Deep Time and Shallow Thermodynamics: How We Know the Age of the Solar System

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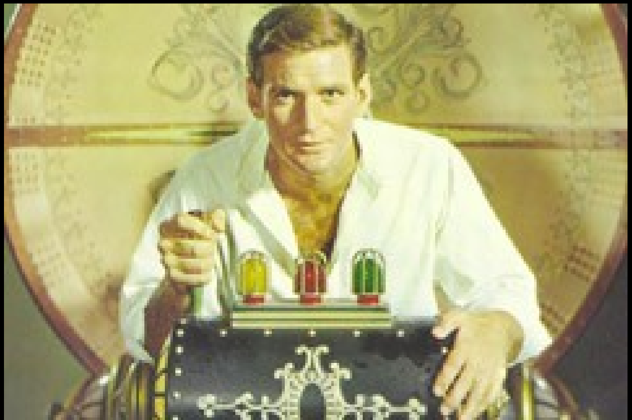
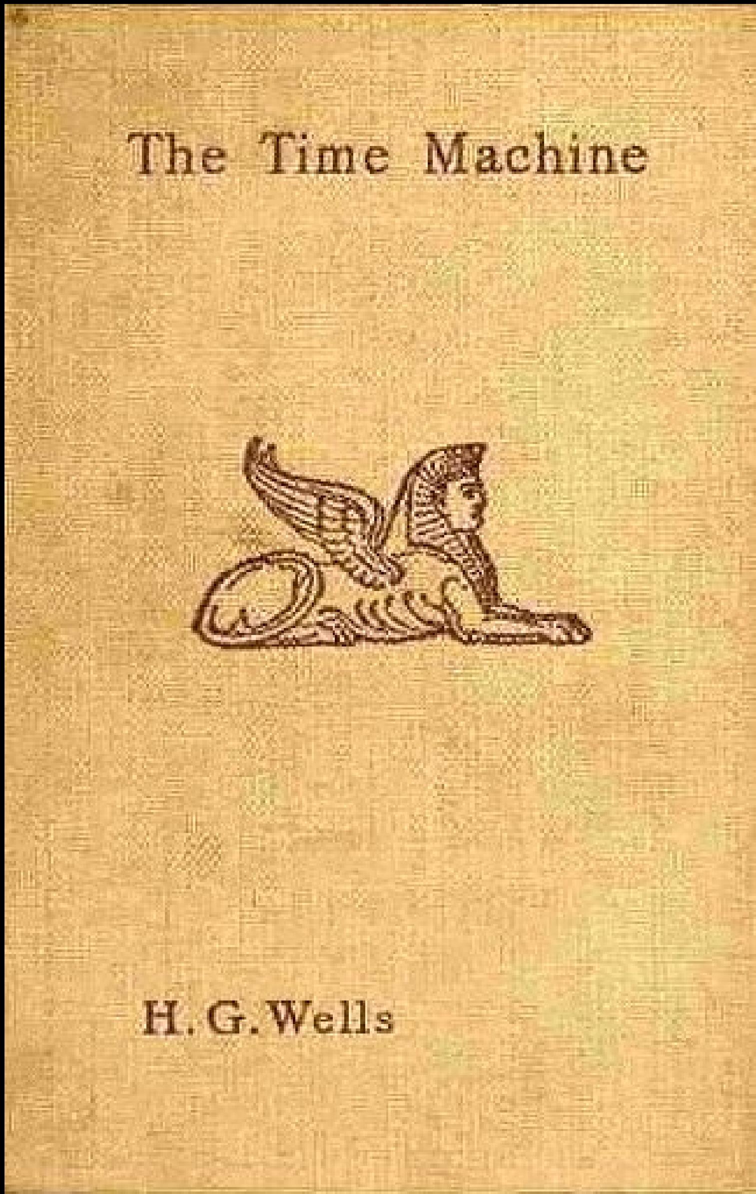
The Time Machine (1895)

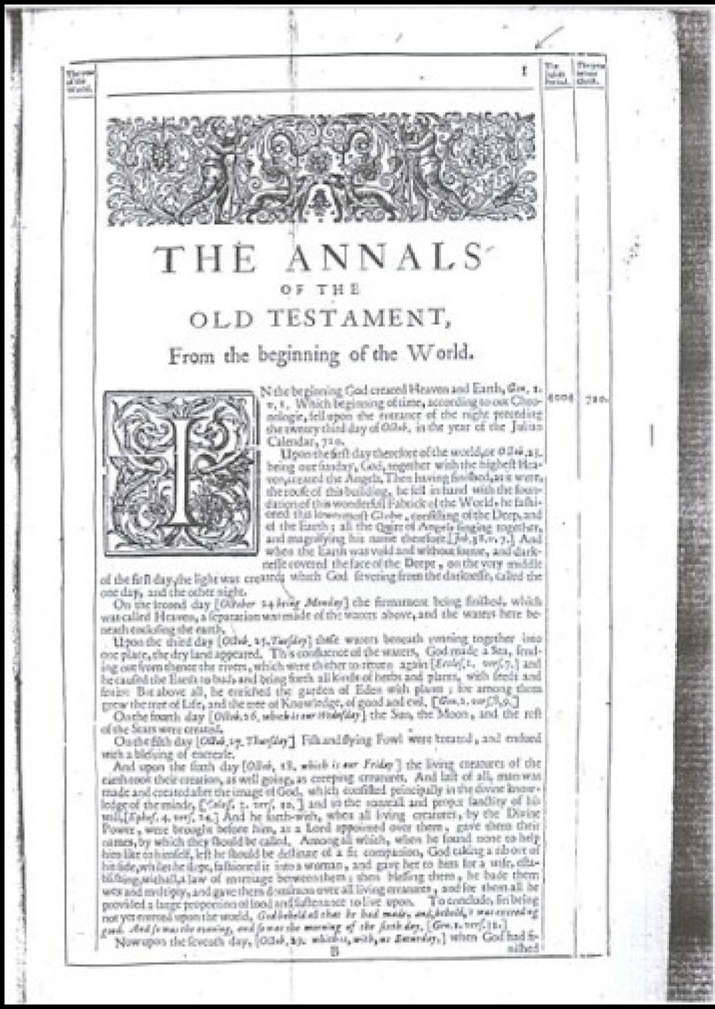
- Reflected the current ideas of geological time
- After messing with the Morlocks, the Traveler goes 30 million years into the future
- Finds the Earth's rotation slowed, the Sun weak and dully red, close to burning out.



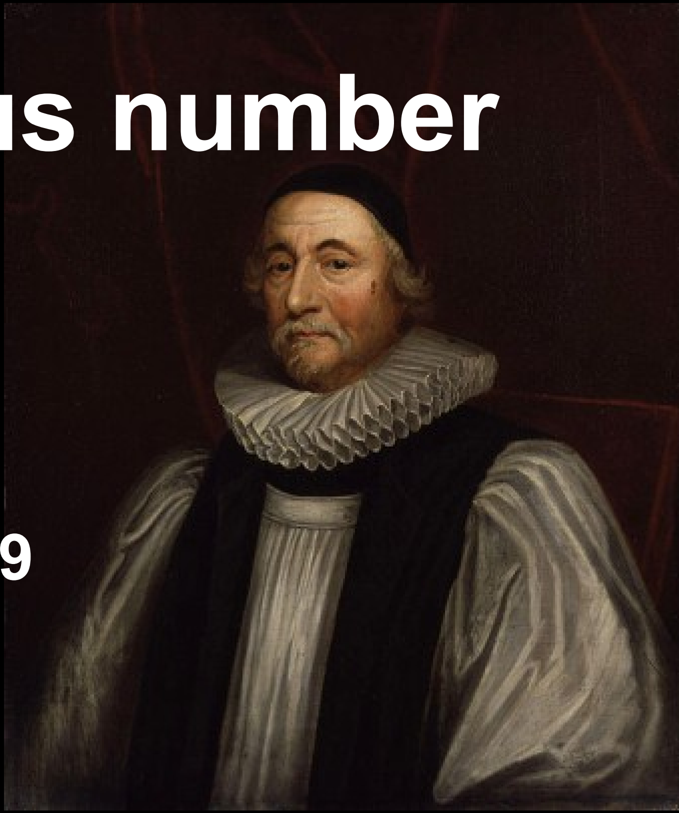


Bishop Ussher

- Church of Ireland Archbishop of Armagh and Primate of All Ireland between 1625–56
- He calculated the beginning of creation as Sunday, October 23, 4004 BC based on he then-widely held belief that the Earth's potential duration was 6,000 years.
  - 4,000 years before the birth of Christ and 2,000 after (note we have now passed that mark)
  - This corresponds to the six days of Creation, on the grounds that "one day is with the Lord as a thousand years, and a thousand years as one day" (2 Peter 3:8)


THE ANNALS
OF THE
OLD TESTAMENT,
From the beginning of the World.

This was a consensus number



- Jose ben Halafta (2nd Century Rabbinical Scholar) 3896 BC
- Bede (7th Century Monk) 3952 BC
- Scaliger (16th Century Scholar) 3949 BC
- Johannes Kepler (17th Century Astronomer) 3992 BC
- Sir Isaac Newton (17th Century Genius) c. 4000 BC
- John Lightfoot (17th Century Vice-Chancellor of Cambridge) 3929 BC

But things were changing….

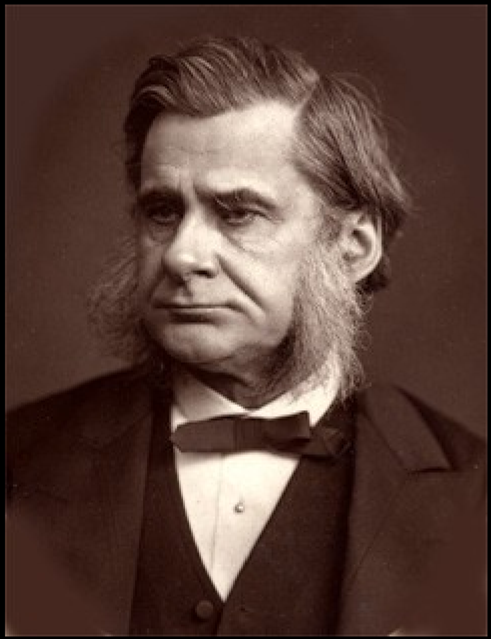
- Geology was developing as a science….
- Steno’s Law (17th Century) Sedimentary layers are deposited in a time sequence, with the oldest on the bottom and the youngest on the top.
- While early geologists had no way of measuring absolute time, it was pretty clear that it took a “long” time to deposit visible strata.

This was mostly driven by Canals

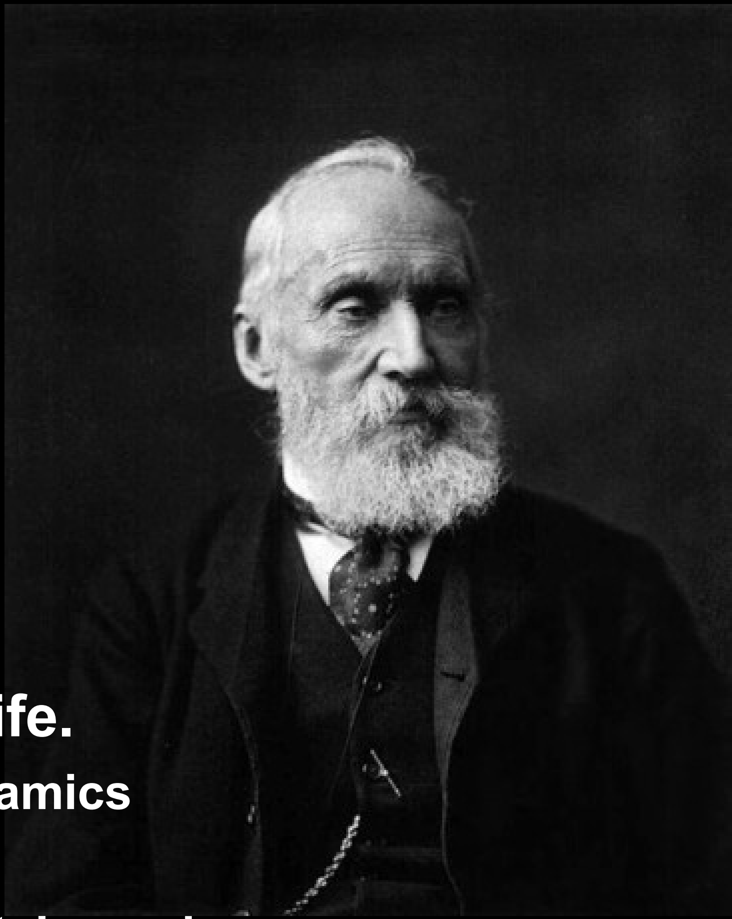
- The 18th century was the great age of canal building in England and Europe.
- To build canals you needed to really understand the local geology

- Early geologists were mostly self-taught.
- They noted that you could trace out layers that had the same fossils over huge areas.
- The approach was to count up the layers and guess at how fast they could be laid down
- The total column of sediment was about 50,000 yards!
- The early estimate was about 96 million years.

- Early evolutionists (ca ~1860s) thought that 100 million years was way too short for the workings of natural selection.
  - Geneticists have subsequently measured the rate of genetic divergence of species, using the molecular clock, to date the last universal ancestor of all living organisms no later than 3.5 to 3.8 billion years ago.



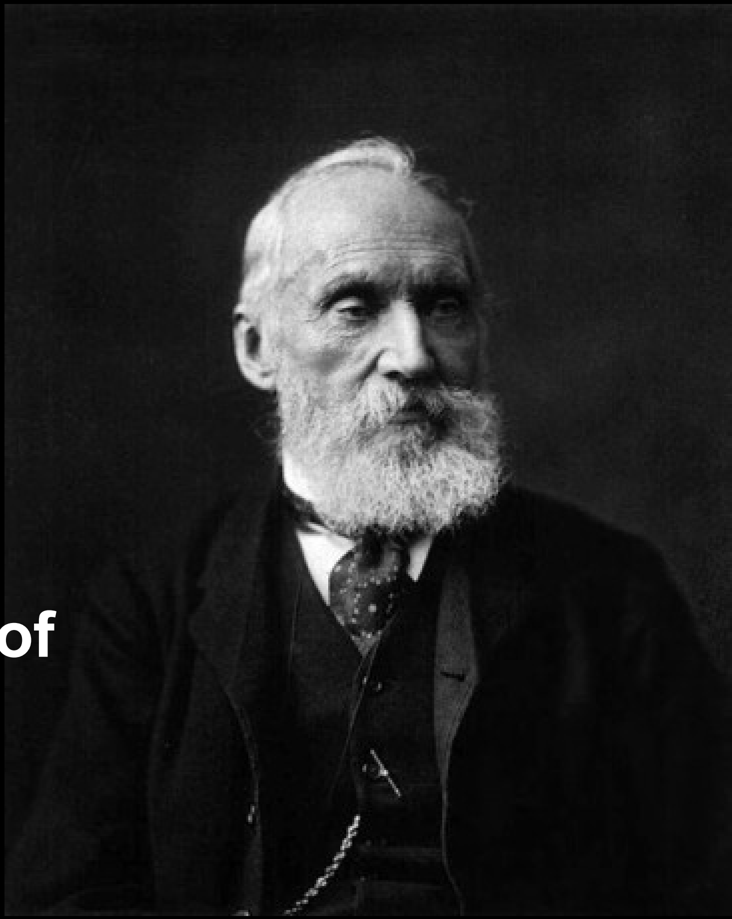
Enter Lord Kelvin



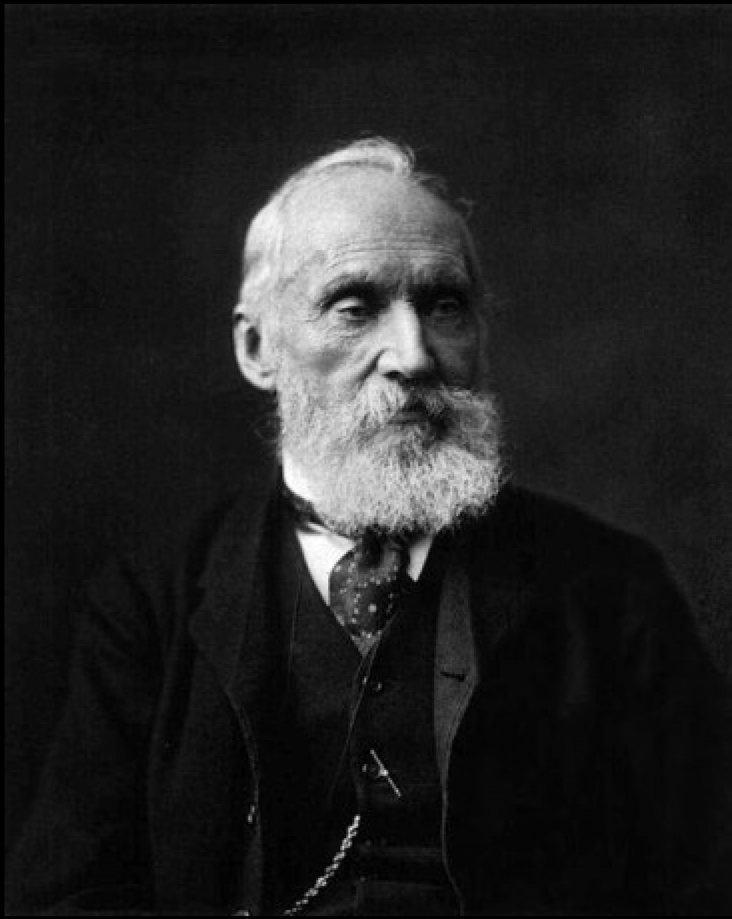
- **William Thomson was a brilliant mathematician and physicist**
  - Professor at 22
  - Fellow of the Royal Society at 24
  - Made a Lord in 1892
  - Buried next to Isaac Newton
- **He made major contributions all his life.**
  - Revolutionized the science of thermodynamics
  - Worked out the Kinetic theory with Joule
  - Was central to establishing transatlantic telegraph communications.
  - Made substantial contributions to electrical theory and measurement.
  - And he dabbled in Earth science.

Enter Lord Kelvin

- Determining the age of the Earth had become BIG science.
- Both the evolutionists and geologists thought that their sciences required "long" periods of time.
- Kelvin thought that thermodynamics could put some limits on the age of the solar system.



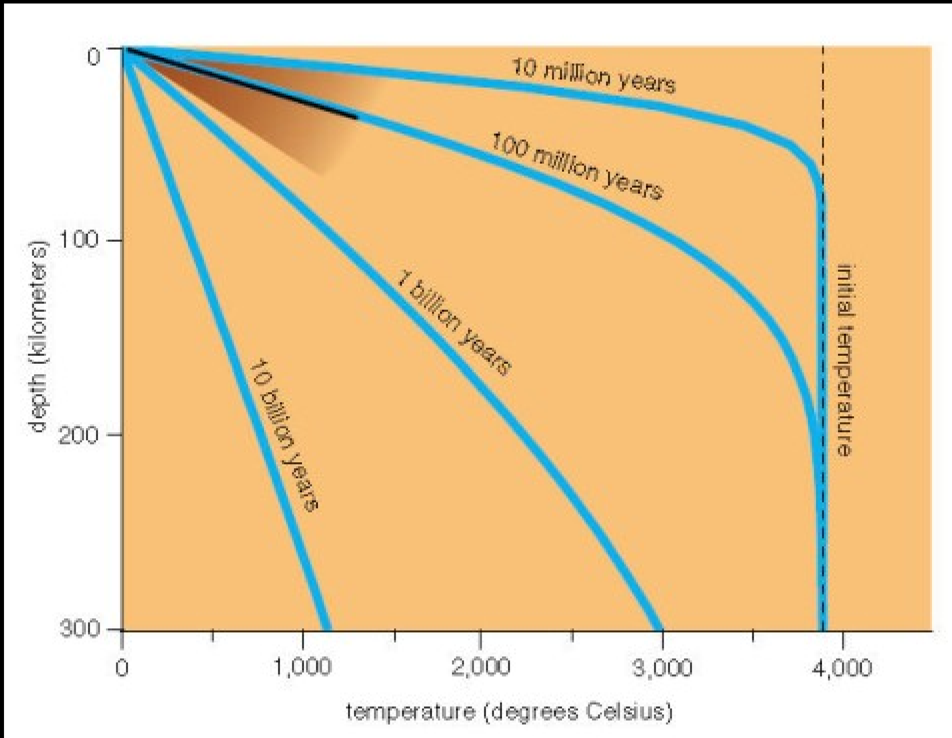
Start with the Sun



- The Sun is shining…..right?
- That energy must come from somewhere.
- The only plausible source for the was internal, derived from the gravitational potential energy released during its accretion.
  - It is easy from Newton to calculate the energy released from accretion and from gravitational contraction.
  - The resulting estimate was that the Sun could shine for about 100 million years (later reduced to 20 My).

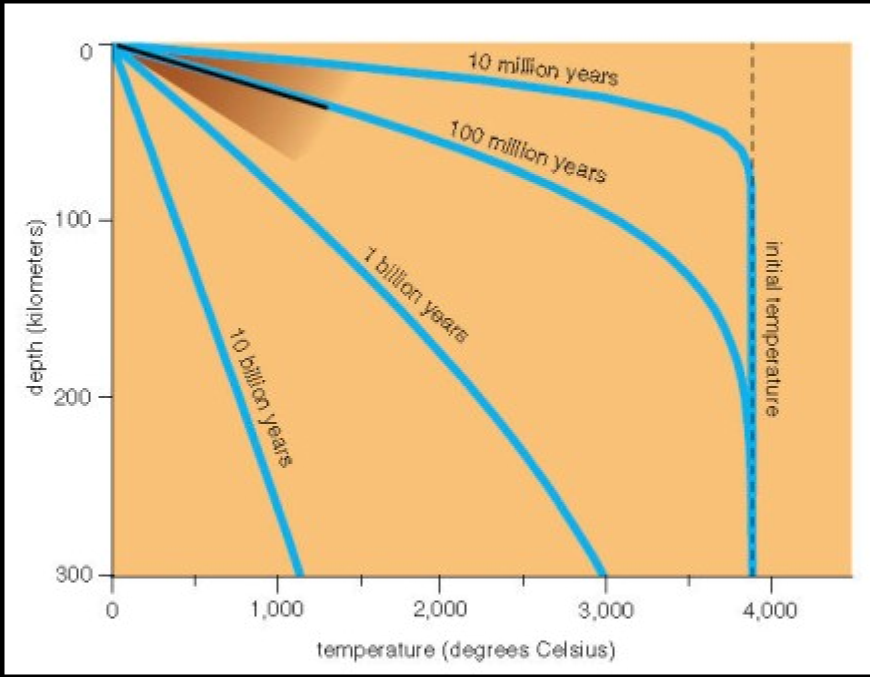
Now the Earth

- **Assume:**
  - the Earth was initially molten.
  - the planet is rigid
  - its physical properties are homogeneous
  - no undiscovered source of energy
- **The initial heat of the Earth should diffuse out and produce a temperature gradient.**
- **The slope of the gradient is a function of the age of the cooling….i.e. the age of the Earth.**

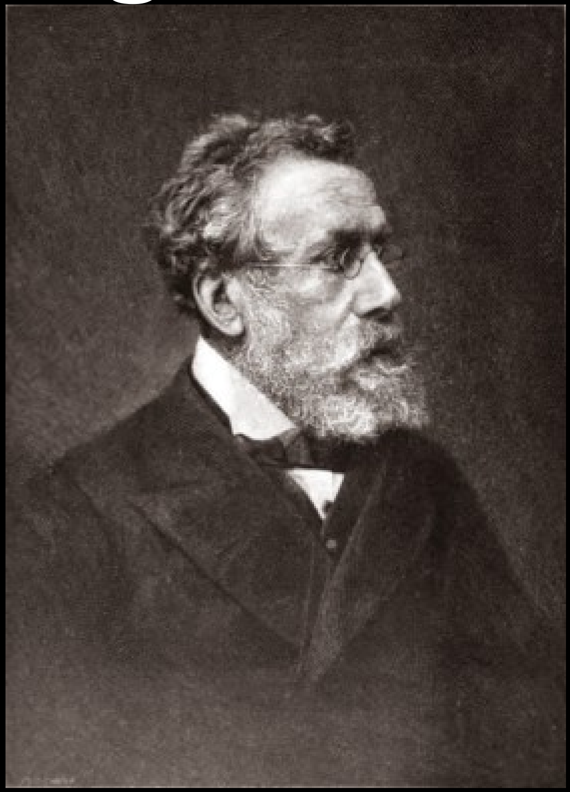


Now the Earth

- **He estimated the gradient at about 1/50th of a degree Fahrenheit per foot(or about 36 degrees Celsius per kilometer).**
  - **Not bad…..modern measurements are 25-30° C/km**
- **He estimated Earth's initial temperature (7,000 degrees Fahrenheit, or 3,900 degrees C) from melting experiments on rocks.**
  - **Also not bad, modern estimates of core temperature are 7,000K.**
- **This gave an age for the Earth of between 24 million and 400 million years given the uncertainties in the geothermal gradient and thermal conductivity.**
  - **If you repeat this calculation using modern numbers for the gradient and conductivity, you get between 24-96 My.**



Why was Kelvin Wrong?



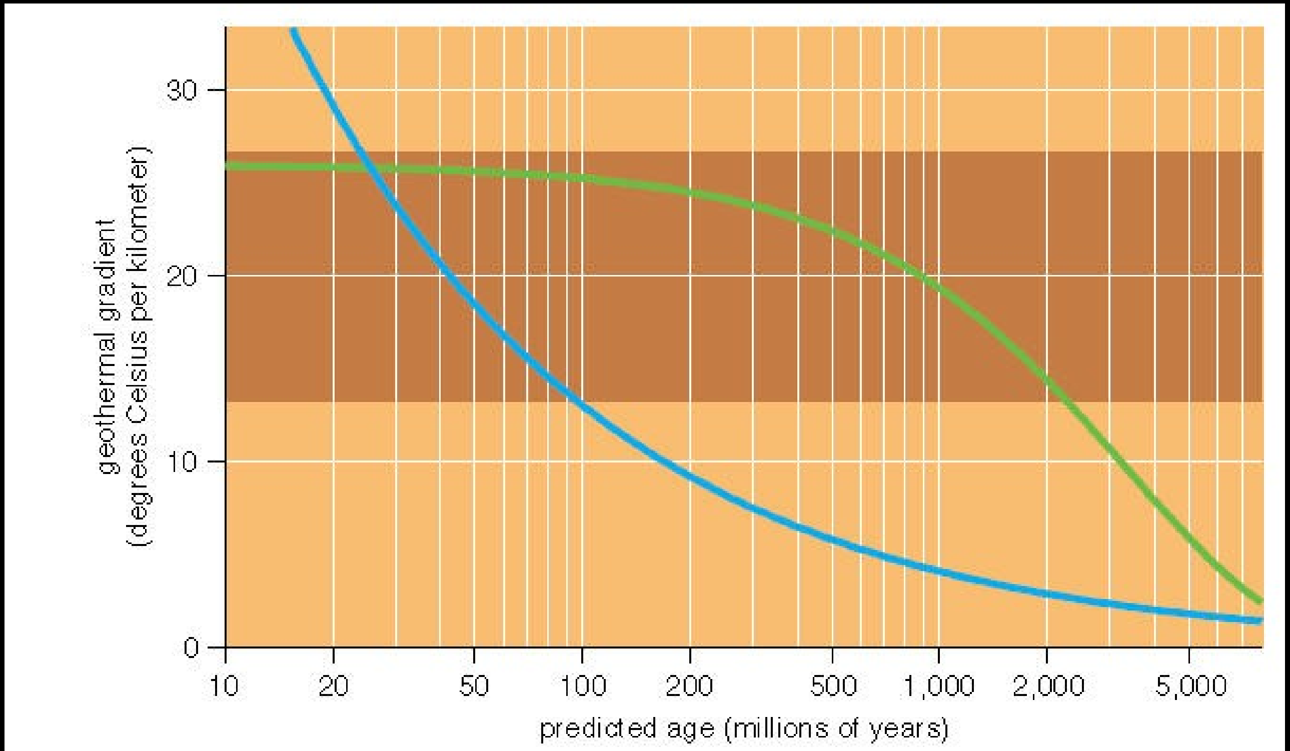
- **This drove the 19th century geologists crazy!**
- ***"I am as incapable of estimating and understanding the reasons which you physicists have for limiting geological time as you are incapable of understanding the geological reasons for our unlimited estimates." (Sir Andrew Ramsay, 1867)***
- **But Kelvin had made a fundamental mistake in his assumptions.**
  - **Most people thought it was the "no undiscovered source of energy" assumption, but no…..**

Enter John Perry

- He was a professor at what is now Imperial College London.
  - He had spent several years as Kelvin’s assistant
- He had the idea that the Earth’s interior was partially fluid and convection, not conduction was the primary mode of heat transport
  - Convention would be much more efficient heat transport, so the core could be much hotter, longer than with convection.
- He privatively raised these ideas with Kelvin and got blown off.

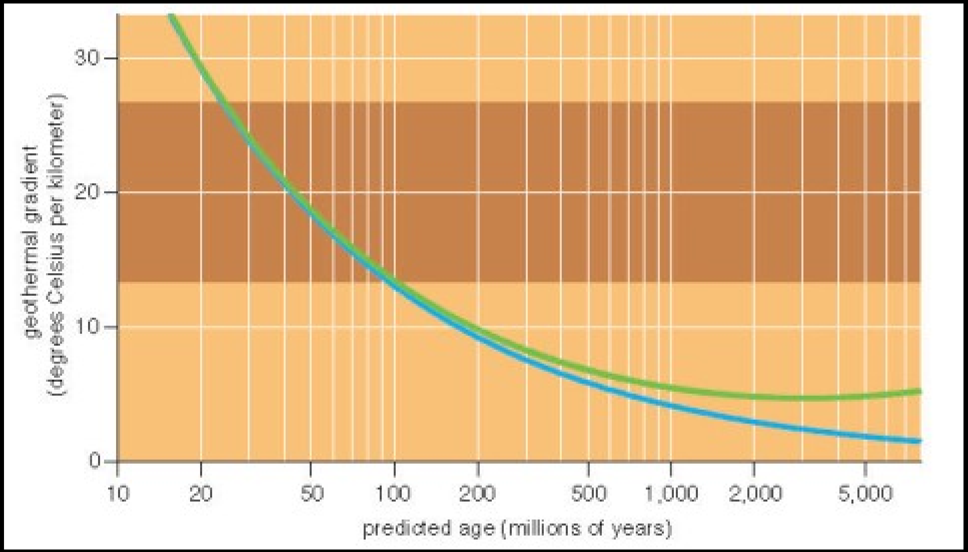
Enter John Perry

- **Perry published in 1896 and showed that if the Earth has a conducting lid of 50 kilometers' thickness, with a convecting fluid underneath, then the thermal gradients near the surface are consistent with any age up to 2 billion or 3 billion years.**

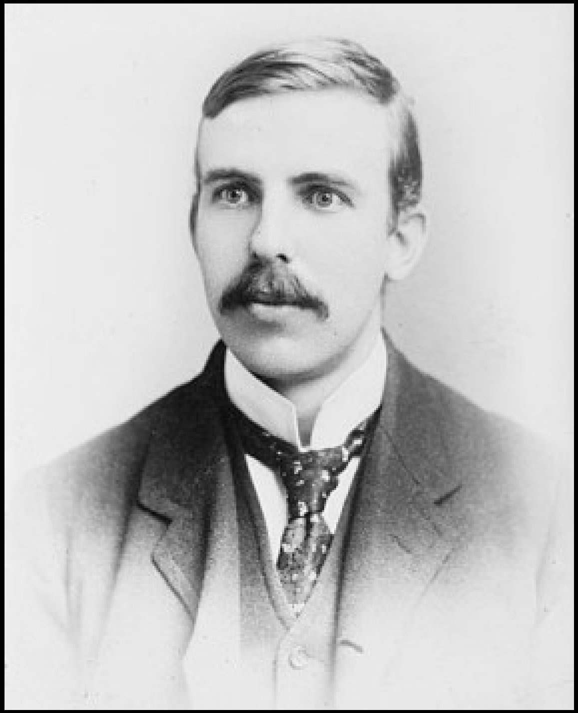


Radioactivity is actually a Red Herring in this debate

- Of course, about this time radioactivity as a heat source is discovered (Curie, 1903)
- Ernest Rutherford proposed 1904 that it was radioactive heat that was actually responsible for a much older Earth than Kelvin had supposed
- BUT, if you keep Kelvin's conduction model, radioactivity doesn't have much effect.



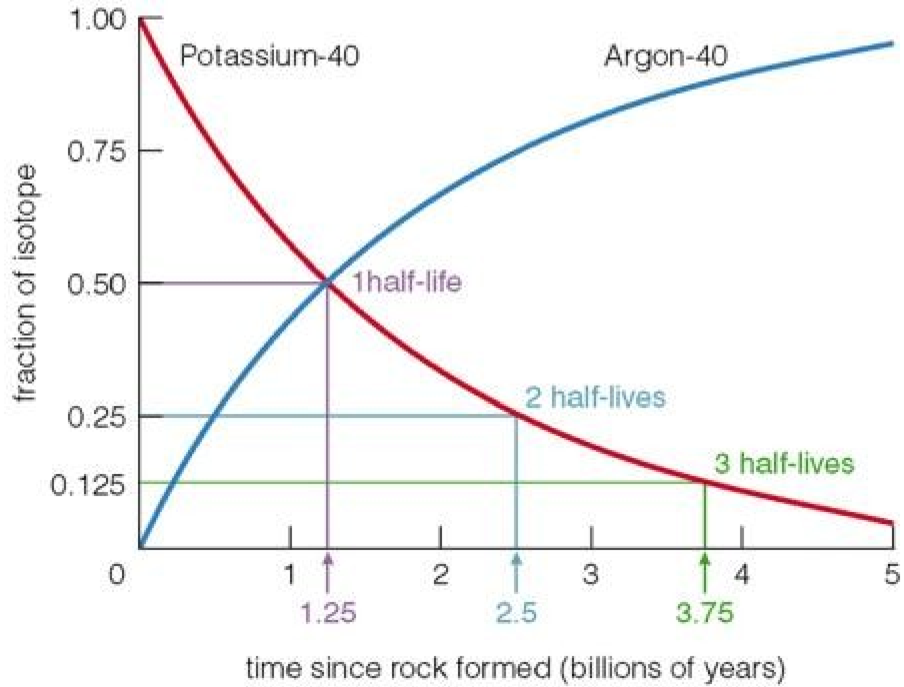
But Radioactivity was Ultimately the Solution



- Rutherford was on to something
- There are 339 isotopes of 84 elements found in nature
  - 269 are stable (calcium has 6 stable isotopes, Tin has 10)
  - 70 are radioactive
- In 1904, Rutherford suggested that the alpha particles released by radioactive decay of radium could be trapped in a rocky material as helium atoms.
  - One of the first rocks dated that way came back with a 40 million year age.
  - By the end of 1905 dates for 26 separate rock samples ranged from 92 to 570 million years

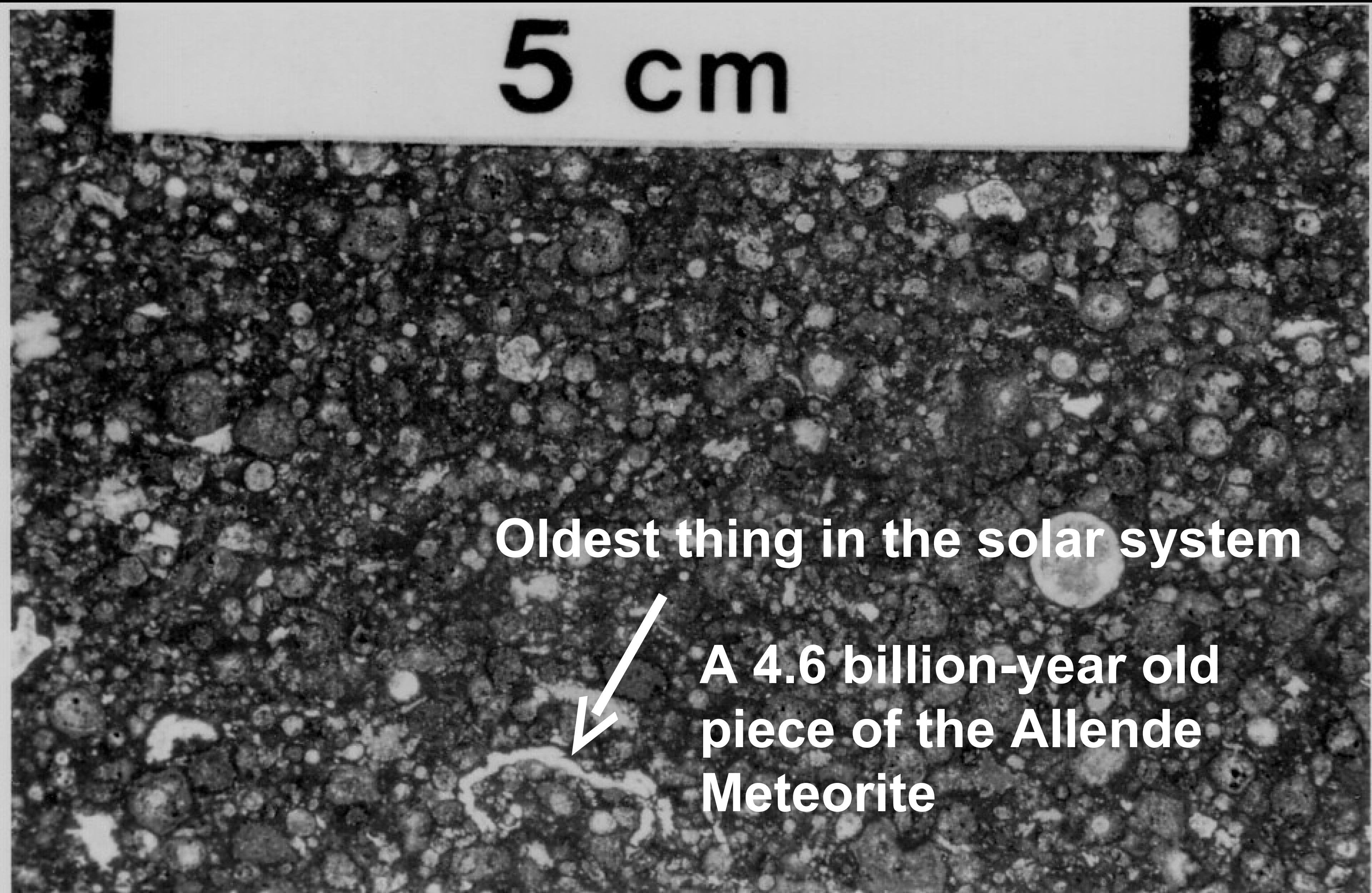
Radiometric Dating

- Elements have isotopes which are unstable i.e. **radioactive**.
- Take Potassium…0.011% of all Potassium is K-40, which is radioactive. It spontaneously changes in to Argon-40 in a process called **radioactive decay**.
- The time it takes half the amount of a radioactive isotope to decay is called its **half life**. In this case about 1.27 billion years

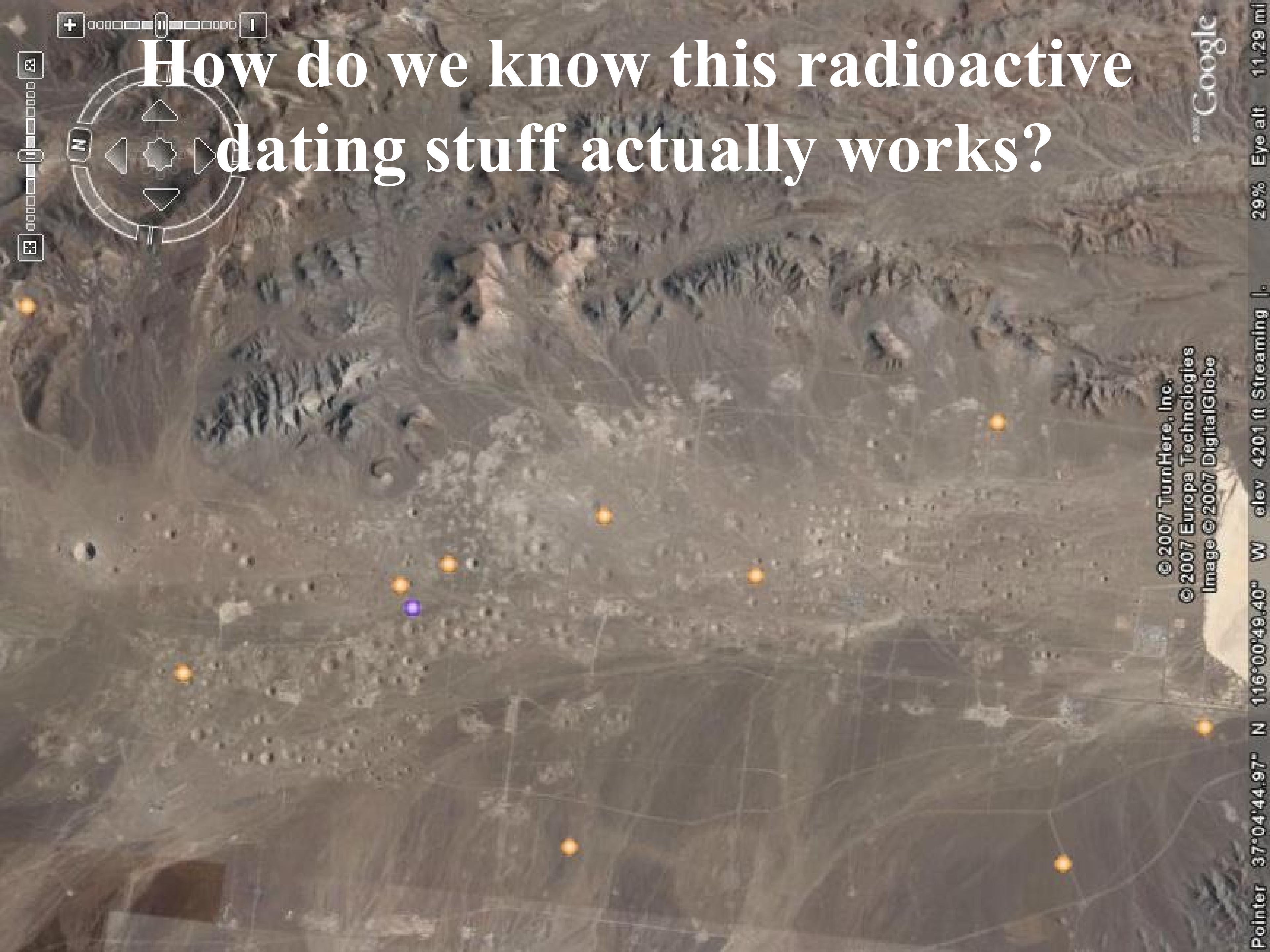


- By knowing rock chemistry, we choose a stable isotope which does not form with the rock…its presence is due solely to decay.
- Measuring the relative amounts of the two isotopes and knowing the half life of the radioactive isotope tells us the age of the rock.

How Old is the Solar System?



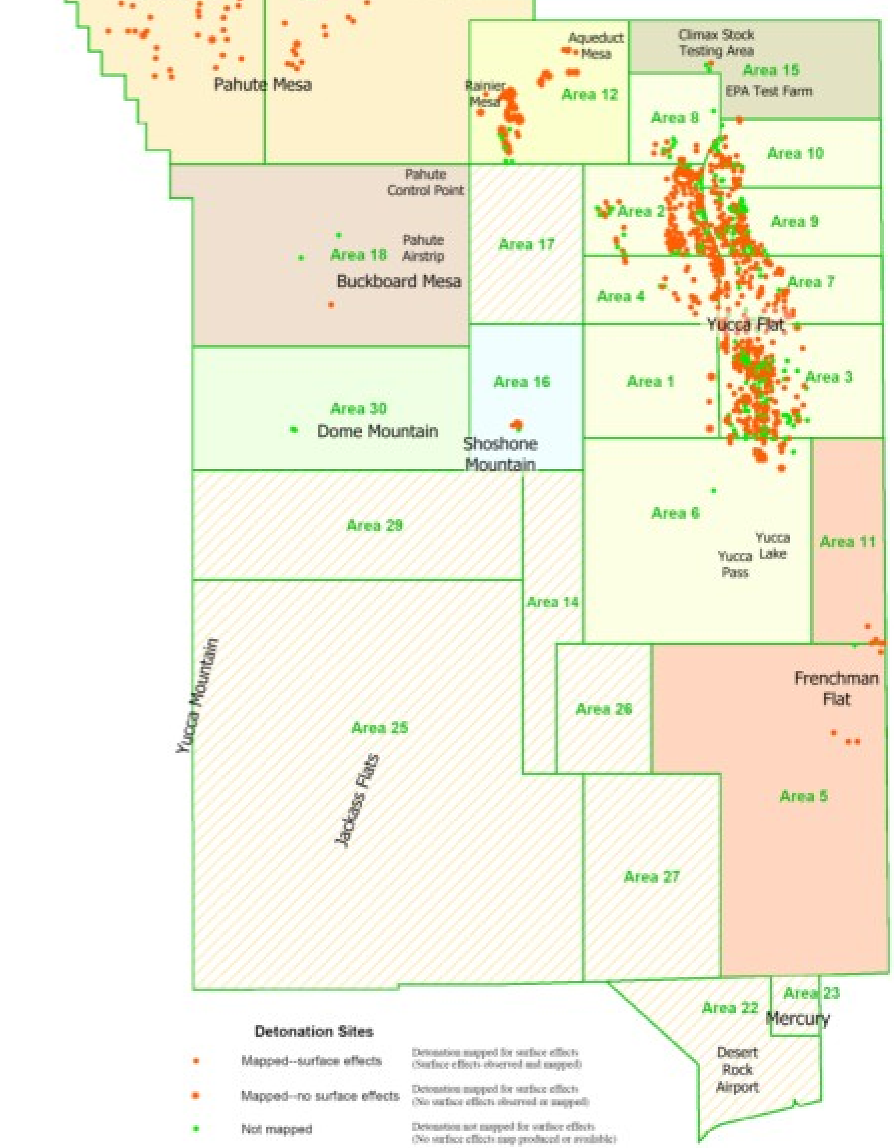
How do we know this radioactive dating stuff actually works?



Nevada Test Site

- 1,021 Nuclear detonations
  - 921 Underground
  - 100 Above Ground

Nevada Test Site



Operation Teapot- 1955

Ooops….

- **December 1970 accidental release**

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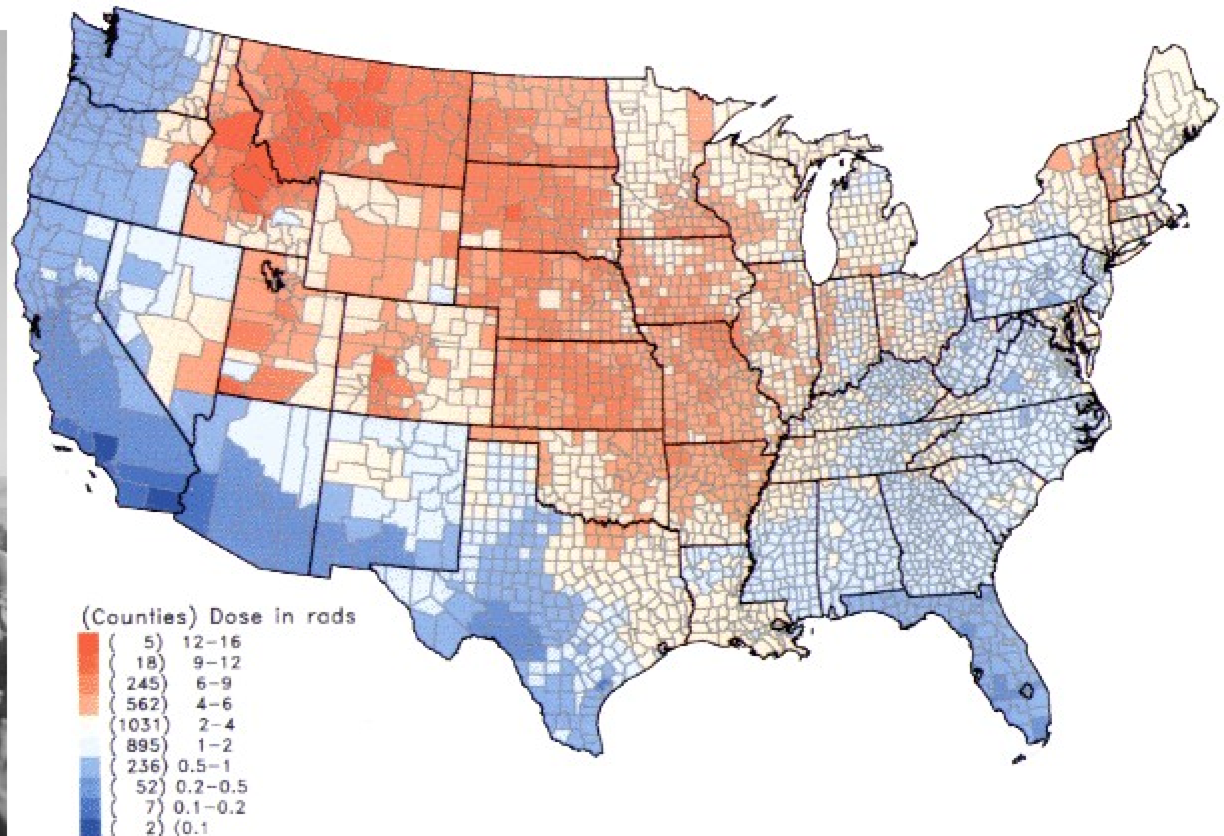

Common Dating Systems

- $K40 \rightarrow Ar40$ 1.27 Billion
- $U238 \rightarrow Pb206$ 4.468 Billion
- $U235 \rightarrow Pb207$ 0.704 Billion
- $Th232 \rightarrow Pb208$ 14.01 Billion
- $Rb87 \rightarrow Sr87$ 48.8 Billion
- $Sm147 \rightarrow Nd143$ 106 Billion
- $C14 \rightarrow N14$ 5730 years
- Errors are generally <0.5%

History of the Solar System

- 4.56 GY: Oldest meteorite dates
- -100,000 years: the solar nebula begins to collapse
- -100,000-10 My: Jupiter and the outer planets begin to form
- -10-100 My: Terrestrial planets form.
- 4.5 GY: Oldest rocks on the Moon
- 4.28 GY: Oldest rock on Earth (Zircons have been dated to 4.4 GY)
- Age of the universe: 13.75 ± 0.11 billion years