***Special Explanation*: How do we determine numerical ages for rock units in the Fells?**

Numerical ages are determined based on our knowledge of the radioactive decay of trace amounts of certain radioactive isotopes in rock formations. Isotopes are varieties of atoms of a single element that all have the same number of protons in their nucleus, which determines the identity of the element, but differing numbers of neutrons. Isotopes are written as the abbreviation of the element's name with a preceding superscript number that gives the total number of protons plus neutrons in the nucleus. This is the isotope's mass number. For example, $^{238}U$ and $^{235}U$ are two different isotopes of uranium. They both have 92 protons, as do all uranium atoms, but one has 146 neutrons for a total of 238 particles in the nucleus, and the other has 143 neutrons for a total of 235 particles in its nucleus. All elements have several isotopes, but one is usually much more abundant than the others. For example, of all carbon (6 protons in its nucleus), there is about 98.9% $^{12}C$, 1.1% $^{13}C$, and an extremely tiny amount of $^{14}C$ (~1.0 x $10^{-10}$%). Isotopes of one element can be stable, or they can be unstable and undergo spontaneous isotopic decay to isotopes of other elements, releasing subatomic particles and energy. This spontaneous decay process is what we refer to as radioactivity. $^{12}C$ and $^{13}C$ are stable, but $^{14}C$, or what has been given the name radiocarbon, is unstable and decays to $^{14}N$ (nitrogen, 7 protons). The decay of $^{14}C$ keeps its abundance very low. It would disappear entirely if it weren't for the continued production of $^{14}C$ by cosmic ray bombardment of Earth's upper atmosphere.

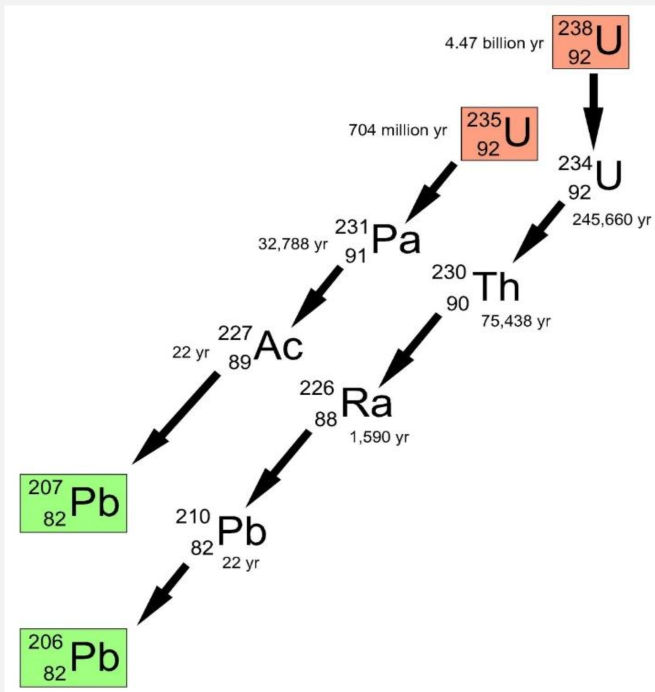
Radioactive isotopes allow us to set up atomic clocks for determining the ages of igneous rocks. Here's how it works. When a rock forms from magma, it has a certain amount of a radioactive isotope in it. This should not alarm you because all things have radioactive material in them, and these amounts are almost always very small and not harmful. The starting isotope in a radioactive decay process is called the parent isotope. Over time, the parent isotope decays to what we call a daughter isotope. It takes a certain amount of time for half of the parent isotope in a rock to decay to the daughter isotope. This time is a constant, which does not change with temperature or pressure, known as the half-life of the parent isotope. Different isotopes have different half-lives, which can vary over many orders of magnitude. Some isotopes have half-lives that are parts of a second while other isotopes have half-lives of billions of years. Sometime after an igneous rock was formed, some of the parent will have decayed. This increases the amount of daughter isotopes and diminishes abundance of the parent isotope. We can determine the age of the rock if we know the half-life of the parent isotope (i.e., its decay rate) and can determine at least two of three things: 1) the abundance of the parent isotope when the igneous rock formed, 2) the current abundance of the parent isotope, and 3) the abundance of daughter isotopes produced only by decay since the time the rock formed. We're lucky if we can determine all three, but items 2 and 3 always add up to item 1, so if we know two, we can calculate the third one. If the rock already had some daughter isotopes when the rock formed, we would have to determine this starting abundance through other measurements.

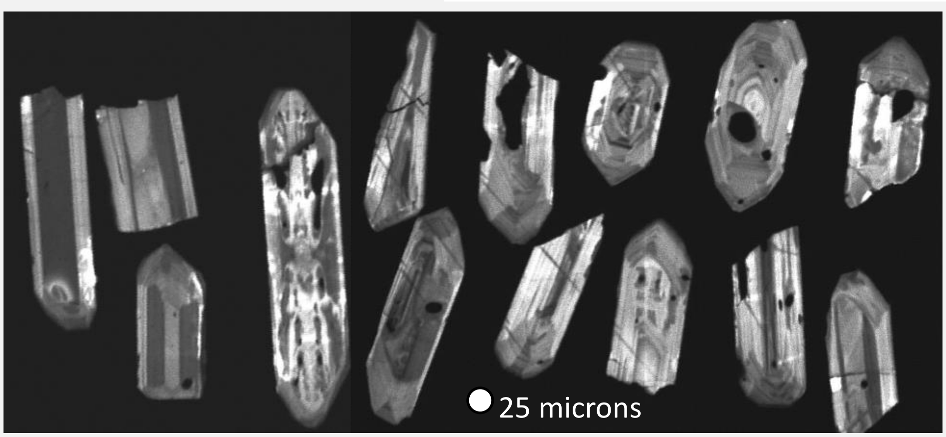
An important consideration in all radiometric dating techniques is that the parent and daughter isotope abundances in a rock, since the time the rock formed, must not later change except by radioactive decay. If parent or daughter isotopes are either gained or lost in a mineral by processes other than radioactive decay, we will not be able to use an analysis of the mineral to determine an accurate age without making additional measurements. As a result, geologists choose certain minerals that occur in igneous rocks for age analysis. These minerals do not allow their interior isotopic composition to change over time except by radioactive decay, unless there is extreme heating or metamorphism. The key here is tiny crystals of a mineral called zircon (zirconium silicate, $ZrSiO_4$) that is found in small quantities in all plutonic igneous rocks and contains trace amounts of uranium. It is very resistant to chemical changes induced by high temperatures or weathering; i.e., its parent and daughter isotopes do not change except by radioactive decay except under extreme conditions.

An important set of reactions used to radiometrically date igneous rocks is the decay of uranium. Through a complex chain of events $^{238}U$ decays in lead ($^{206}Pb$). Simplified decay chains for $^{238}U$ and $^{235}U$ are shown below with the half-lives of intermediate steps. The intermediate steps have very short half-lives and don't significantly slow down the decay process from uranium to lead. The total half-life of $^{238}U$ as it decays to $^{206}Pb$ is about 4.5 billion years. For example, if a rock had equal amounts of $^{238}U$ and $^{206}Pb$, it would be one half-life old, or about 4.5 billion years old. Any measurement of the ratio of $^{238}U/^{206}Pb$ can be applied to a decay equation that will provide the age of the rock. However, there is one huge problem: all the $^{206}Pb$ in the igneous rock has to be the result of $^{238}U$ decay since the rock formed. However, some $^{206}Pb$ could have been in the original magma when the rock formed. If we knew how much $^{238}U$ was in the rock when it formed, we could circumvent this problem, but we would never know this unless we already knew the age of the rock. Our solution is that we also measure the abundance of parent and daughter isotopes in another uranium isotope decay series: $^{235}U$ decaying to $^{207}Pb$. The two decay sequences together, along with some complex calculations, provide the information needed to determine the ages of igneous rocks from the oldest rocks preserved on Earth from about 4.5 billion years ago to about 1 million years ago.

This is just one example. There are about 40 radiometric dating techniques that can now be applied to determining numerical ages of geologic events from the early history of Earth (billions of years ago) to just a few years ago. Geologists apply different radiometric dating techniques to different parts of the geologic time scale and to different rock and sediment types being studied.

To determine the age of a rock, we must crush it and extract tiny zircon crystals for analysis. This is a very tedious process! Abundances of uranium and lead isotopes in multiple zircon crystals are then measured using a mass spectrometer. These abundances allow us to determine the age of crystallization of the igneous rock, i.e., when the zircon crystallized and trapped the uranium isotopes. Below are some scanning electron microscope images of zircon crystals from rocks in the Fells that have been analyzed for radiometric ages. These crystal are tiny, about 0.2 mm long on average, and they are very hard so that removal of surrounding rock has not damaged their crystal shapes.



The dating of plutonic igneous rocks seems relatively straightforward, but how do we date sedimentary or metamorphosed sedimentary rocks such as sandstones and metasandstones? We must remember that sandstones are composed of sand grains eroded from earlier rocks. Some of those grains are zircon crystals that easily survive weathering and erosion. The zircon crystal were originally crystallized in igneous rocks. The zircon grains are separated in the same process used for igneous rocks. They will be rounded grains like you see in a sedimentary rock and not the well-formed crystal shapes shown on the last page. The zircon grains will have a range of ages reflecting the ages of igneous source rocks that contributed sand grains to the original sandstone. The zircon grains are obviously older than the sandstone, since the sandstone is made of pre-existing eroded rock. So, the youngest zircon grain age gives us an upper limit for the age, or oldest possible age, of the sandstone. In the case of a metasandstone this also applies, provided that the metamorphism didn't heat the zircon grains at too high a temperature and recrystallize them. Below is a microscope view of the Westboro Formation from Sheepfold showing really tiny zircon grains (red arrows) in a metasandstone. Currently, the youngest zircon grain age for the Westboro is 909 Ma (mega annum or millions of years ago). Also remember that this unit is intruded by the Spot Pond Granodiorite dated at 609 Ma. This places upper and lower age constraints on the Westboro of 909-609 Ma. Since the Westboro predates a period of metamorphism that none of the other rock units in the Fells experienced, it is likely that the Westboro is in the upper end of this age range.