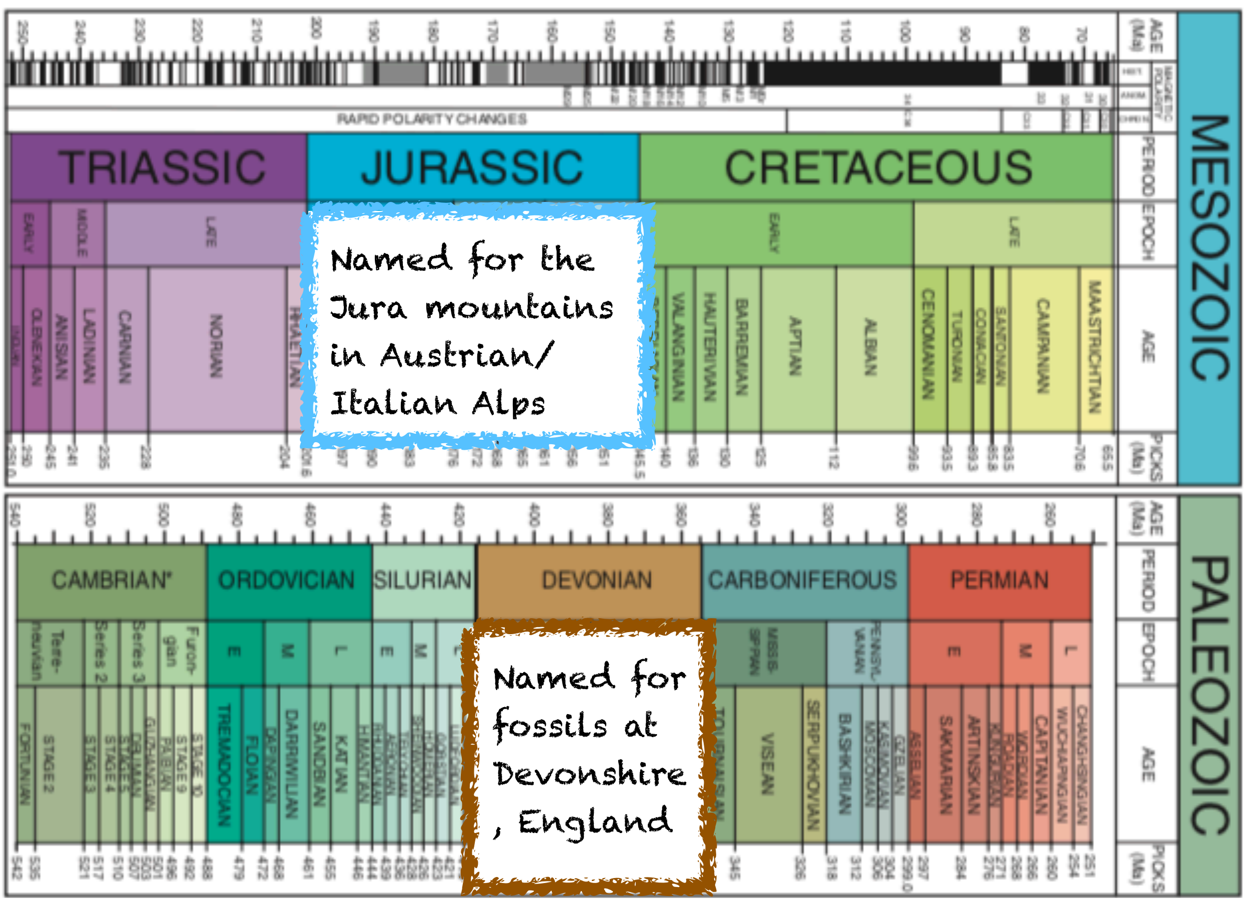
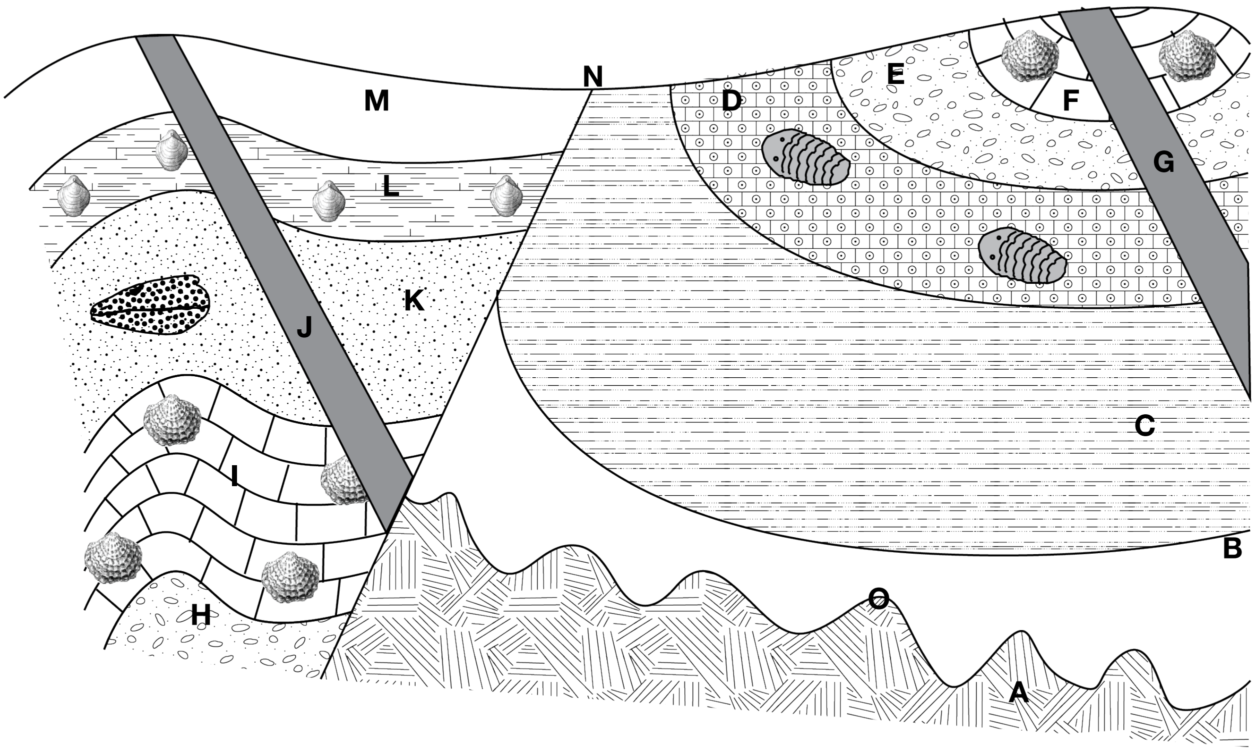
How long ago did that happen, anyway?

Today, we know that the Earth is some 4.5 billion years old and that the dinosaurs went extinct at ~ 65 Ma. Prior to the beginning of written records at ~ 3300 BCE and the discovery of radioactivity in 1896, it was very difficult to know exactly when something happened in the past. Darwin's unification of biology through the theory of evolution (1865) provided some guidance because it demonstrated that life evolves forward, and implied that fossils could be used to provide a sense of ***relative time.*** The discipline of Geology developed around the same time as publication of Darwin's On the Origin of Species, so the structuring of geologic time in the Phanerozoic came about by tracking how fossils changed in the various layers of rocks. It also allowed for the correlation of rocks in time from very distinct locations. All of the arcane names in the Periods of the geologic timescale are place names were key fossils that marked the disappearance (extinction) of one fossil and the first appearance of a new species occurs.



1. **Relative time exercise**: Using the table below, please determine correct sequence of events from oldest to youngest. If there are any letters that correspond to the same period of time place them in the lower row.

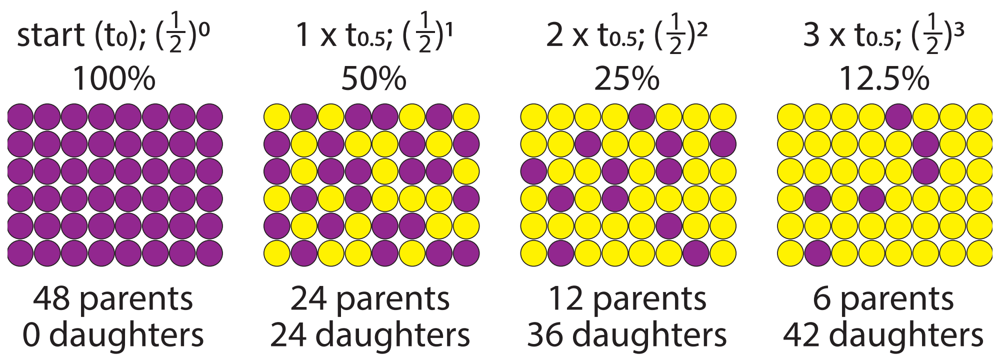


Oldest <———————————————————— > Youngest

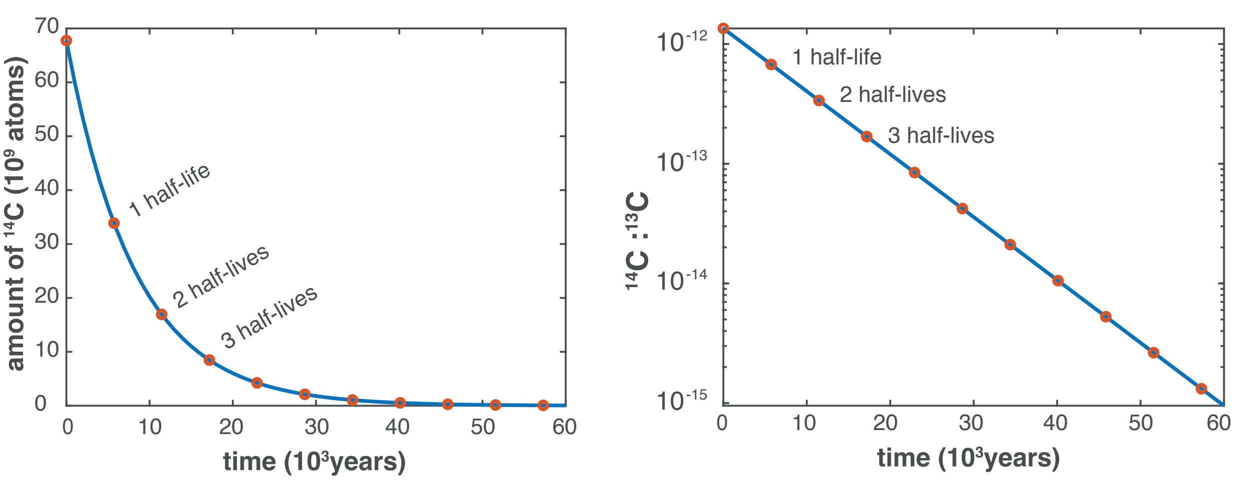
2. **Absolute Time**

The exercise above creates a definitive sequence of events that occurred over some duration of time, presumably millions of years. If, however, we knew how much time actually passed, to would be possible to know the ***rates*** associated with, for example, the evolution of organisms or how quickly sediment is laid down. To glean absolute time we need a chronometers that help measure the passage of time. Examples of chronometers that provide annual resolution include banding in trees (10s to 1000s of years); couplets of deposition in lake sediments (varves, 100s to 1000s of years), however, these still must be tied to an absolute timescale. ***Absolute time*** is always determined using the ***radioactive decay*** of elements in biological or geological materials, with the most famous example being carbon-14 dating of materials less than approximately 45,000 years old.

Every radioactive element has a characteristic rate of decay, which is often expressed as a ***half-life***, $t_{(1/2)}$, which is ln(2)/λ,where λ is the decay constant. For each half-life, half of the radioactive element "parent" decays into a different element "daughter."



above: *Conceptual illustration of radioactive decay over three half-lives starting with an initial 48 radioactive parents.* ***below:*** *Evolution of the amount of ^{14}C over time for one gram of carbon in a hypothetical sample (left) and the change in the ratio of ^{14}C to ^{12}C over time.*



Each radioactive element has a different half-life and radioactive elements with different isotopes have different half lives (see table below). The half life combined with the ability to accurately measure minute isotopic ratios dictates the useful age range of a geochronometer. For example, Notice that because 238U and 235U decay to different stable isotopes of Pb at different rates, the ratio of these isotopes is also a chronometer, in fact the age of the Earth is calculated using “Pb-Pb dating”.

Table 1. Common radioactive elements used as geochronometers

Element/ isotope	decay product	half-life	decay constant $^{-a}$ (λ)	useful age range (yrs)	common materials
^{14}C	^{14}N	5730 a	1.21 x 10^{-4}	< 50,000	shell, bone, corals, tissues, charcoal
^{40}K	^{40}Ar	1,251 Ma	5.55 x10^{-10}	10^3 to 10^9 yrs	mica, orthoclase (feldspar), pyroxene, amphiboles
^{238}U	^{206}Pb	4,468 Ma	1.55 x10^{-10}	10^5 to 10^9 yrs	zircon, monazite
^{235}U	^{207}Pb	703.8 Ma	9.79 x10^{-10}	10^5 to 10^9 yrs	zircon, monazite

To apply each chronometer requires that a certain set of conditions are met to ensure that the clock is accurate– largely that the clock remains closed to outside contamination such as the addition of, for example, extra parent, resulting in a younger age. In the case of radiocarbon dating, the biggest assumption is that the ratio of stable to C to ^{14}C is constant. The present day ratio of carbon ^{14}C to stable ^{12}C is $1.176\text{x}10^{-12}$. To determine the radiocarbon age the following equation is employed:

$$Age = -\frac{1}{\lambda}\ln\left(\frac{R_{meas}}{R_{fixed}}\right)$$

where R_{meas} in the measurement of the unknown and R_{fixed} is the known modern ratio.

Exercise 2. Calculate the age of a mastodon

Workers excavating the foundation of an office building near Salamanca, NY uncovered the remains of a mastodon. A team of Earth scientists come to describe the deposits that hosts the remains and collect the bones. A piece of bone is sampled for ^{14}C dating and sent off to a laboratory for accelerator mass spectrometry analysis of the ratio of ^{14}C to ^{12}C.

The lab reports $^{14}C/^{12}C$ of $5.151\text{x}10^{-14} \pm 1.545 \text{ x } 10^{-15}$. When was the Mastodon buried in the sediments and how does the measurement uncertainty translate into age uncertainty?

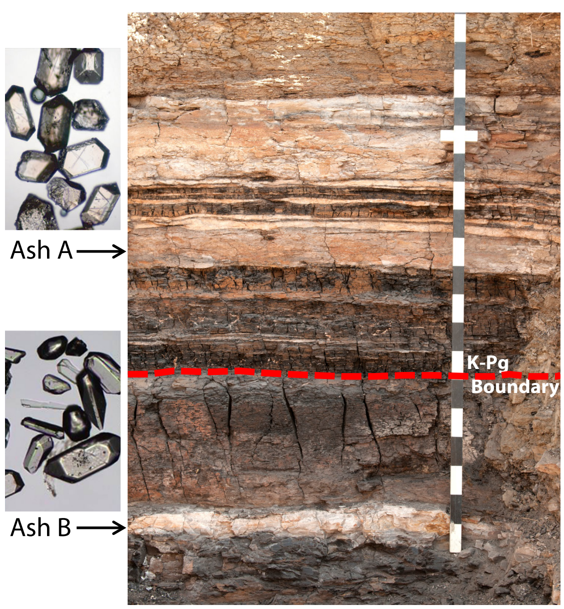
Exercise 3. When did the Chicxulub impact occur?
Paleontologists long recognized the boundary between the Cretaceous and the Paleogene (also the boundary between the Mesozoic and Cenozoic). In the early 1980s the global iridium spike was discovered linking the extinction event to an asteroid impact. To determine exactly when it happened it was essential to find volcanic deposits bracketing the iridium spike that contain the mineral zircon ($ZrSiO_4$), which is an exceptional geochronometer because when it forms U substitutes for Zr, and there is no initial daughter Pb in the crystal lattice. Recall that there are two isotopes of uranium, ^{238}U and ^{235}U, each with different half-lives, so the mineral zircon contains two independent clocks. The Pb:U ratio for either isotope is described by the equation below, with the only difference being the decay constant, λ, for ^{238}U and ^{235}U.

$$\frac{Pb}{U} = e^{t \cdot \lambda_u} - 1$$

A **mass spectrometer** measures the ratios of U and Pb present in each sample, which is typically from a mineral grain that is 0.072 mm^3 (0.2 mm x 0.06 mm x 0.06 mm), or smaller in size! What we really want to know is time, t, which is buried in the exponent in the equation above. In order isolate t, we must do some algebra and take the natural logarithm of each side of the equation, doing so yields:

$$t = \ln\left(\frac{Pb}{U} + 1\right) \cdot \frac{1}{\lambda_u}$$

Now it is possible to directly calculate the age from the measured ratios of U and Pb.



The picture on the left is an exposure of approximately 2 meter for rock from the Denver Basin, USA. The red dashed line shows the location of the Cretaceous/ Paleogene boundary, or as it is commonly called, the Cretaceous/Tertiary boundary. There are two volcanic ashes that bracket the boundary and are separated by ~ 90 cm distance. The mineral zircon (pictured) was isolated from each and analyzed via thermal chemical separation of U and Pb followed by mass spectrometer analysis to determine the U/Pb ratios yields the results in the table below:

Sample	$^{206}Pb/^{238}U$	2σ (%)	$^{207}Pb/^{235}U$	2σ (%)
Ash A	0.010308	0.13	0.06701	1.24
Ash B	0.010306	0.08	0.06754	0.72

Tasks:
A) Using the equation for time above, determine the ages $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages of Ash A and Ash B.

B) How much time elapsed between the deposition of Ash A and Ash B, and what was the mean rate of sediment deposition?