How to Date a Rock

Steve Ziskind

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- This presentation will explain, in a very simplified way, several techniques for dating rocks.
- All of the methods rely on results from chemistry, physics, astrophysics, etc. We will not try to justify these results.
- The presentation is based on Chapter 3 of Dalrymple's book, listed in the bibliography on the last slide.

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- What it will mean for us/geologists is driven by what we can determine.

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- As we will soon see, we will measure the time since a rock became solid. That is, since it solidified = froze = crystallized. That is, how long since the rock became a rock.

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- Atoms, such as Ar or Fe or U, have nuclei composed of protons and neutrons. Electrons are also present outside the nucleus. Protons and neutrons have nearly identical masses. Electrons have practically no mass. The number of protons determines which element is it, and the total number of particles in the nucleus is the mass of the atom (the nucleon number).

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- A ~~very~~ mature and precise technology called Mass Spectroscopy can measure the relative amounts of any given isotopes in a sample of material.

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- Among many known decay mechanisms, 3 are of particular interest to the dating problem: electron emission (a.k.a. β^- decay), electron capture (e.c.), and alpha (α) emission. An alpha particle is a He nucleus, 2 protons and 2 neutrons.

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- Alpha emission, in the cases that interest us, only starts a long chain of breakdowns. For example, $^{238}\mathrm{U}$ becomes $^{206}\mathrm{Pb}$ by a sequence of 14 emissions (8 α and 6 β^-), which ends in a stable isotope of lead. For our purposes, the entire chain will be treated as a single transformation. Another one of interest will be $^{235}\mathrm{U} \to {}^{207}\mathrm{Pb}$. These two uranium transformations share no intermediate products, so knowing the final lead isotope tells us the initial uranium isotope.

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- In this equation P is the amount of material, the parent, that decays into some other material D, the daughter. λ is the decay constant. The solution of the equation is:

$$P(t) = P_0 e^{-\lambda t}$$

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- Here are some important values:

reaction	$\lambda(yr^{-1})$	half-life (Ga)
$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ar}$	$5.54 * 10^{-10}$	1.25
$^{87}\mathrm{Rb} \rightarrow {}^{87}\mathrm{Sr}$	$1.42 * 10^{-11}$	48.80
$^{235}\mathrm{U} \rightarrow {}^{207}\mathrm{Pb}$	$9.85 * 10^{-10}$	0.704
$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb}$	$1.55 * 10^{-10}$	4.470

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- We know λ for the process, and the D/P ratio can be measured with mass spectroscopy. Our problem is solved!

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- When molten rock contains K it will produce Ar before it solidifies, and Ar may be present for other reasons. However, in a molten state the Ar will escape, being a gas, and will not combine with anything else, being non-reactive. Thus, at solidification, there is practically no Ar, but it will be trapped from that point.

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- An amusing footnote: Our atmosphere is 1% Ar, and it is believed that nearly all of it is the product of K decay.

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- An idea: if we took multiple samples of mineral from a rock then we might hope that D_0 would be the same from each. Then we would have multiple (D,P) points on a D-P graph, and the common slope would give us the information we need.

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- This puzzle was cleverly solved in 1961 by L.O.Nicolaysen. The idea is to normalize the equation by using a stable, non-radiogenic isotope of the daughter. To be specific we consider the rubidium-strontium decay, whose unmodified equation is:

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- A stable, non-radiogenic isotope of Sr is $^{86}\mathrm{Sr}$. Consequently the amount of this isotope is the same throughout time for any particular sample. i.e.: $^{86}\mathrm{Sr}_0 = {}^{86}\mathrm{Sr}_t$

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- Divide the prior unmodified by the ^{86}Sr values to obtain:

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- The initial strontium ratio is the key to the method. Unlike the absolute amount of $^{87}\mathrm{Sr}$ in any sample, which can vary widely at initial time, that of the Sr/Sr ratio will be the same at time zero. The reason is this. While the material that will form the mineral is fluid, there is no chemical distinction between the two isotopes, and whatever $^{87}\mathrm{Sr}$ forms from Rb decay will disperse freely throughout the material.

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- Once the material solidifies, the amount of daughter Sr that forms will depend on the local $^{87}\mathrm{Rb}$ concentration, and it cannot disperse.

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- The form of this last normalized equation is $y = mx + b$, where the slope is $e^{\lambda t} - 1$ and the y intercept is $\left(\frac{^{87}\mathrm{Sr}}{^{86}\mathrm{Sr}}\right)_0$.

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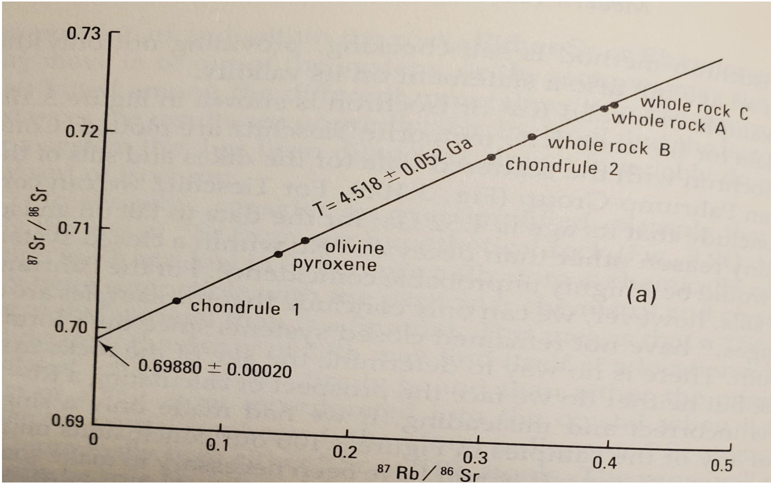
- Another commonly used decay that is amenable to the isochron method is $^{147}\mathrm{Sm} \to {}^{143}\mathrm{Nd}$ via alpha decay. And there are others.

Second Method - Isochron

- Here is figure 3.10 from Dalrymple's book, showing the isochron for the meteorite Tieschitz.



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- The problem with these systems is that Pb has a low melting point and some can readily be lost from a rock if heating after the initial rock formation causes some fraction of the Pb to be lost. It could be anywhere from some to all. The loss of some of the daughter makes the first two methods unapplicabile.

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- If we calculate the daughter/parent ratio for the two U/Pb systems, and plot them on the x and y axes, we get the following curve.

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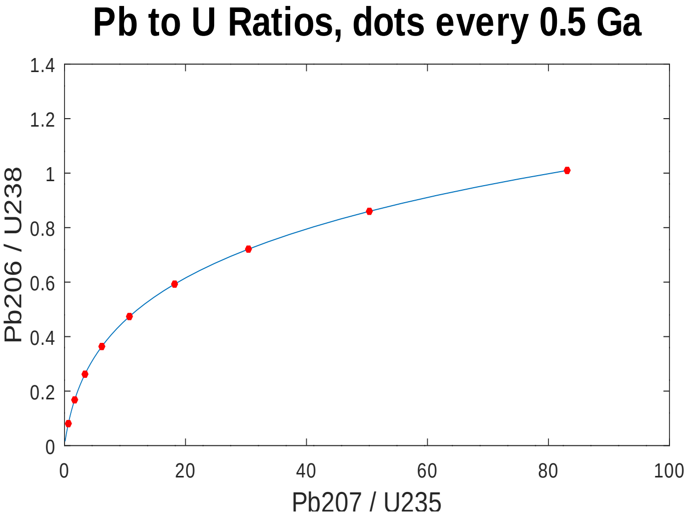

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- The assumption that no lead was initially present is generally true when the mineral under examination is a Zircon.
- Zircon is a mineral (Zirconium-Silicate) that is commonly found in rocks in very small crystals. It can also form large gemstone crystals. The crystals are physically and chemically tough. Uranium and Thorium are commonly incorporated into zircons in trace amounts during formation, but not lead, so the assumption of zero initial daughter is satisfied.

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- Different crystals from a rock will lose differing amounts of Pb from heating, depending on grain size, composition, crystal imperfections, etc.

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- After heating, at time=t, the amount of daughter is the sum of what remained after heating plus the amount freshly generated from the parent between h and t

$$\begin{aligned} D_t &= \alpha P_0(1 - e^{-\lambda h}) + P_h(1 - e^{-\lambda(t-h)}) \\ &= P_0\left[\alpha(1 - e^{-\lambda h}) + e^{-\lambda h} - e^{-\lambda t}\right] \end{aligned}$$

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- Dividing by P_t and simplifying we find

$$\frac{D_t}{P_t} = \alpha e^{\lambda t}(1 - e^{-\lambda h}) + (e^{\lambda(t-h)} - 1)$$

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- If $\alpha = 0$, then the ratio is $e^{\lambda(t-h)} - 1$, which is the same as starting over after h years, and running for t-h years. For $\alpha = 1$, nothing has been lost. and the ratio simplifies to $e^{\lambda t} - 1$

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- For given values of t and h, this is a linear function of α, and both of the Pb/U ratios will scale by the same amount, so the final ratios, plotted on the Concordia graph, will lie on a line that connects these two extreme α values.

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- Finding these intersections just requires us to obtain grains from a rock which have lost different fractions of their lead.
- Using values t=4.5 Ga, h=1.5 Ga, and α chosen from 0, 1/4, 1/2, 3/4, 1, the previous Concordia graph becomes the following Discordia graph.

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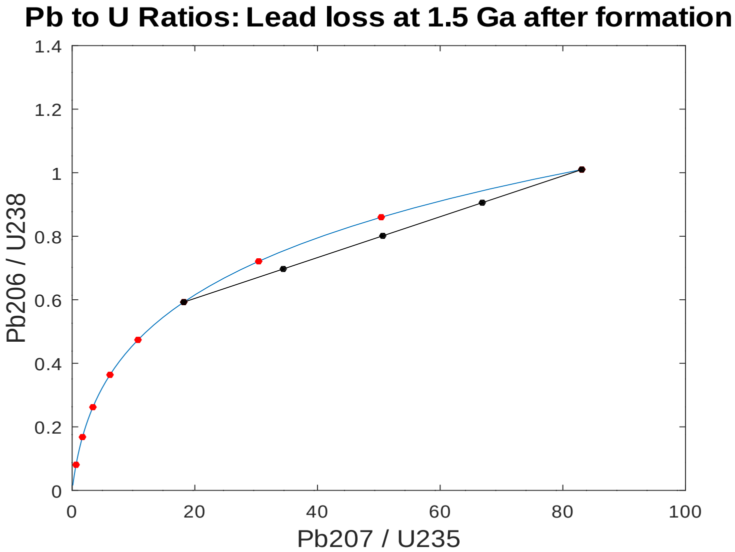
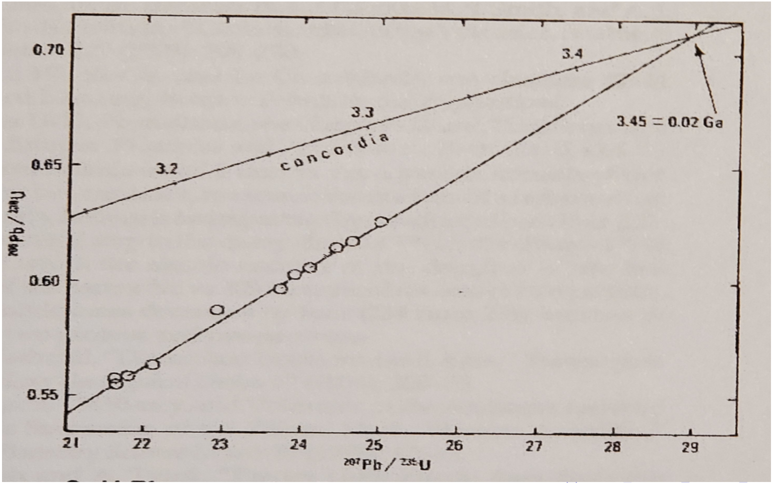


Third Method - Concordia/Discordia

- Here is figure 8 from Young's article, showing the concordia/discordia plot for zircons taken from rocks in Western Australia.



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