniques. Although several techniques exist, all rely on the fact that radioactive "parent" isotopes decay into stable "daughter" isotopes at a constant rate. With knowledge of the decay rate, ratios of parent and daughter isotopes then can be used to derive an absolute date, in years, for the age of a given mineral sample.

The purpose of this lab is to introduce the principles and concepts associated with both relative and absolute dating.

Relative dating
The relative order of geologic events can be established in most cases by applying four or fewer basic principles. (1) The Principle of Original Horizontality states that sedimentary rocks are deposited as horizontal or nearly horizontal layers. Any marked deviation from horizontality indicates that some movement or deformation of the Earth's crust occurred after deposition of the inclined layer. (2) The Principle of Superposition states that in an ordinary vertical sequence of sedimentary rocks, the layer at the bottom of the sequence is oldest, and successively higher layers are successively younger. (3) The Principle of Cross-cutting relationships states that geologic features such as faults and igneous intrusions, which cut through rocks, must be younger than the rocks through which they cut. (4) The Principle of Inclusion states that if rocks or rock fragments are included within another rock layer, the rock fragments must be older than
the layer in which they are included. Examples of the application of these principles are given in the following block diagrams (Figure 1).

Unconformities are especially useful in reconstructing Earth history. An unconformity is a surface that corresponds with a gap in sedimentation, either nondeposition or erosion. Rocks above an unconformity are younger than those below it. Three main types of unconformities are recognized (Figure 2): (1) angular unconformity, in which beds above and below the surface are not parallel; (2) nonconformity, in which sedimentary layers overly crystalline rocks (either igneous or metamorphic); and (3) disconformity, in which beds above and below the surface are parallel, but the surface itself is irregular, exhibiting evidence of erosional relief. In geologic block diagrams and cross-sections, unconformities are usually drawn as a wavy line.
Relative dating exercises

For each of the following five block diagrams (A–E), label with letters and/or numbers each sedimentary rock layer, igneous rock body, fault, and unconformity, and then determine the correct order in which the various rock units and other features occurred.
F. Repeat the ordering procedure for the block diagram below, which is already labeled.
**Absolute dating**

As mentioned, determination of the actual age, in years, of minerals is accomplished by radiometric dating techniques. Radiometric dating is possible because certain naturally occurring isotopes are radioactive and their decay rates are constant. The **half-life** of a radioactive isotope is the length of time required for one-half of a given number of "parent" atoms to decay into stable "daughter" atoms. The relationship among parents, daughters and half-life is illustrated below in Figure 3.

![Graph showing the relationship between half-life and parent and daughter atoms.](image)

*Figure 3*—In a closed system, the number of radioactive parent atoms decreases by 50% each half-life, and the number of daughter atoms increases correspondingly.

The principle of radiometric dating can be expressed by the following relationship:

$$ T = \frac{N_d}{N_p \lambda} $$  \hspace{1cm} *(formula 1)*

Where $T$ = time in years, $N_d$ = amount of daughter atoms, $N_p$ = amount of parent atoms, and $\lambda = $ decay constant. The decay constant, $\lambda$, is defined as
0.693/half-life. Table 1 lists some commonly used radioactive parents / daughters, their half-lives, $\lambda$’s, and effective dating ranges.

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>Half-life</th>
<th>$\lambda$</th>
<th>Effective dating range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}$U / $^{206}$Pb</td>
<td>$4.46 \times 10^9$ years</td>
<td>$1.55 \times 10^{-10}$</td>
<td>$&gt; 100$ m.y.</td>
</tr>
<tr>
<td>$^{40}$K / $^{40}$Ar</td>
<td>$1.25 \times 10^9$ years</td>
<td>$\lambda_\varepsilon = 0.581 \times 10^{-10}$</td>
<td>$&gt; 100,000$ years</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\lambda_\beta = 4.96 \times 10^{-10}$</td>
<td></td>
</tr>
<tr>
<td>$^{87}$Rb / $^{87}$Sr</td>
<td>$4.88 \times 10^{10}$ years</td>
<td>$1.42 \times 10^{-11}$</td>
<td>$&gt; 100$ m.y.</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>5730 years</td>
<td></td>
<td>$\sim 50,000$–70,000 years</td>
</tr>
</tbody>
</table>

Radiometric dates reflect the time that has elapsed since a mineral formed and its chemical composition was set. Because the dating procedure requires measuring the existing amounts of parent and daughter isotopes, it is critically important to analyze only those mineral grains that have remained closed systems since their time of origin. A key requirement in radiometric dating is that there has been no loss or gain of parent or daughter atoms through partial melting, metamorphism, weathering, or any other agent.

Another requirement in radiometric dating is that no daughter atoms were originally present in the grain to be analyzed. If some daughter atoms were originally present, then they must be corrected for.

For $^{238}$U/$^{206}$Pb dating, the general relationship in formula 1 (above) can be rewritten as follows:

$$T = \frac{1}{\lambda} \times \log_e \left[ \frac{D_p - D_i}{P_p} + 1 \right] \quad (\text{formula 2})$$

Where

- $D_p$ = present amount of daughter
- $D_i$ = initial amount of daughter
- $P_p$ = present amount of parent
- $T$ = time in years since crystallization of the grain

Formula 2 must be modified for $^{40}$K/$^{40}$Ar dating, because $^{40}$K decays into two daughter products, $^{40}$Ca and $^{40}$Ar. The modified equation is:

$$T = \frac{1}{(\lambda_\varepsilon + \lambda_\beta)} \times \log_e \left[ \left( \frac{^{40}\text{Ar}}{^{40}\text{K}} \times \frac{\lambda_\varepsilon + \lambda_\beta}{\lambda_\varepsilon} \right) + 1 \right] \quad (\text{formula 3})$$
Because of the extremely long half-life of $^{87}$Rb, the practical formula for radiometric dating with the $^{87}$Rb/$^{87}$Sr method is:

(formula 4)

\[
\frac{^{87}\text{Sr}}{^{86}\text{Sr}_{\text{measured}}} - \frac{^{87}\text{Sr}}{^{86}\text{Sr}_{\text{initial}}} = \frac{^{87}\text{Rb}}{^{86}\text{Sr}_{\text{measured}}} \times \lambda \]

Finally, because $^{14}$C has a very short half-life, the $^{14}$C method is useful in dating organic material only as old as about 70,000 years. Laboratory work using very precise, Geiger counter-like instruments established a relationship between the "specific activity" of an organic substance and its age. Specific activity is a measure of the amount of remaining $^{14}$C, expressed in counts/min/gm of material. This relationship is given in the graph in Figure 4.
Figure 4—Empirical relationship between specific activity of 14C in organic material and age of the material.
**Absolute dating exercises**
Examine the block diagram in Figure 5. Five samples have been collected from various rocks and sediments in this area. Sample A is a contact metamorphic rock with datable zircon grains that can be used to establish the timing of metamorphism. Sample B contains datable biotite from an igneous dike. Sample C contains biotite from a separate dike. Sample D is a fragment of wood from ancient sediments now preserved on top of a mesa. And Sample E is wood from sediments along the shore of a modern lake.

*Figure 5—Block diagram showing collecting localities of five samples for radiometric dating.*
a. Use information in Table 1 and formulae 2-4 to help you calculate the absolute age of each sample. Complete Table 2 by filling in the “Age” column.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Analysis</th>
<th>Age (in years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$^{238}$U and $^{206}$Pb were measured. Of the total of these two isotopes, 78% are $^{238}$U and the remaining 22% are $^{206}$Pb. Assume there was no $^{206}$Pb originally</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>$^{40}$Ar/$^{40}$K ratio = 0.030</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>$^{87}$Sr/$^{86}$Sr$<em>{\text{measured}}$ = 0.75, $^{87}$Sr/$^{86}$Sr$</em>{\text{initial}}$ = 0.70, $^{87}$Rb/$^{86}$Sr$_{\text{measured}}$ = 5.0</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Specific activity = 1 ct/m/gm</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Specific activity = 8 ct/m/gm</td>
<td></td>
</tr>
</tbody>
</table>

b. Use your knowledge of relative dating to determine the correct sequence of igneous, metamorphic and sedimentary rocks in this diagram. Do the absolute ages you calculated in part a (above) agree with the relative ages of the five samples?