Session 32: Geological dating

Relative dating – the order of events, with at best a rough idea of timescale, especially of duration of events
Absolute dating – real measure of deep time to place geological events on an independently determined timescale.

Relative dating depends on use of principles of uniformitarianism (present is key to past), original horizontality (sedimentary layers are laid down flat) and superposition (newer layers on top of older). So essentially the realm of sedimentary deposits and structural events (folding, faulting etc). Also lava flows and large intrusions, but not sill intrusions. Then add in principle of lateral continuity (same bed would have continued sideways until it peters out) and cross-cutting relationships, and we can more or less work out the sequence of events in an essentially sedimentary context, including intrusions. But these in effect form just a sequence of 'before and after' relationships – no dates.

Rough timescales can be proposed based on estimated rates of deposition of sediments, and rates of evolution of living organisms, but then need to correlate events across large distances to establish a **stratigraphy.**

Nile delta: known thickness of sediment deposited since the Pharaoh Rameses II, 3000 years ago
> average rate of sedimentation = 1 metre in 1200 – 1500 years – but this an environment of rapid sedimentation, not typical, and ignores any intervening erosion and denudation

Varve counting in glacial melt-water lakes: in summer, rapid glacial melt, lots of rapid meltwater flow carrying glacial sediments. Coarser material settles rapidly to lake bed in summer, while finer material settles slowly during winter. Gives a sequence of lighter coarse bands and darker fine bands called *varves* (cf tree rings). Varying annual weather gave rise to distinctive patterns of bands enabling correlation over wide areas. Correlation across Scandinavia up to recent deposits of known date gives an absolute timescale for final retreat of Ice Age across Scandinavia over 16,000 yrs! BUT this hardly scratches the surface of an absolute timescale over geological time.

The same applies to **daily** growth rings in corals, which can be applied to fossil corals, and gives an absolute lifespan for the coral – but not an absolute date. However these fossil coral studies have revealed the change in day-length over geological time, from 21 hrs in the late Precambrian to 24 hrs now.

Sedimentary layers: Are we sure the beds are the right way up? Could they have been turned upside down by earth movements? Or stood on end, but which way round? Evidence from graded bedding (fining upwards), cross-bedding (top usually eroded), erosion surfaces (unconformities).

Fossil record: Same fossils in rocks in different places, a range of fossils in rocks in the same place – all pieced together to form a story with a qualitative timescale. Tracing the evolution of a phylum/class/order/family/ genus/species through the rock record. Which leads to **stratigraphical tables**!

Each fossil species exists for a limited period as evolution rolls on, so each rock 'zone' can be identified by its 'zone fossils'. A **biostratigraphic unit** is a thickness of strata characterised by one or more diagnostic zone fossils. In their turn, trilobites, brachiopods, graptolites, corals, ammonites and many others have served us well. Faunal assemblages at one place can give a narrow time zone in which all species present existed at the same time – easier for Pleistocene and Holocene fossils than for anything older.

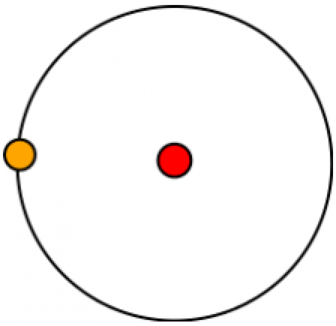
Use of DNA: evolution as the result of natural selection working on random mutations in species DNA, giving divergence over time into new species. But need to know the average generation time. This is the molecular clock method of dating. Count the differences and divide by rate of mutations – but do we really know the latter. Current debate about the date of splitting of hominins from orang-utans and from chimps is fraught with incorrect estimates when matched against known dates of sediments in which fossils are found. One day we may get more reliable agreement…. Only if good DNA records and good range of fossils, and then only over a few million years – not much use for geology.

Absolute dating by radioisotopes: reliable, reasonably accurate, uses rock samples themselves – don't need to find fossils, but we need to understand how it works.

Basics of the Universe: made from only 90 fundamental substances, the naturally occurring elements (plus some 20 artificial ones made in the last 100 years). The Periodic Table. All other materials are compounds of these elements – or mixtures of elements or compounds.

A Universe made of particles – the reference particle being the **atom,** the basic particle of an element. Use of symbols for atoms of elements – H for hydrogen, N for nitrogen, Na for sodium, Mg for magnesium, and so on. Vast numbers of atoms needed to make even the smallest visible piece of an element.

Particles inside particles – atoms themselves are made of smaller particles – for now, we need to consider three of these. Inside the hydrogen atom we find two of them:

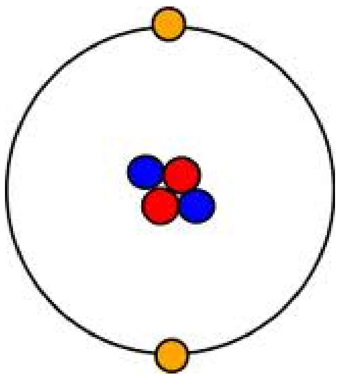


electron has 1/1840 of the mass of this atom, carries a – electric charge, and orbits the nucleus consisting of a…

proton, which has the rest of the mass of this atom and carries a + electric charge

All other elements have atoms with a third particle – the **neutron**.

As we run across the Periodic Table, row by row, each successive element has an atom with one more proton in it, as well as a number of neutrons.



In a neutral atom there is always an equal number of protons and neutrons. Example:

- element number 2 is helium
- its atom has 2 electrons in orbit
- in the nucleus are 2 protons
- but there are also 2 neutrons in the nucleus which help to glue the nucleus together

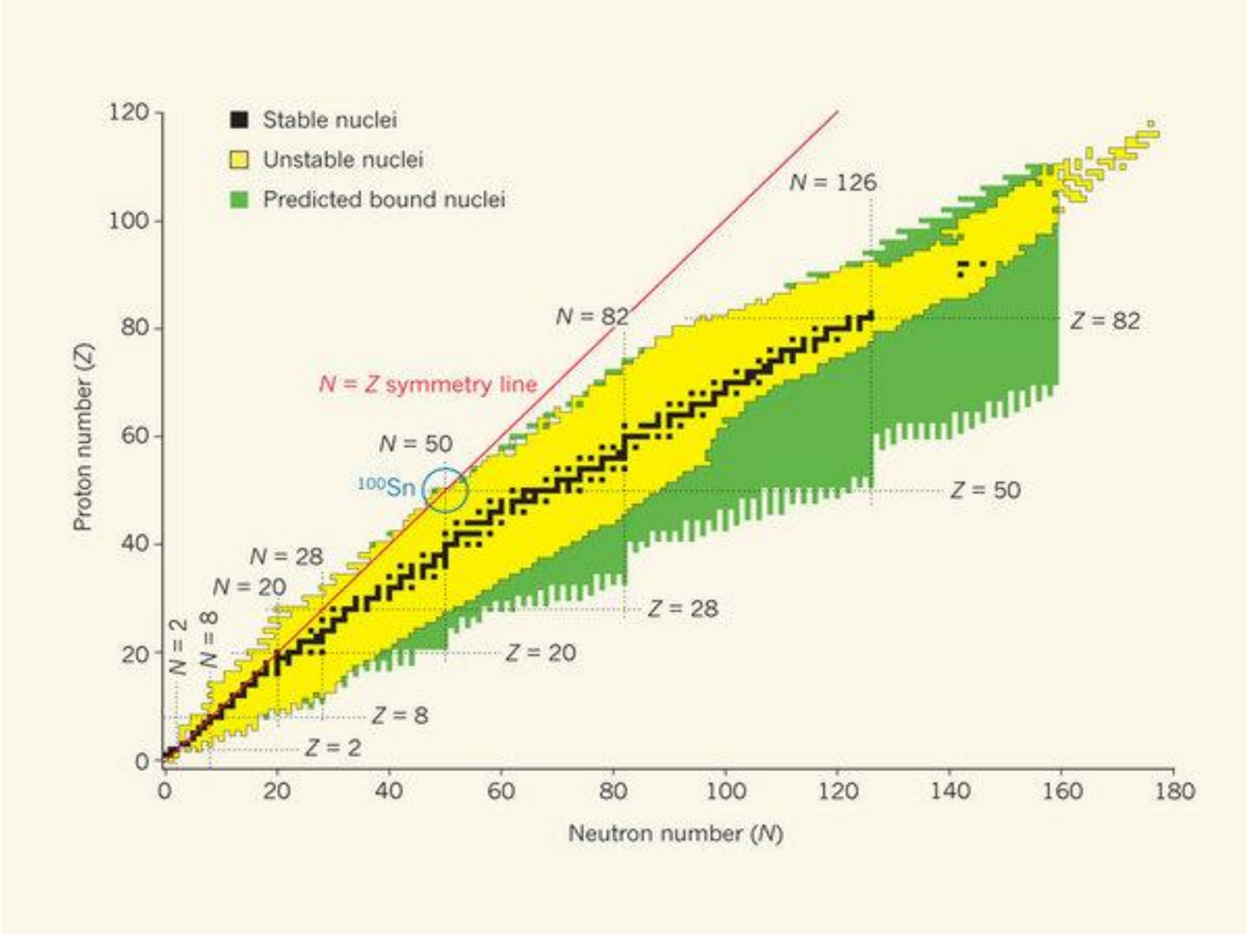
So to build an atom, we need:
for nucleus: protons: mass = 1, +ve charge   neutrons: mass = 1, no charge
in orbit: electrons: mass = 1/1840, -ve charge
Atomic number = no. of protons = place in Periodic Table   **Mass number** = sum of p's & n's
Let's build an atom of lead: atomic number of lead = 82; symbol for atom = Pb
So we need 82 protons for the nucleus, and 82 electrons in orbit. But how about the glue – the neutrons?

For this we need to check with the chart of the nuclides – those nuclei known to exist, or predicted as possible, whether stable or unstable. The stable nuclides are shown in black, the unstable known ones in yellow, and possible ones yet to be made in green. From the chart it appears we need 126 neutrons to supply enough 'nuclear glue' to 82 protons (check along y-axis to Z = 82, and read off the x-axis where you find one or more black sdots). Mass number for this atom = 82 + 126 = 208.

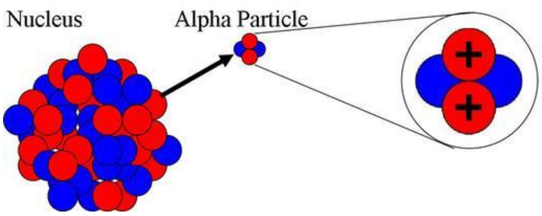
We have built one possible atom for lead, with 82 protons making it a lead atom, represented by $^{208}_{82}\mathrm{Pb}$.

We have built one possible atom for lead, with 82 protons making it a lead atom. The number of neutrons can be varied, providing less or more than enough 'nuclear glue'. Some of these occur naturally, others are man-made/artificial. These variants are called **nuclides.** A sample of an element made of atoms all of the same nuclide is called an **isotope.** Most nuclides are unstable – **radioactive.**

Too few neutrons = not enough glue, and bits can be ejected from the nucleus - mainly in the case of larger nuclides. OR a proton can turn into a neutron, ejecting a positron (positive electron) - smaller nuclides.



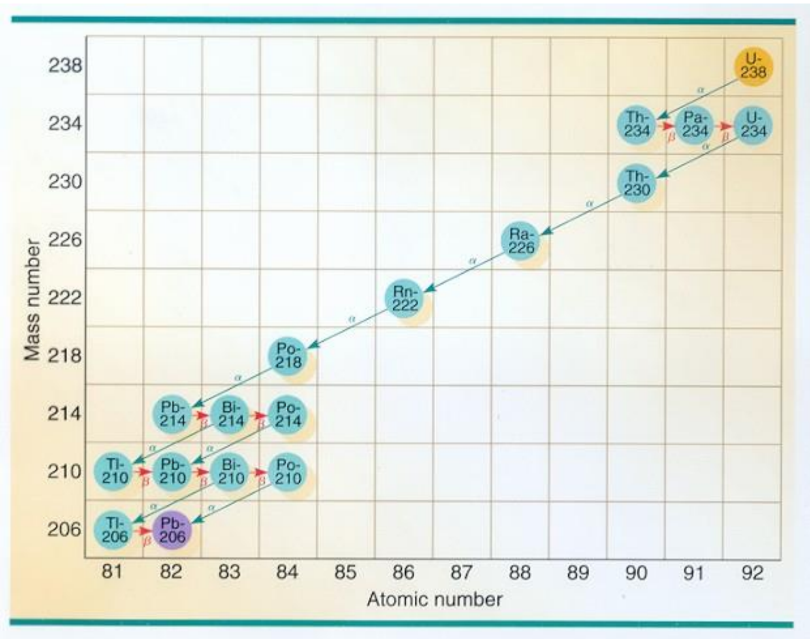
- The bit ejected from the nucleus is called an α-particle, composed of 2 protons and 2 neutrons…
- …which has the effect of turning this into a **nuclide of element with an atomic number two places lower**
- The α-particle itself is a helium nucleus



So from **uranium-238,** we get **thorium-234** and an alpha particle – follow this on the chart above.

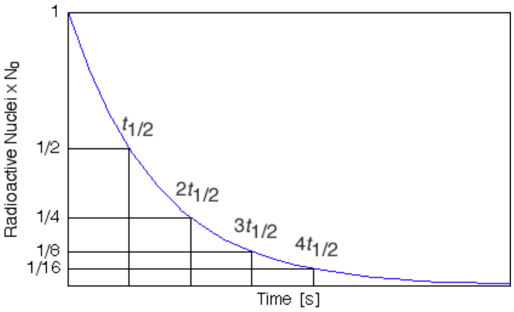
$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$$

But thorium-234 is itself unstable, and does something unexpected by turning a neutron into a proton and an electron. The result of that change is that the atomic number goes up by one unit (to element 91 – protoactinium/Pa), but the mass number is unchanged at 234.

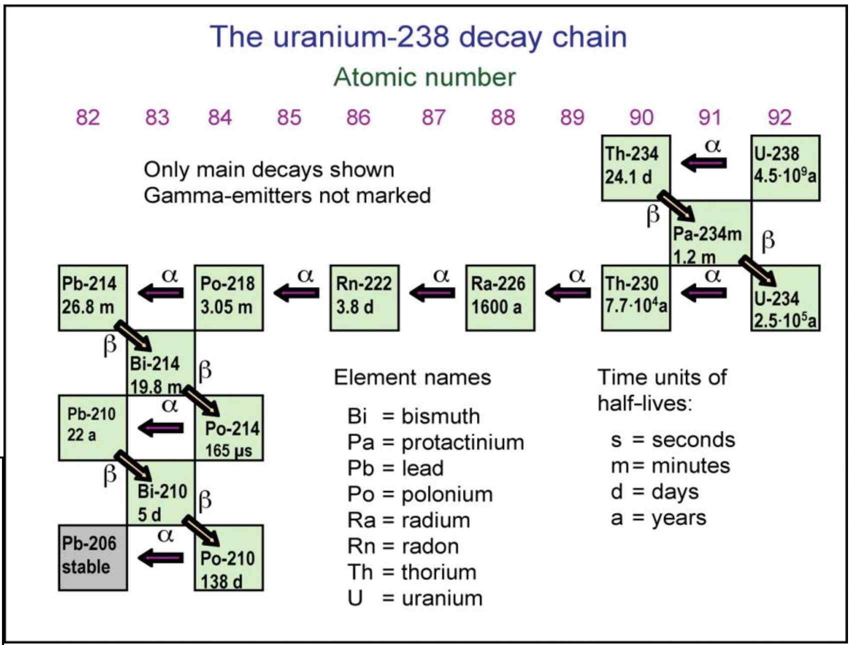


$^{234}_{90}Th \rightarrow ^{234}_{91}Pa + ^{0}_{-1}e$ However Pa-234 is also unstable, a sequence of instability that continues until a stable nuclide is reached – $^{208}_{82}Pb$, which has 124 neutrons.

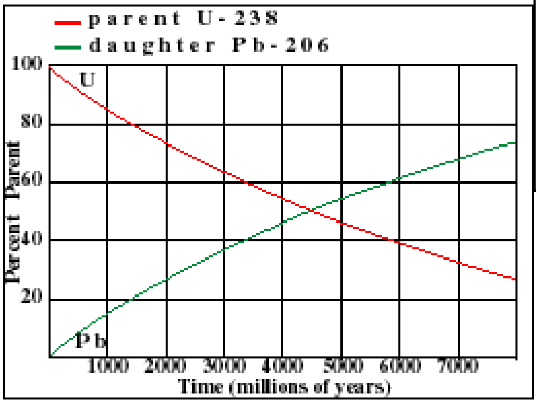
Timescale for radioactive decay: spontaneous, random, a chance event, unpredictable for any one nucleus, but with a **probability** that is different for every different nuclide. For any particular isotope there is a characteristic time for half of the unstable nuclei present to decay – the **half-life**, a reliable constant property of that isotope.



Applying this to the U-238 decay series:



U-238 is by far the longest lived member of this series, $t_{1/2} = 4.5 \times 10^9$ years (4.5 Ga) about the same as the age of the Earth!



So the ratio of U-238 : Pb-206 in a rock should tell us the age of that rock, provided there was no Pb-206 in the rock at the start, or acquired by another process since.

Pb-206 is an isotope that occurs naturally as one of the normal isotopes of lead. Most of lead atoms occurring naturally are Pb-208, which does not form as a result of radioactive decay of anything else!

So if we know the natural Pb-206:Pb-208 ratio, we can establish how much of the Pb-206 was the result of radioactive decay of U-238. We can date rocks – if they contain uranium minerals! <u>**Radiometric dating.**</u>

Useful decay series for dating rocks: U-238 → Pb-206 $t_{1/2}$ = 4.467 Ga ⎫ And combining these two gives a
U-235 → Pb-207 $t_{1/2}$ = 704 Ma ⎭ third method, using Pb-206:Pb-207 ratio

Rb-87 → Sr-87 $t_{1/2}$ = 48.8 Ga

K-40 → Ar-40 $t_{1/2}$ = 11.93 Ga

Sm-147 → Nd-143 $t_{1/2}$ = 106 Ga

Minerals containing these isotopes:

Parent	Half-life (10^9 yrs)	Daughter	Materials Dated
^{235}U	0.704	^{207}Pb	Zircon, uraninite, pitchblende
^{40}K	1.251	^{40}Ar	Muscovite, biotite, hornblende, volcanic rock, glauconite, K-feldspar
^{238}U	4.468	^{206}Pb	Zircon, uraninite, pitchblende
^{87}Rb	48.8	^{87}Sr	K-micas, K-feldspars, biotite, metamorphic rock, glauconite

<u>Rb-87 > Sr-87</u> used for ages 10 Ma and over for

- Formation of igneous rocks from cooling magma
- Dates of metamorphic events
- Dates of sediment deposition that includes glauconite

<u>K-40 > Ar-40</u> used for ages 100 ka and over for similar applications as for Rb-Sr BUT note problems due to Ar being a gas that can be lost

<u>U-238 > Pb-206</u> for ages over 20 Ma; particularly useful for granites

<u>Pb-206:Pb207</u> for ages over 400 Ma – most useful way of dating Earth's oldest rocks and meteorites

Carbon-14 Dating

$t_{½}$ = 5730 years – is this really useful for geological dating??? Yes, for Pleistocene! For foregoing radiometric dating methods, $t_{½}$ is generally so large that the age of a rock is less than a few half lives – not accurate enough.

About 10 half lives can go by, and still produce detectable activity > range a bit more than 50,000 years. Can go back further using a different technique – mass spectrometry > ~70,000 yrs

Production of C-14:

With such a short half life, the amount in the Earth system must be under constant renewal – otherwise there would not be any! Cosmic rays (particles from Sun and rest of Universe) enter atmosphere at high energy. High energy particles collide with nitrogen atoms in atmosphere; these collisions occasionally produce neutrons:

$$^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}p \qquad \text{then} \quad ^{14}_{6}C + O_2 \rightarrow ^{14}_{6}CO_2$$

which mixes freely with $^{12}_{6}CO_2$ and a tiny proportion of $^{13}_{6}CO_2$ in the atmosphere.

Present ratio $^{12}_{6}CO_2 : ^{14}_{6}CO_2 = 10^{12}: 1$, in which ratio the isotopes are taken up by photosynthesis into the biosphere. Once into the biosphere, the $^{14}_{6}C$ cycles through respiration, feeding and further photosynthesis, so that while an organism is alive, $^{12}_{6}C : ^{14}_{6}C$ remains constant in the organism.

But when the organism dies, feeding and photosynthesis no longer replenish losses by radioactive decay, so $^{14}_{6}C$ decays in line with the half life of 5730 years.

$$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{1}_{-1}e$$

By measuring the ratio of $^{12}_{6}C : ^{14}_{6}C$ in the remains of the dead organism, a date for the death of the organism BP can be calculated.

BUT BEWARE: assumptions in this may not be valid. Especially the assumption that the ratio $^{12}_{6}CO_2 : ^{14}_{6}CO_2$ was the same when the organism died as it is now! Also that losses of carbon in the remains after death did not discriminate between the isotopes, nor any carbon added from circulating groundwater. So the C-14 timescale needs calibrating from other sources!

Tree-ring dating – recent timber for past 1000 years, bristlecone pine up to 6000 years!

Bristlecone pines are the oldest living organisms, with a life span ~5000 years. The characteristic sequence of tree rings responding to annual climate variations stretches back 5000 years in living trees. Cross matching wood from dead trees enables the record to be extended past 6000 years.

C-14 dating of the wood in selected rings enabled cross-correlation with C-14 dates, which show close matches for last 2500 years, but at 6000 years the error is 800 years.

Hence the use of calibration curves from other sources to obtain more reliable dates. So more useful for archaeology than geology, but of enormous importance for dating the recent Pleistocene and Holocene.