Radiometric Dating

by

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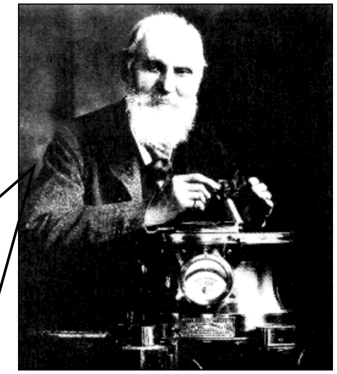
(with thanks to the UNC “Virtual Geology” project, Talk.origins, and the American Scientific Affiliation)

Sir William Thomson, Lord Kelvin

(1824-1907)

The limitation of geological periods imposed by physical science. . . does seem sufficient to disprove the doctrine that transmutation has taken place through ‘descent with modification by natural selection.’



Kelvin estimated the age of the Earth, and got an age that, while vast by human standards, seemed too short to accommodate Darwin's concept of evolution.

“. . . experimental investigation has supplied much of the knowledge then wanting regarding the thermal properties of rocks to form a closer estimate of the time which has passed since the consolidation of the earth, we have now good reason for judging that it was more than 20,000,000 and less than 40,000,000 years ago, and probably much nearer 20 than 40”.

Kelvin’s reasoning went like this:

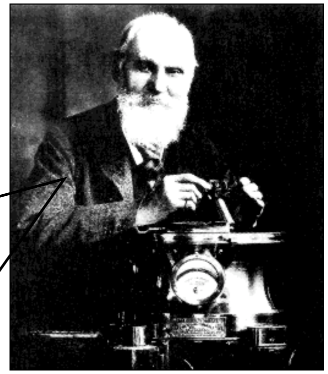
- The Earth has internal heat (as shown by volcanoes, the heat in deep mines, etc.)
- A warm body in cold space must radiate that heat away to space, at a rate governed by the laws of physics.
- For the Earth to be at its current temperature and losing heat at its current rate, it must have been molten recently—too recently for Darwinian evolution to have had any effect.

Although he was a great physicist, Kelvin's track record was not always perfect. . .

"X-rays will prove to be a hoax."

"Radio has no future."

"I can state flatly that heavier-than-air flying machines are impossible."



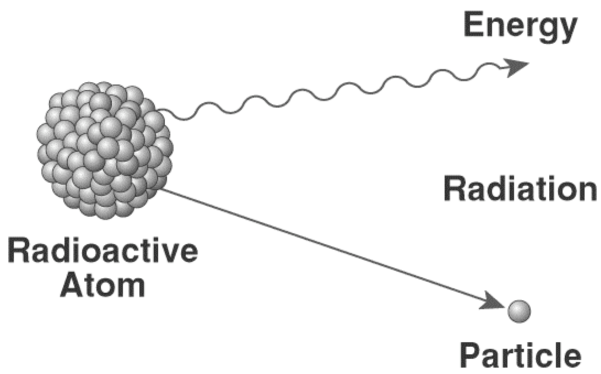
Yeah,

BUT. . .

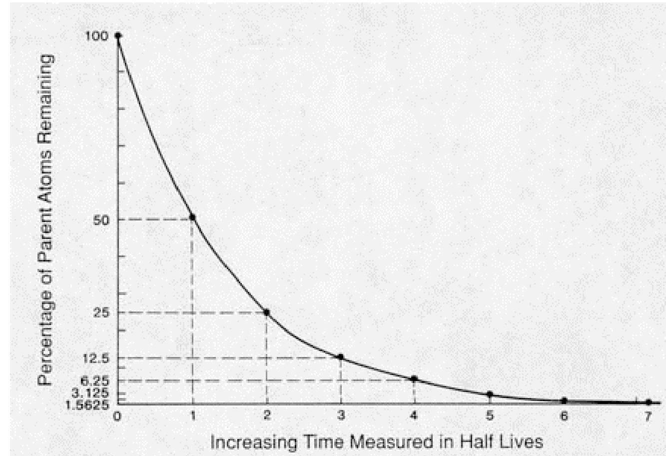
Beginning in 1895, physicists discovered and began to study a strange new phenomenon: *radioactivity*. Here's Marie and Pierre Curie with their great discovery, the new, rare, and highly radioactive element *radium*.

Natural radioactivity in the Earth maintains the Earth's temperature. The Earth isn't cooling down, as Kelvin had thought, because it has an internal source of heat!

Certain atoms are inherently unstable, tending to give off energy and particles as they *decay* into atoms of other elements.



The rate of decay of a redioactive element is given by its *half-life*, the length of time it takes for half of the atoms in a sample to decay.



Half a life is better than none. . . .

- Some half-lives of elements used in radiometric dating. . .
  - ^{14}C -> ^{14}N: 5730 years
  - ^{238}U -> ^{206}Pb: 703.8 million years
  - ^{40}K -> ^{40}Ar: 1.25 billion years
  - ^{235}U -> ^{207}Pb: 4.468 billion years
  - ^{87}Rb -> ^{87}Sr: 48.8 billion years

Half a life is better than none. . . .

- Let $[P_n]$ be the concentration of the parent element at the present time, and $t_{1/2}$ be the half-life. . .
  - Then $[P_n] = [P_{orig}]\, 2^{[-age/t_{1/2}]}$
- Let $[D_n]$ be the concentration of the daughter element, equal to $[P_{orig}] - [P_n]$ Solve the above formula for the age, and you get. . . .

$$\text{Age} = (t_{1/2}) \log_2 [1 + ([D_n]/[P_n])]$$

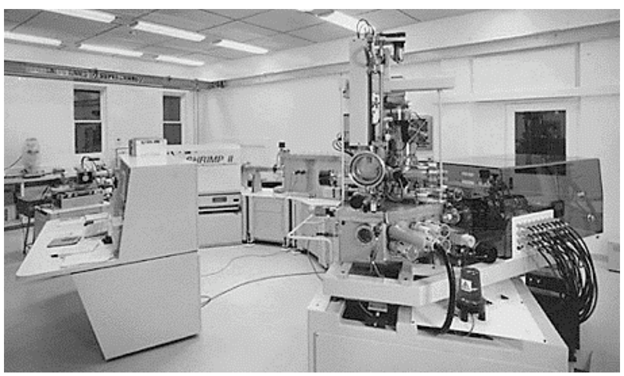
But there would seem to be three potential problems for radiometric dating. . .

- How do we know that decay rates have remained constant?
- How do we know the initial amounts of the parent and daughter element in a sample?
- How do we know that a sample hasn't gained or lost some of its parent or daughter element after formation?

How do we know that decay rates have remained constant?

- No factor is known that will alter the rate of normal radioactive decay, at least not more than a few percent.
- If decay rates had ever been much faster, radioactive elements would have released more energy, with effects we'd notice (e.g. Adam and Eve glowing in the dark)
- Quantum mechanics—the most successful theory in physics—provides no mechanism for changing rates

We've gotten better at *measuring* the rate, and at counting atoms in minute samples. . .



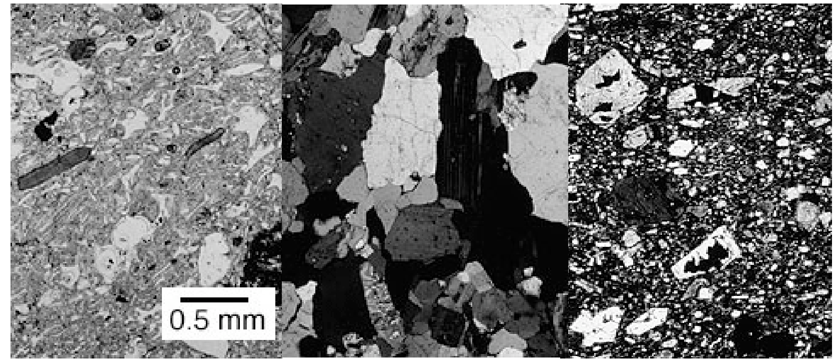
. . . which means that estimates of half-lives are sometimes revised for elements with long half-lives.

Because analytic techniques have improved, dates are always being refined and revised—and this may give the impression that the method's unreliable, for those who don't know any better. . . .

- How old are the oldest rocks with definite animal fossils?
  - 1960s estimate: ~600 million years
  - 1980s estimate: ~570 million years
  - Most recent: 544 million years

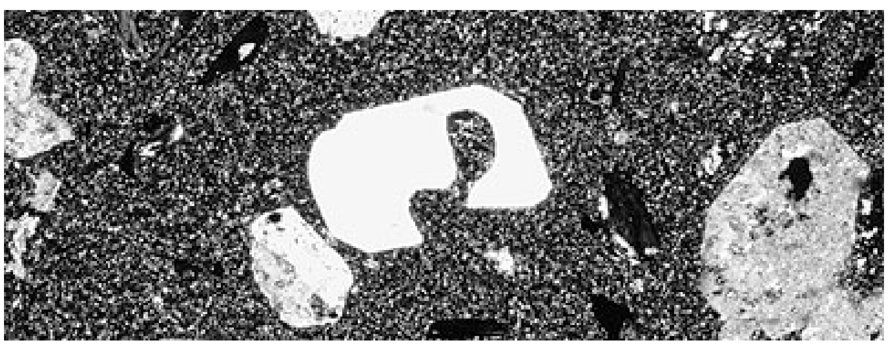
Usually, the only rocks you can directly date are igneous rocks. . .

. . .as they cool down, different minerals precipitate out of the melt—as you should know by now.

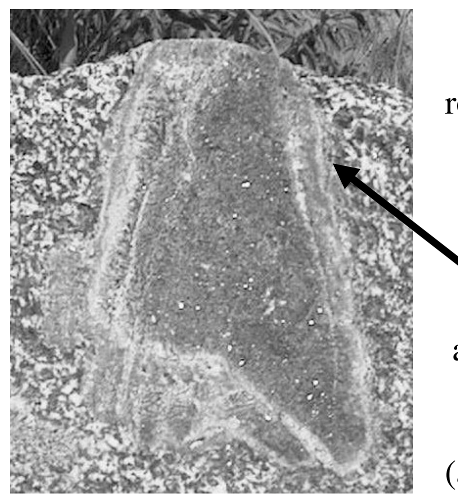


welded tuff | biotite granite | nepheline basalt

For dating to work, all of the minerals must have formed from the same source at the same time.



In other words, the sample must be *cogenetic*.



Sometimes the rock's not cogenetic—for example, a lump of older surrounding rock may fall into the molten lava/magma, forming a *xenolith*. Here's one in granite—note the *reaction rim*, showing where the xenolith was chemicallly altered and partially melted. This wouldn't give an accurate radiometric date (although it might give you a lower bound. . .)

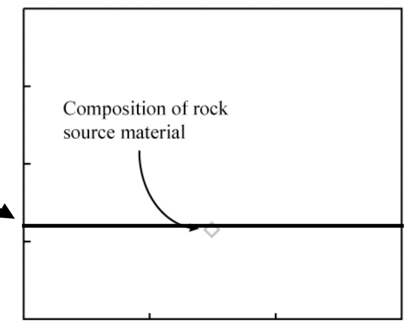
OK. . . so?

- If all minerals in a sample formed from a common source, they all crystallized from a source with a single concentration of the parent element.
- But some minerals won't contain much of the parent element, and others will contain more. (Why? *Because* they're different minerals! With different chemical compositions!)

We can graph it like this. Start with a common source, a common pool of liquid rock. . .

[daughter element]

For now assume that this is zero — we'll see in a minute what happens if it's not. . .

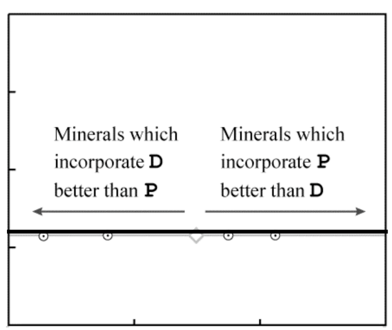


[parent element]

As it cools, it fractionates into several minerals, each with a different value for [P], the concentration of the parent element . . . .

[daughter element]

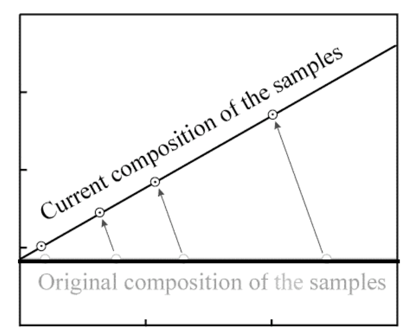
For now assume that this is zero — we'll see in a minute what happens if it's not. . .



[parent element]

And look what happens to the line over time. . .

[daughter element]



[parent element]

Isochron Dating

- These straight lines are called *isochrons*.
  - Their slope is proportional to the age of the sample.
- They provide an automatic cross-check:
  - Different minerals have different potentials to gain or lose atoms
  - If the sample has gained or lost isotopes, that will affect different minerals differently. . .
  - and the points will not lie along a straight line!
- Here's a more <u>in-depth discussion</u> of the method and how potential errors are detected and corrected

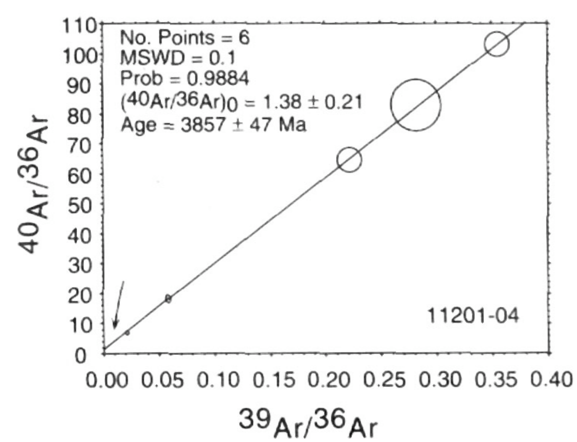
Hold it! What if the rock formed with some of the daughter element already in it? Won't that make it look older than it is??

- Good point—but we already thought of that! Take K-Ar dating as an example. . .
  - Most of the argon in the world is argon-36—which is *non-radiogenic* (it doesn't come from radioactive decay) and is stable.
  - Potassium-40 decays into argon-40, which is *radiogenic*, but is also stable.

Objection overruled!

- So a sample starts out with a certain ratio of, in this case, $^{40}Ar/^{36}Ar$
- Over time, the amount of ^{36}Ar doesn't change, because ^{36}Ar isn't radiogenic. . .
- . . . but the amount of ^{40}Ar does. . .
- . . . and the value of $[^{40}Ar]/[^{36}Ar]$ *increases* with time.

Sample isochron from a moon rock. (The ^{40}K was artificially altered to ^{39}Ar, because it's easier to measure it more accurately that way.)



Source: Culler, T. S. et al. 2000. Lunar impact history from $^{40}Ar/^{39}Ar$ dating of glass spherules. Science 287: 1785-1788.

It gets better. . .

- If you use uranium and lead to date a rock, you get three usable dating series for the price of one:
  - ^{238}U / ^{206}Pb
  - ^{235}U / ^{207}Pb
  - ^{207}Pb / ^{206}Pb
- A good sample should have these ratios related to each other in a particular mathematical way, which is predicted by a relationship called a *concordia curve*.

In this example (from rocks 555.3 million years old from Russia), the point where the line (ellipses give the data) intersects the numbered curve gives you the actual date. This is the *concordia* dating method.

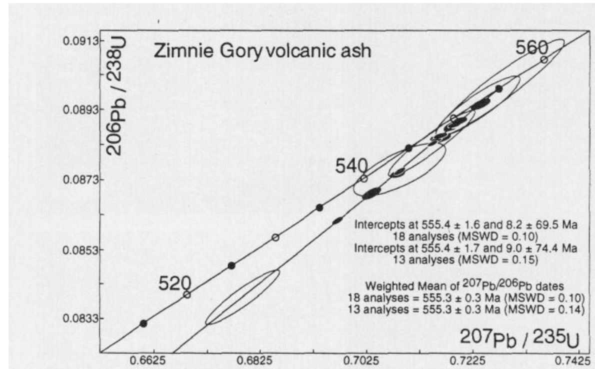
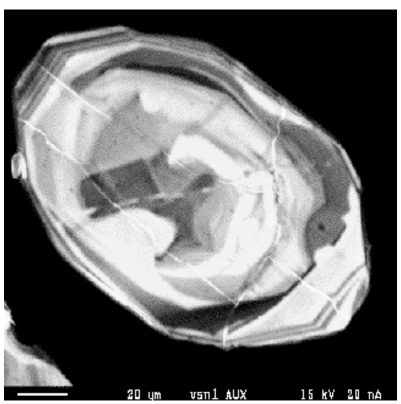


Fig. 3. U-Pb concordia diagram for Zimnie Gory volcanic ash.

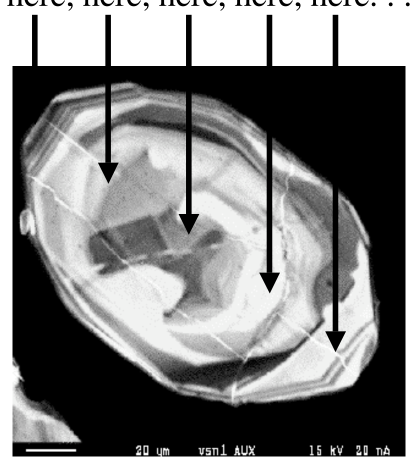
Source: Martin, M. W. et al. 2000. Age of Neoproterozoic bilaterian body and trace fossils, White Sea, Russia: Implications for metazoan evolution. Science 288: 841-846.

Yet another cross-check: It's possible to date a single microscopic crystal of minerals such as this zircon, meaning that many dates can be calculated for one rock—but how do you know argon hasn't leaked out?

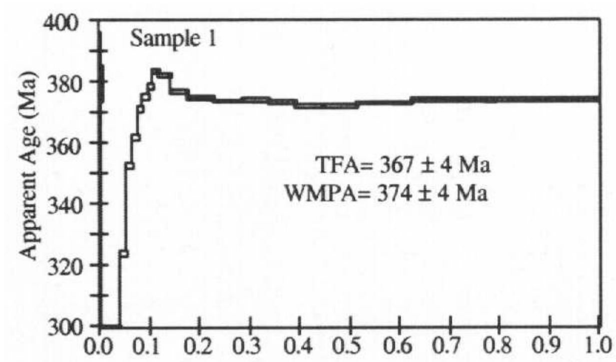


Answer: You release Ar by blasting the crystal with a laser

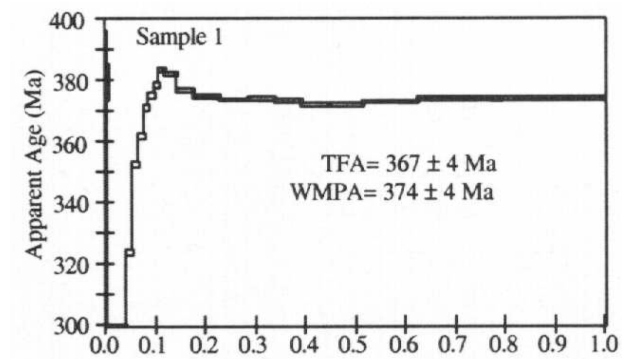
here, here, here, here, here. . . .



. . . and you get a diagram like this. The drop-off at the left shows that argon has diffused out close to the surface of the zircon. . . .

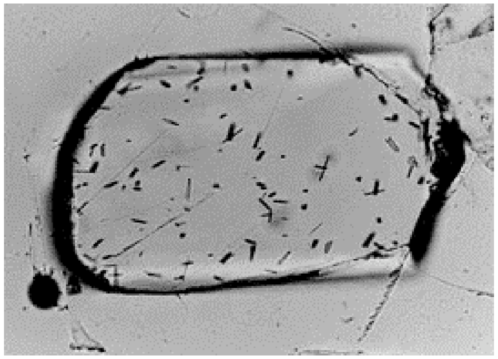


. . . the plateau shows that argon loss didn't go all the way to the core. Age is proportional to plateau height.



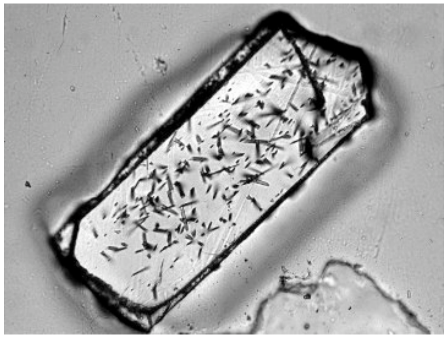
Source: Beane, R. J. and Connelly, J. N. 2000. 40Ar/39Ar, U-Pb, and Sm-Nd constraints on the timing of metamorphic events in the Maksyutov Complex, southern Ural Mountains. Journal of the Geological Society 157: 811-822

When a radioactive atom decays, it may release a high-energy particle which leaves a trail behind it as it passes through the surrounding matter. . .



. . . these trails can be seen here, in this microscopic crystal of the mineral *apatite*.

This is the basis of *fission-track dating*—the density of particle tracks is proportional to the sample age.



Check out WWW pages at Union College or Geotrack if you want the technical specs. . . .

In general, we can often cross-check a date from one isotope system with another one.

Consider the rocks of the Isua Series, in Greenland. . .

In general, we can often cross-check a date from one isotope system with another one.

- Age of the Isua Series rocks of Greenland, according to five different studies:
  - U-Pb: 3.60 (+/- 0.05) billion years
  - Pb-Pb: 3.56 (+/- 0.10) billion years
  - Lu-Hf: 3.55 (+/- 0.22) billion years
  - Sm-Nd: 3.56 (+/- 0.20) billion years
  - Rb-Sr: 3.62 (+/- 0.06) billion years

(Data borrowed from "Radiometric Dating: A Christian Perspective", which has even more dates for the Isua Series.)