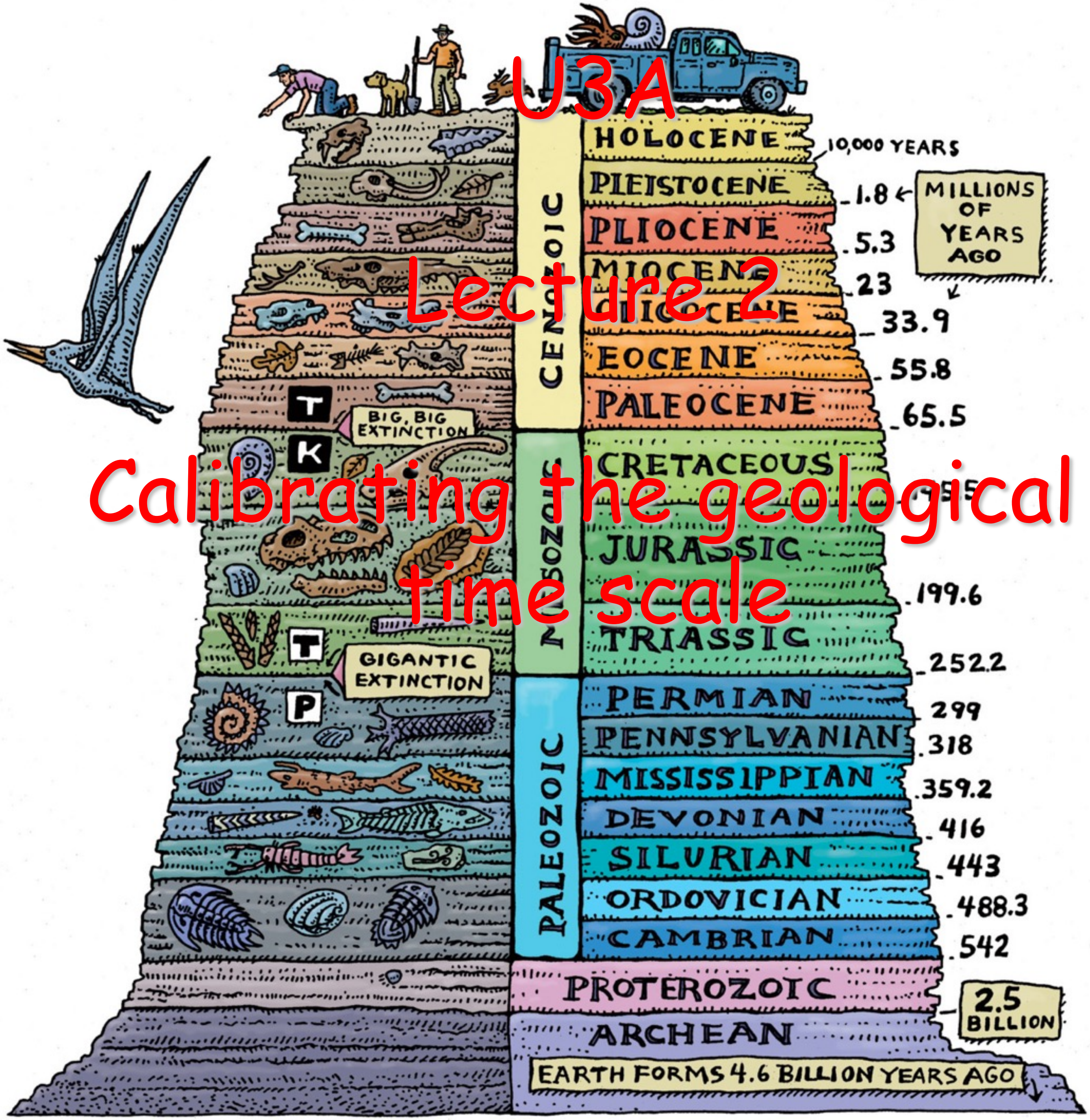
U3A

Lecture 2

Calibrating the geological time scale



The relative Geological time scale

Eon	Era	Period
Phanerozoic	Cainozoic	Quaternary Tertiary
	Mesozoic	Cretaceous Jurassic Triassic
	Palaeozoic	Permian Carboniferous Devonian Silurian Ordovician Cambrian
PRE-CAMBRIAN	Proterozoic Archaean	

Geological timescale

- Detailed timescale only evident in Phanerozoic that represents only 545myr of geological time beginning when there was an explosion in life forms that enabled us to use fossils for dating
- in contrast the Precambrian represents 7/8 of geological time
- reason for lack of sub-division in Precambrian → inability to use fossils and faunal succession
- fossils of bacteria date back more than 3.7billion years, but they were microscopic organisms that changed little over thousands of millions of years

Early attempts at calibration

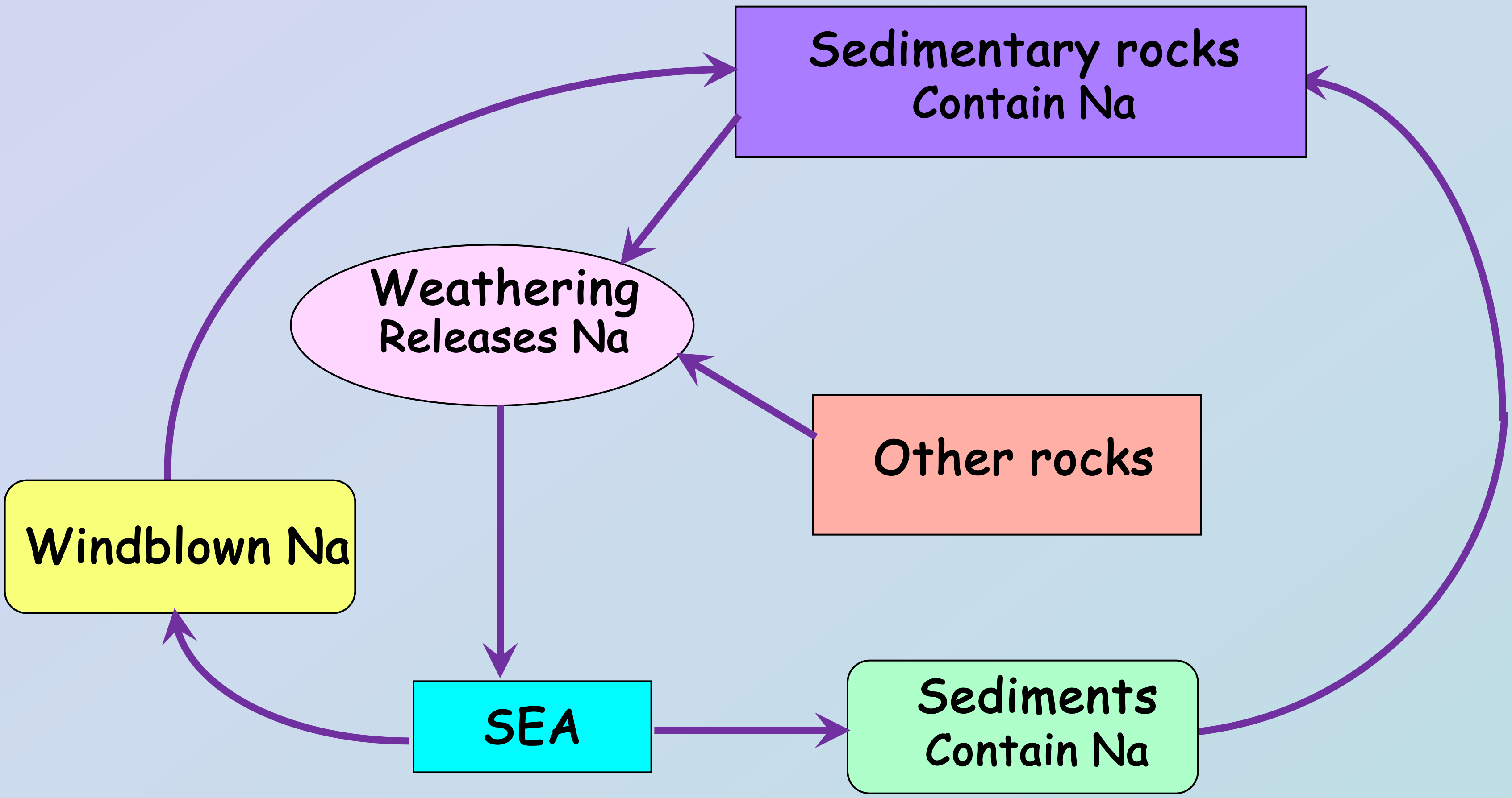
- By the end of the 19th century, attempts were being made to quantify the timescale applying Principles of Uniformitarianism

- John Joly, 1899
  - Irish physicist
  - estimated age of oceans to be 90 million years from rate of salt entering the sea
  - based on assumption that ocean → originally fresh water → salt has accumulated over geological time
  - rivers acquire salt from weathering of rocks → added continuously to the sea
  - serious flaws in his calculations

Flaws in Joly's calculations

- Joly assumed → salt is never removed from the ocean → massive beds of salt have formed through evaporation of seawater e.g. whole of Mediterranean dried up ~5.5Ma → became desert depositing thick salt deposits → underlie Mediterranean
- Mediterranean → subsequently dried up a number of times
- thick Permian salt deposits underlie large areas of Europe → ancient Zechstein Sea dried up several times
- other ways and places that salt is removed from the sea → sodium cycle → basic assumptions of Joly are flawed → but supported the belief in a many millions of years old Earth

The sodium cycle



Sedimentary rocks
Contain Na

Weathering
Releases Na

Other rocks

Windblown Na

SEA

Sediments
Contain Na

Estimation based on rates of sedimentation

- Estimation of geological time based on modern rates of sedimentation and measuring the thickness of sedimentary piles

- failings using this approach:

  (1) does not account for rocks that are not sedimentary

  (2) no account made for unconformities → major periods of time missing from the geological record → there was no way of measuring time gap

- estimates (17- 1584myr) still support a very old age for the Earth

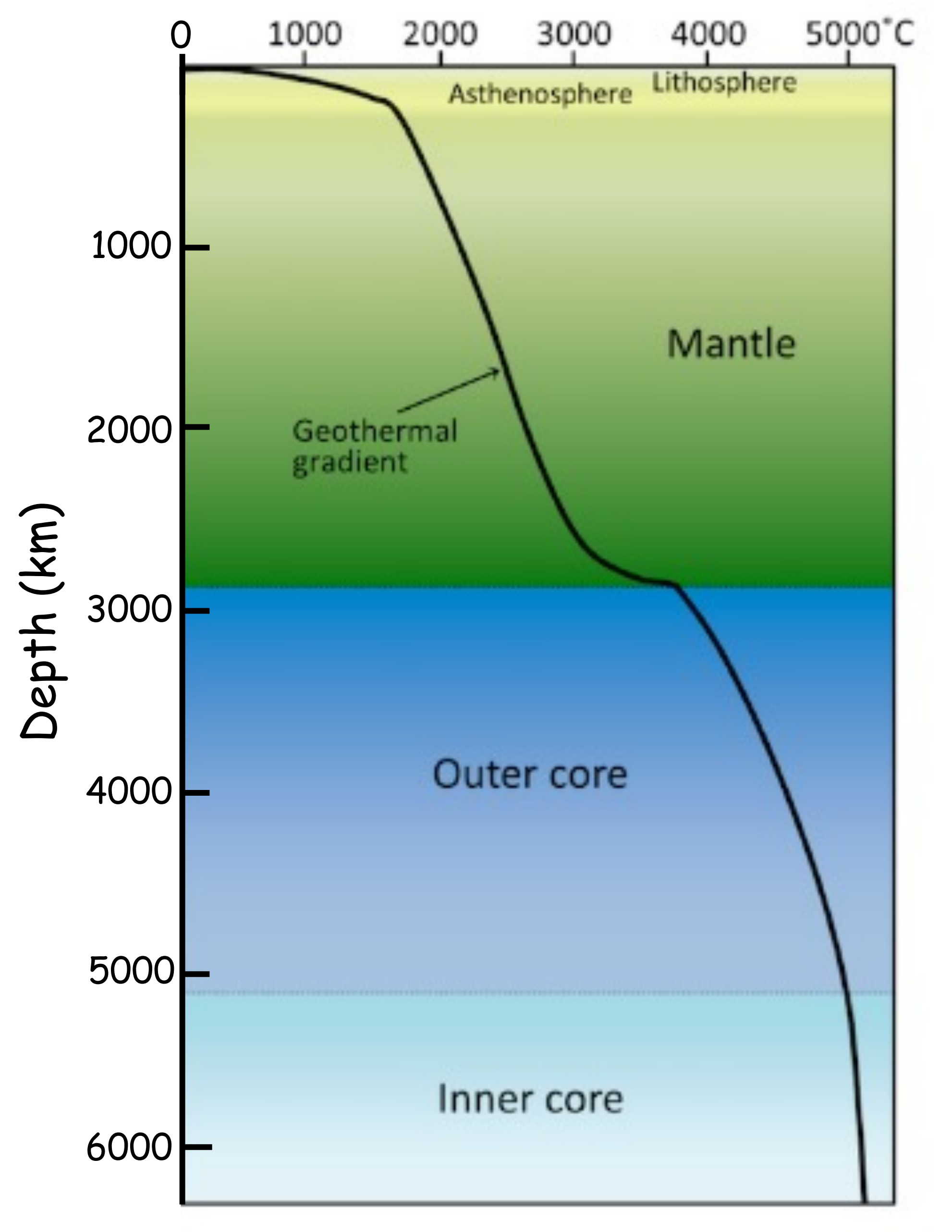
Estimates of the age of the Earth based on rates of sedimentation

Date	Author	Maximum thickness (in feet)	Rate of deposition (years/ft)	Time (millions of years)
1860	Phillips	72,000	1,332	96
1869	Huxley	100,000	1,000	100
1871	Haughton	177,200	8,616	1,526
1889	Croll	12,000	6,000	72
1890	de Lapparent	150,000	600	90
1892	Wallace	177,200	158	28
1893	McGee	264,000	6,000	1,584
1883	Upham	264,000	316	100
1895	Sollas	164,000	100	17
1908	Jolly	265,000	300	80
1909	Sollas	335,000	200	67

Lord Kelvin

- Lord Kelvin → leading Victorian-age physicist at end of 19th century
- using erroneous assumptions → calculated the age of Earth to be no younger than 25myr and no older than 100myr
- estimate based on loss of heat from Earth → presumed that Earth was originally molten → cooled over time → assumed no other source of heat other than residual heat
- Henri Becquerel demonstrated otherwise → showed that radioactive decay was exothermic adding heat to Earth's interior we now know that the Earth's heat budget is in a steady state

Geothermal gradient



Radioactivity as a natural clock

- The discovery of radioactivity

  - Becquerel 1896

  - recognised that certain elements decay over time to form other elements

  - demonstrated that radioactive decay is an exothermic process evolving heat

Henri Becquerel

  - heat evolved by this process balances heat loss → Earth's heat budget → in steady state

  - knowledge of radioactive decay led to radiometric dating

Atoms and isotopes

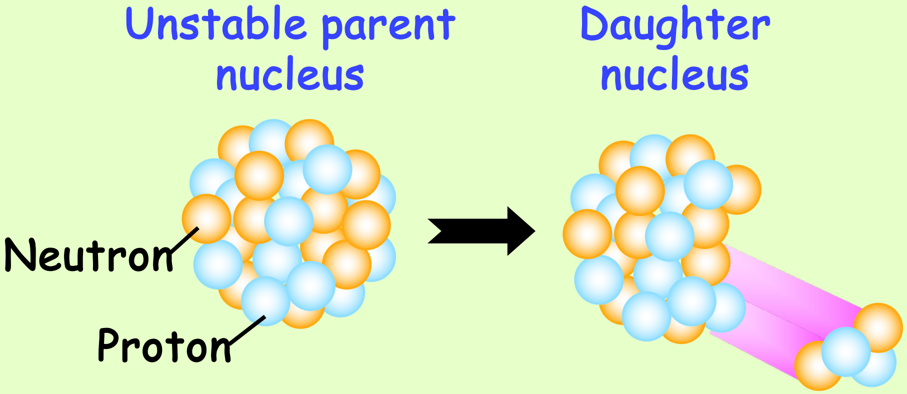
- Nucleus of atom is composed of protons (+ve charge) and neutrons (no charge)
- positive charge neutralised by electrons (-ve charge)
- number of protons in nucleus (atomic number) determines the atomic species e.g. Uranium has 92 protons in nucleus

  → atomic number = 92
- mass number is the number of protons + neutrons in nucleus
- isotopes are atomic species with the same number of protons (same atomic number) but different mass number (different number of neutrons) e.g. ^{238}U, ^{235}U, ^{234}U

Radioactive decay

- Radioactive and stable isotopes
  - a radioisotope is an atom with an unstable nucleus that spontaneously decays to form a different nuclide
  - a stable isotope is one that does not undergo spontaneous radioactive decay e.g. ^{34}S, ^{36}S
- radioactive parent atoms $\xrightarrow{\text{decay}}$ daughter products
- radioactive decay rates → exponential (characterised by half-life)
- three common decay modes form basis for most radioactive dating

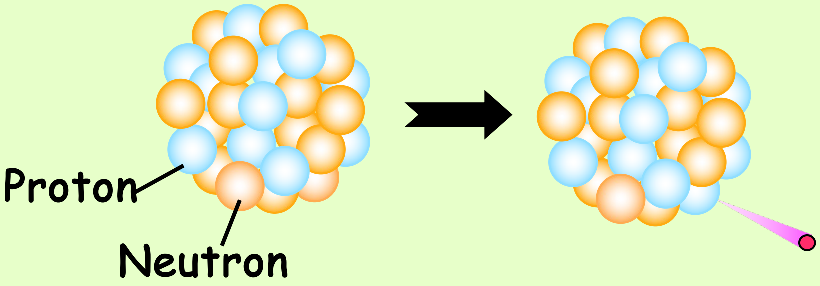
Radioactive decay



Atomic number
→ 2 fewer
Atomic mass
→ 4 fewer

(α particle emission)

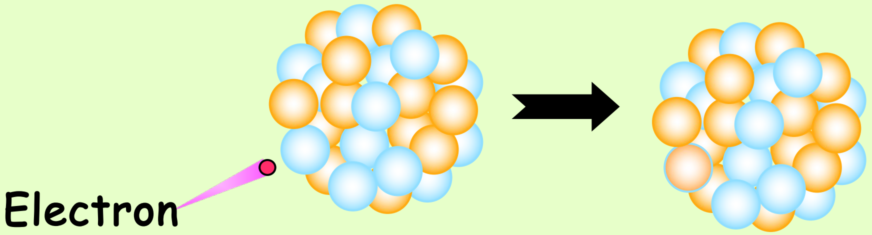
Alpha decay



Atomic number
→ 1 higher
Atomic mass
→ no change

β particle emission
(electron from a neutron)

Beta decay

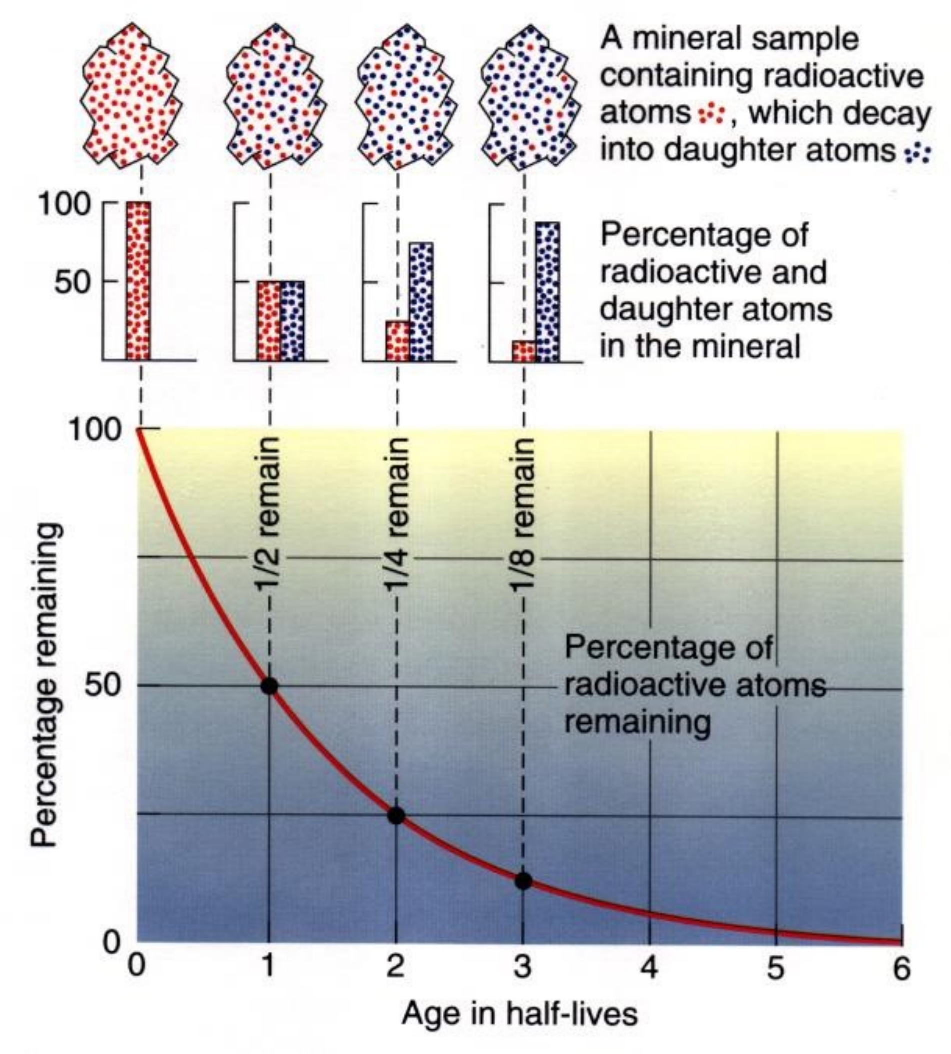


Atomic number
→ 1 fewer
Atomic mass
→ no change

Electron capture

Exponential decay and half-life

Radioactive decay can be described as exponential decay and is characterised by half life



Radioactive decay in minerals

- By measuring the ratio of daughter atoms to parent atoms, and calculating the number of half lives it is possible to estimate the time that has elapsed since decay began

- radioactive systems that are most useful for geological dating are those with long half lives

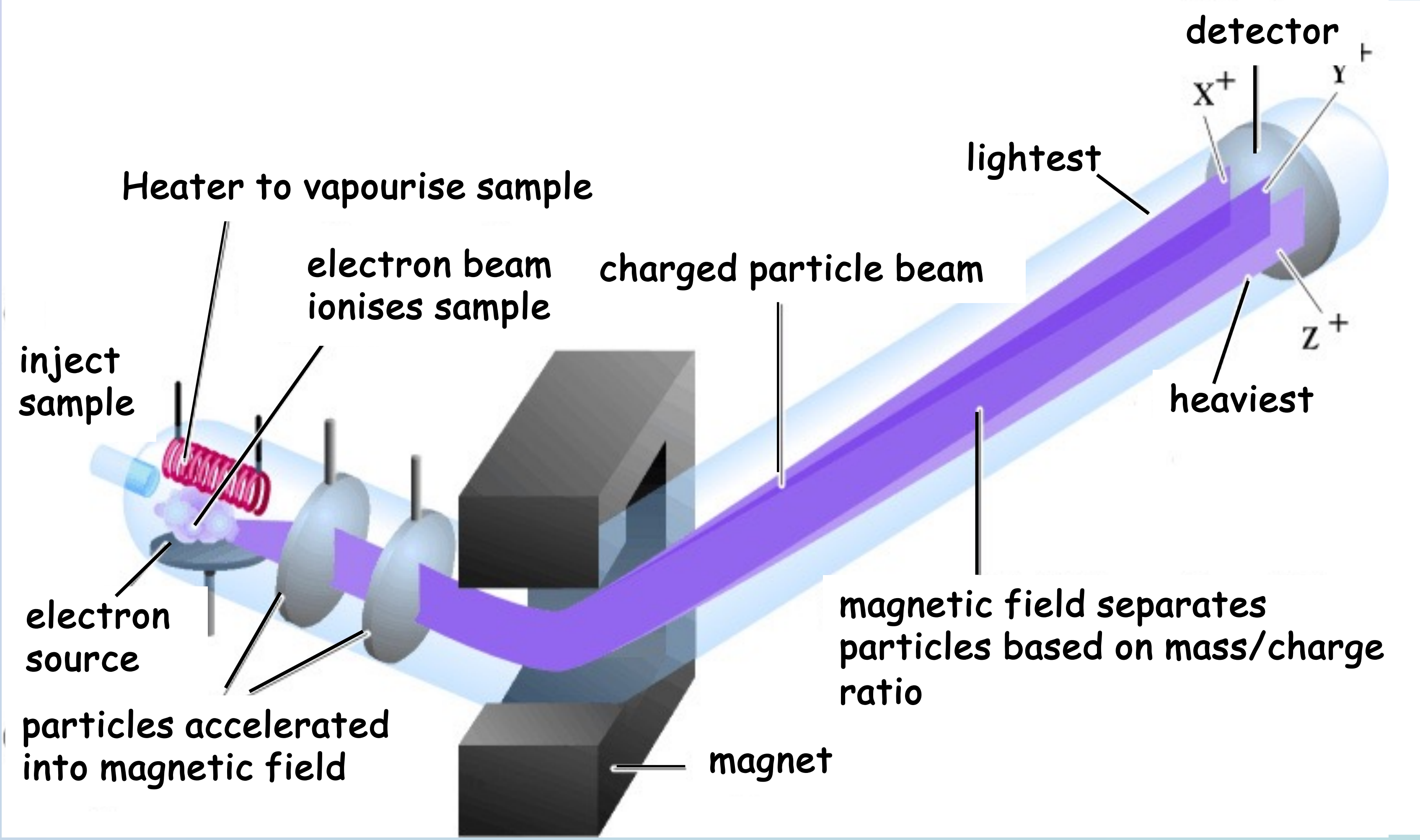
- some minerals geochemically select only certain elements to include in their structure when they form e.g. zircon ($ZrSiO_4$) includes U but not Pb
- any Pb detected in chemical analysis of a zircon must be derived from radioactive decay of U

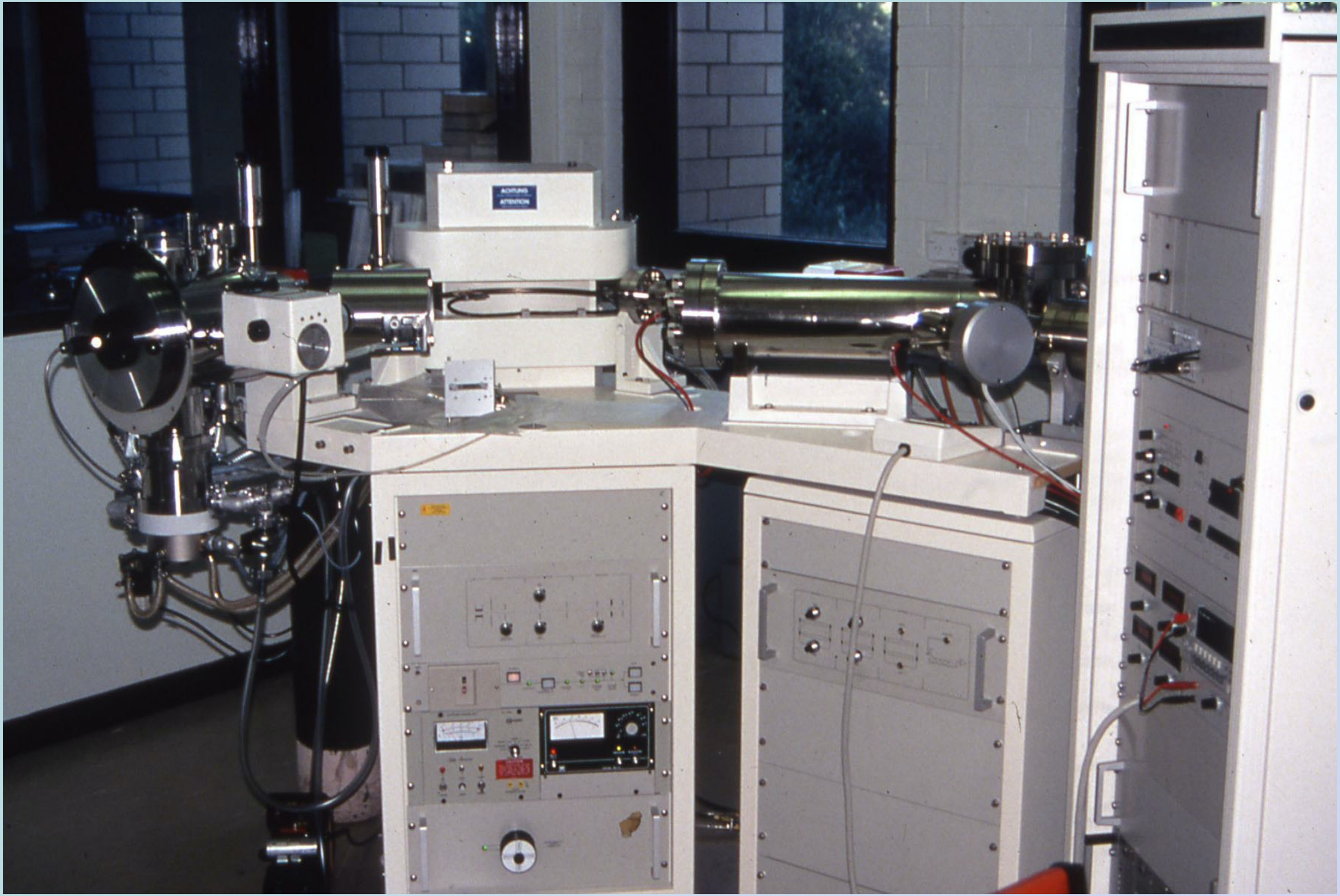
Radioactive decay in minerals

- In a mineral that at time zero has a certain number of radioactive parent atoms but no daughter products
- after 1 half life 50% of original parent atoms would have decayed to form daughter products
- if our sample contains 50% parent isotopes and 50% daughter products → zircon age = half life age
- this is true because there were no daughter products in the mineral when it formed
- if daughter products are present at formation, another strategy must be used to calculate an age

Mass spectrometry

- Ratios of isotopes are measured using mass spectrometry





Finnegan MAT-262 Thermal Ionisation Mass Spectrometer,
Earth Sciences, Department La Trobe, University

Dating geological samples

- Radiocarbon dating
  - Developed in 1940s, much publicised
  - $^{14}N \xrightarrow{\text{Cosmic rays}} {}^{14}C$
  - living organisms exchange ^{14}C with atmosphere
  - on death, exchange with atmosphere ceases → ^{14}C decays to form ^{12}C → decrease in $^{14}C/^{12}C$
  - Half-life = 5730years
  - after ~40,000years → essentially no ^{14}C left in sample

* Popular in archaeology → rarely relevant to geology

Dating geological samples

- Uranium-Thorium-Lead methods

Decay through a complex chain of α decays and ϒ emissions

^{238}U → ^{206}Pb decay chain Half-life = 4,468 Ma

^{235}U → ^{207}Pb decay chain Half-life = 704 Ma

^{232}Th → ^{208}Pb decay chain Half-life = 1,410 Ma

- Used for measurements on:

- U-Th-bearing minerals e.g. zircon, sphene, monazite $(Ce,Th,La)PO_4$

- Uranium ore minerals e.g. uraninite, pitchblende

- modern mass spectrometers → extremely sensitive → accurate to >10 decimal places with accuracy of ~ 0.1%

More geological dating methods

- Potassium-Argon method

$^{40}K \rightarrow {}^{40}Ar$ Electron-capture Half-life = 1,250Ma

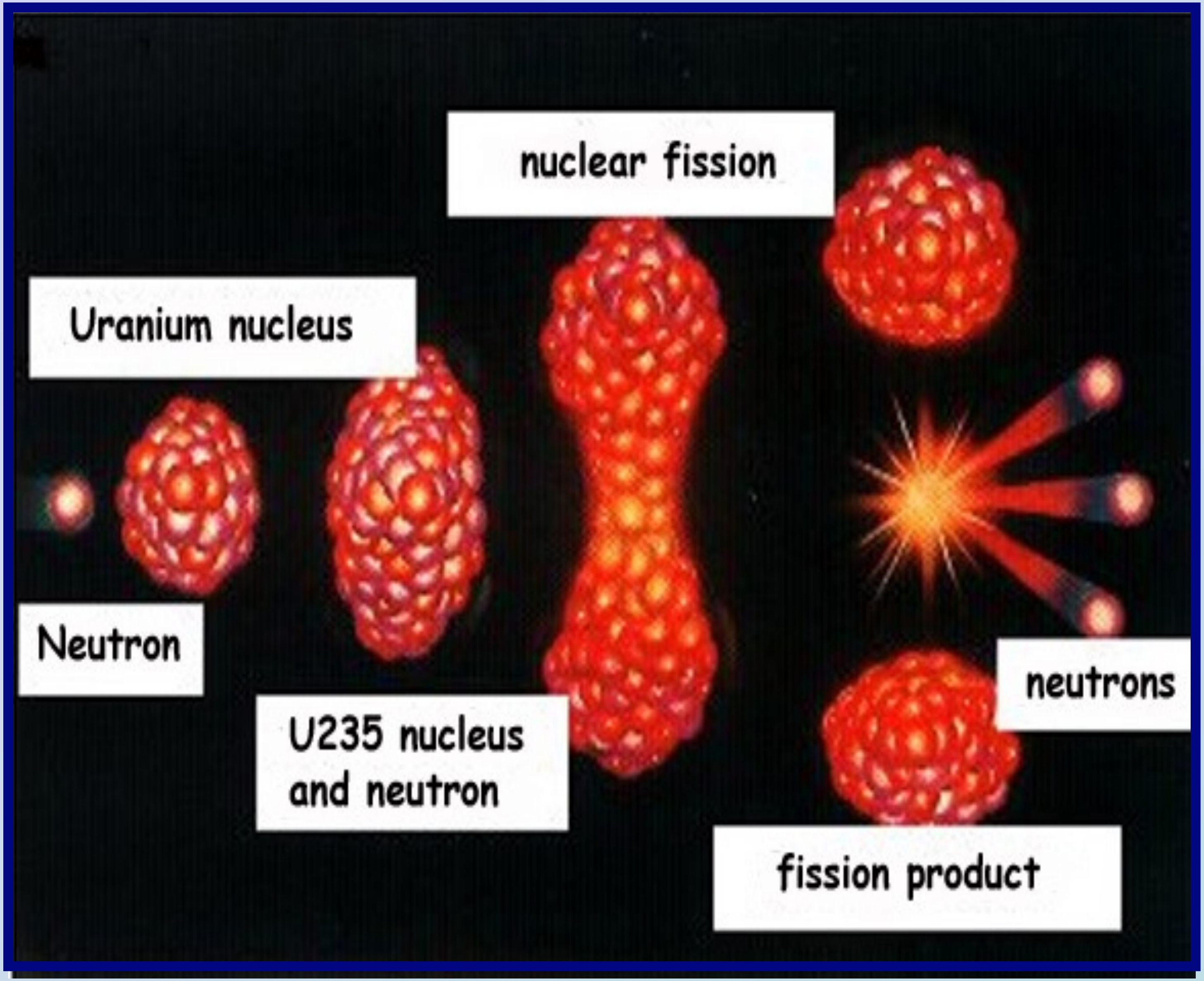
- Popular technique for dating younger volcanic rocks
- used for: micas, feldspars, hornblende, whole rock samples
- particularly useful in dating volcanic rocks that have a clear beginning (mainly >50,000yr)

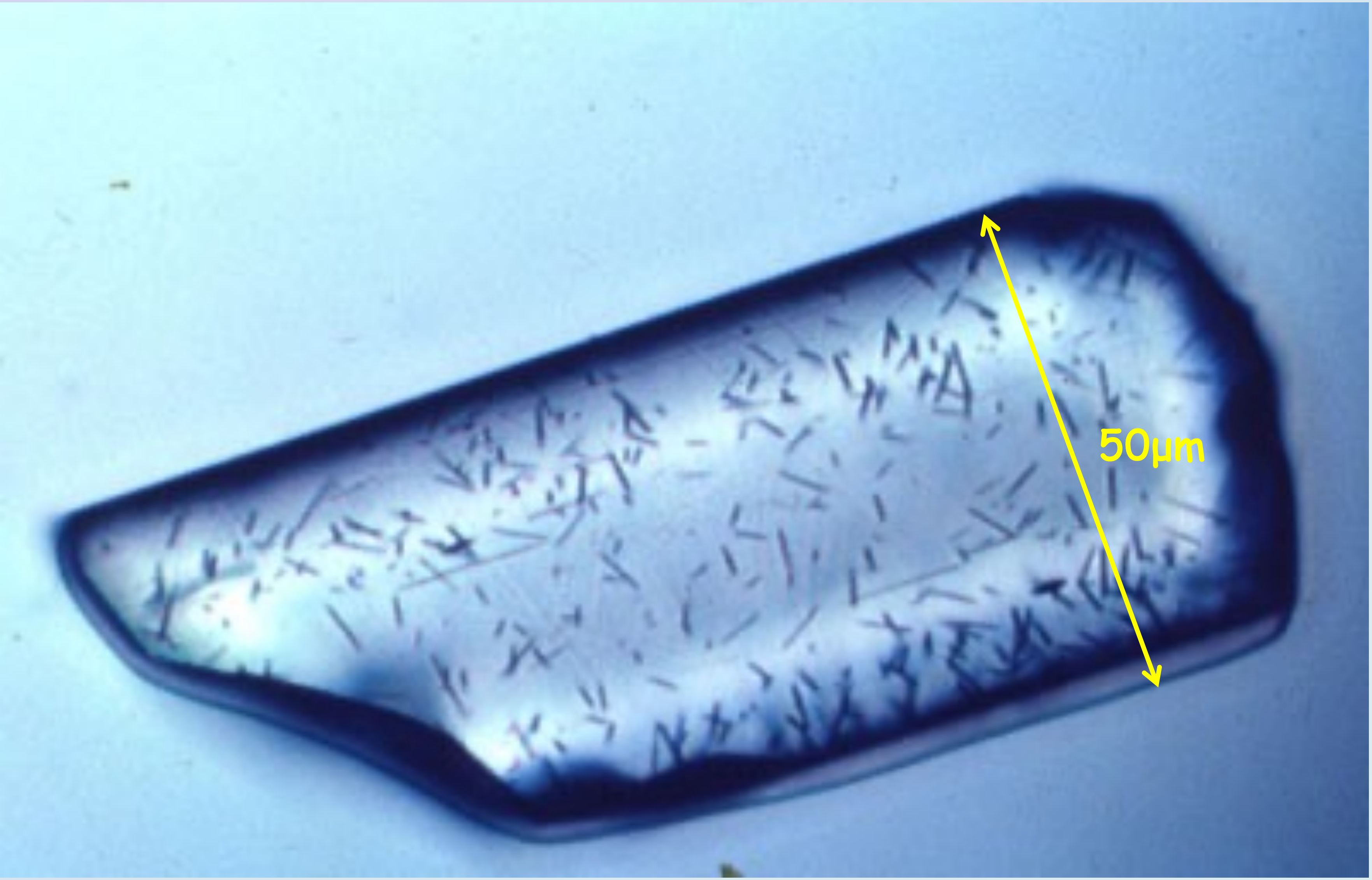
Hawaiian eruption

Fission track method

- Measured by optical microscopy
- spontaneous nuclear fission of ^{238}U About 1 in 10million U atoms decay violently disintegrating into two halves → leave a track through the mineral
- number of tracks → function of U content and age
- Half-life = 10^{16} years → small amount of decay → sensitive detection
- used for: apatite, zircon, sphene
- counting number of tracks (function of age and U content) → estimate age of mineral

Nuclear fission tracks





Fission tracks in zircon crystal

(surface of zircon is polished and etched)

Initial condition

- Not all rocks and mineral species have a clear isotopic origin
- In applying radioactive dating, the initial amount of the daughter isotope either:

must be zero e.g. K-Ar dating, some U-Pb methods, fission-track dating

OR

must be able to be measured e.g. Rb-Sr can be measured by various manipulations of the data e.g. analysis of coeval samples

Rubidium –Strontium method

- Rb and Sr occur in most rocks in trace amounts
- Rb concentrates in K-rich rocks and minerals, Sr concentrates in Ca-rich rocks and minerals

$^{87}Rb \rightarrow {}^{87}Sr$ beta-decay Half-life = 48,800 Ma

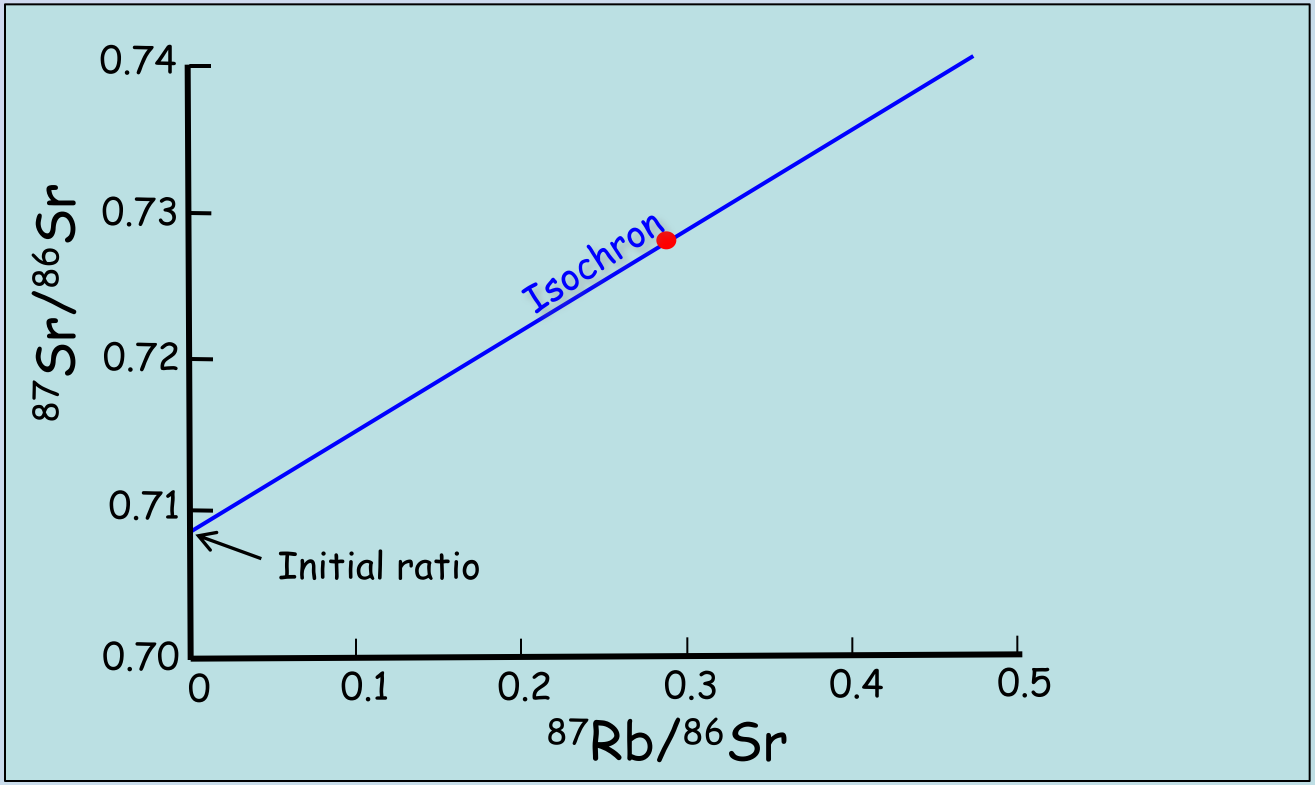
- used for dating: micas, feldspars, whole-rock samples
- measured by mass spectrometry
- a Rb-Sr isochron diagram enables dating of material and allows determination of initial $^{87}Sr/^{86}Sr$ ratio of parent melt
- isochron → line on isotope ratio diagram containing analyses of rocks and/or minerals that are coeval

Rubidium-Strontium isochron diagram

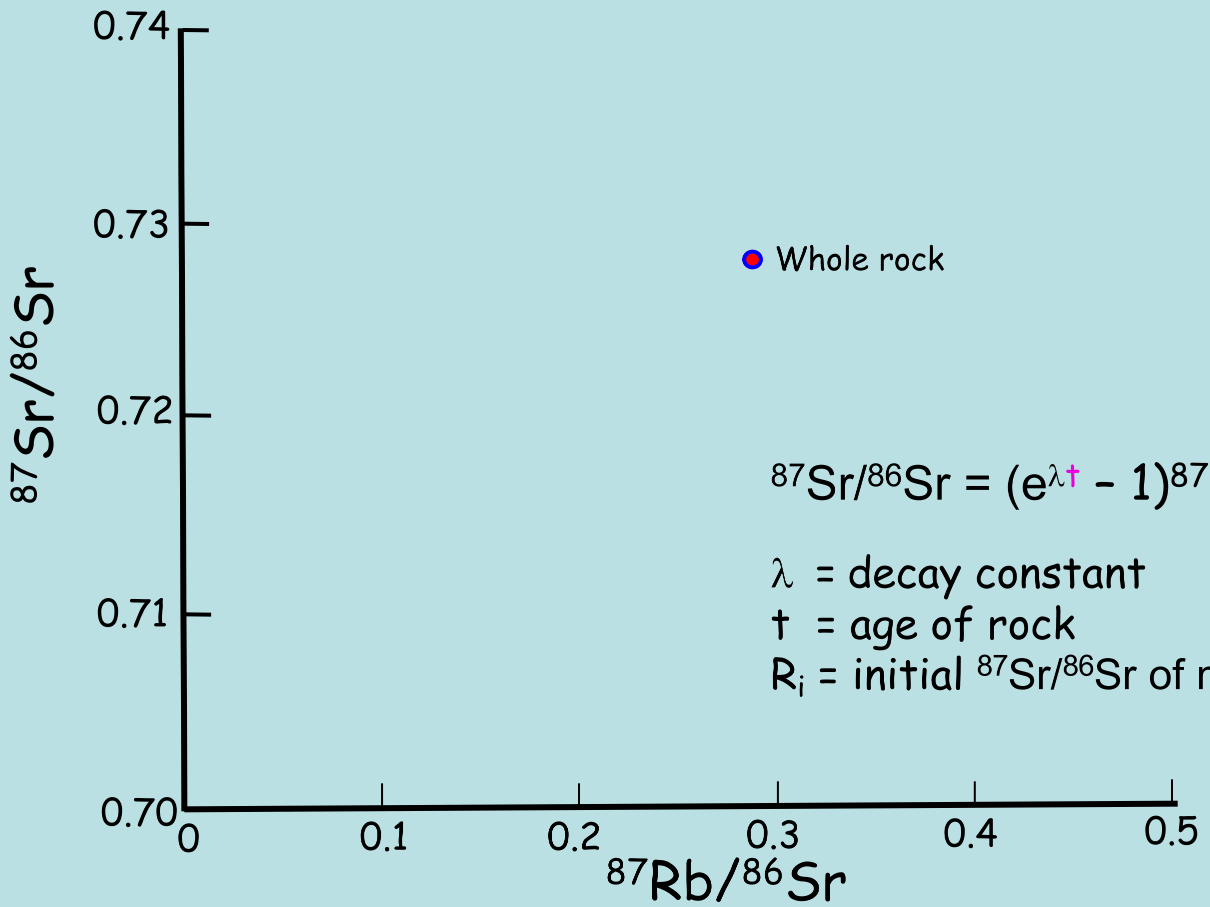
Age of sample is derived from isochron equation

$$^{87}Sr/^{86}Sr = \underline{(e^{\lambda t} - 1)^{87}Rb/^{86}Sr} + R_i \qquad (y = mx + c)$$

λ = decay constant
t = age of system
R_i = initial $^{87}Sr/^{86}Sr$ of melt



Rubidium-Strontium isochron diagram



$$^{87}Sr/^{86}Sr = (e^{\lambda t} - 1)^{87}Rb/^{86}Sr + R_i$$

λ = decay constant

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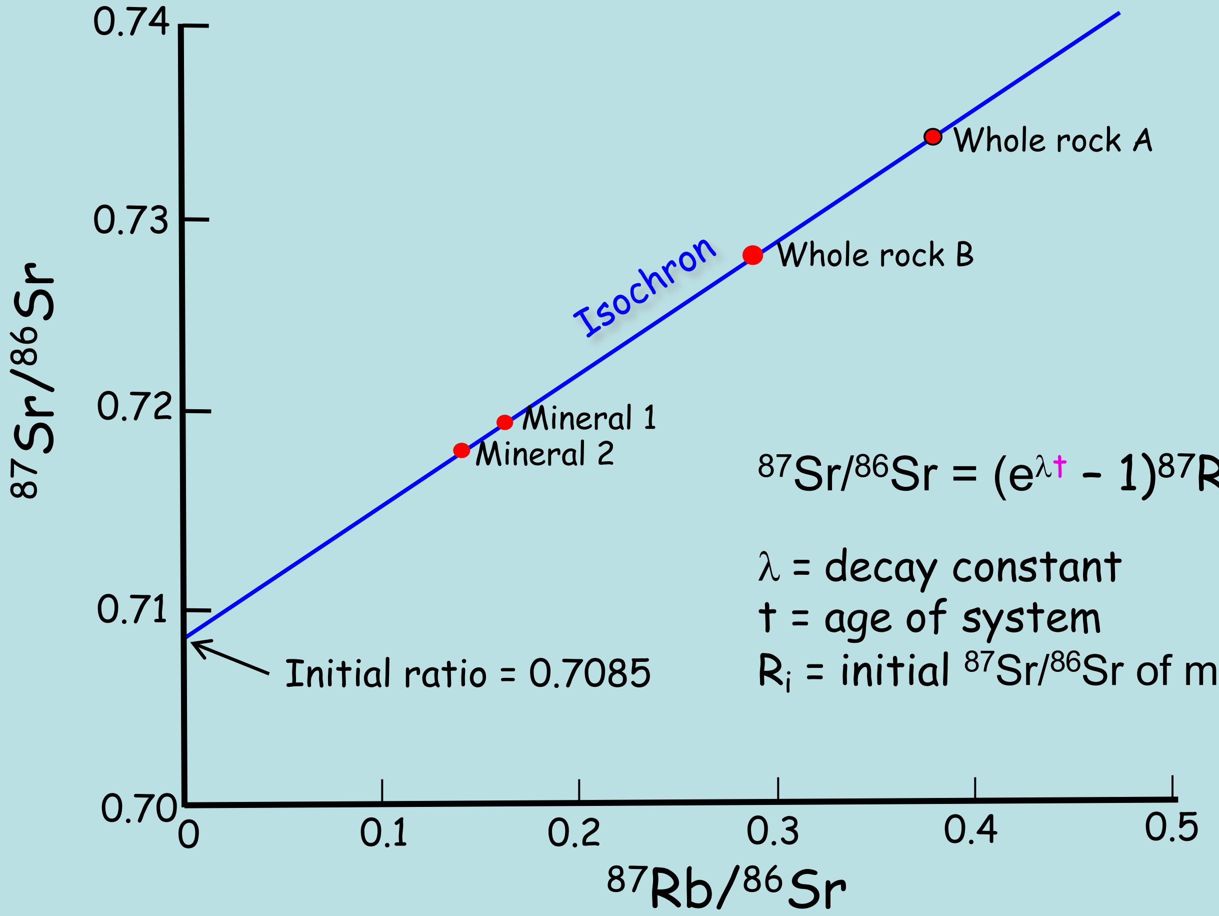
Rubidium-Strontium isochron diagram



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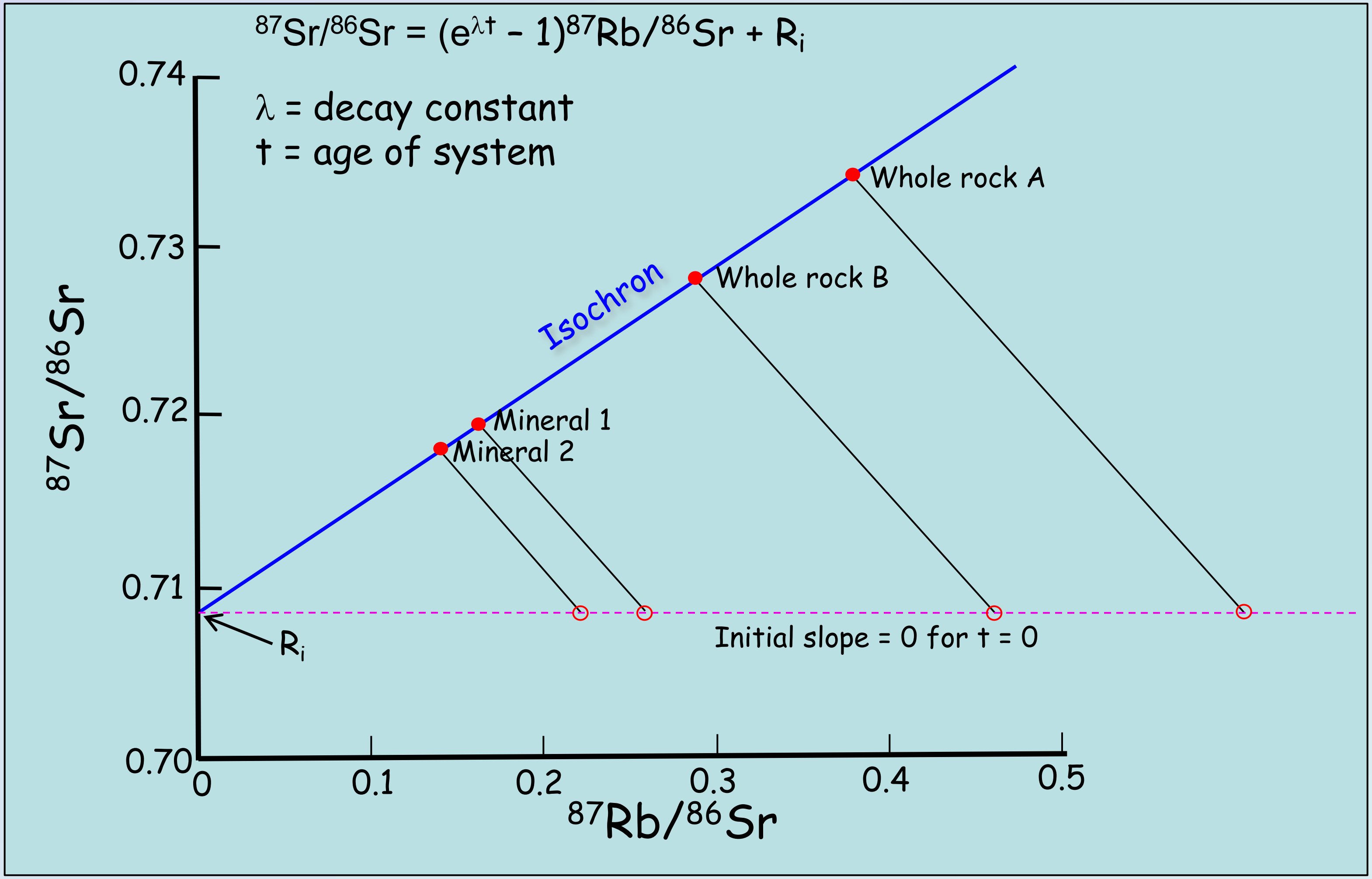


$^{87}Sr/^{86}Sr = (e^{\lambda t} - 1)^{87}Rb/^{86}Sr + R_i$

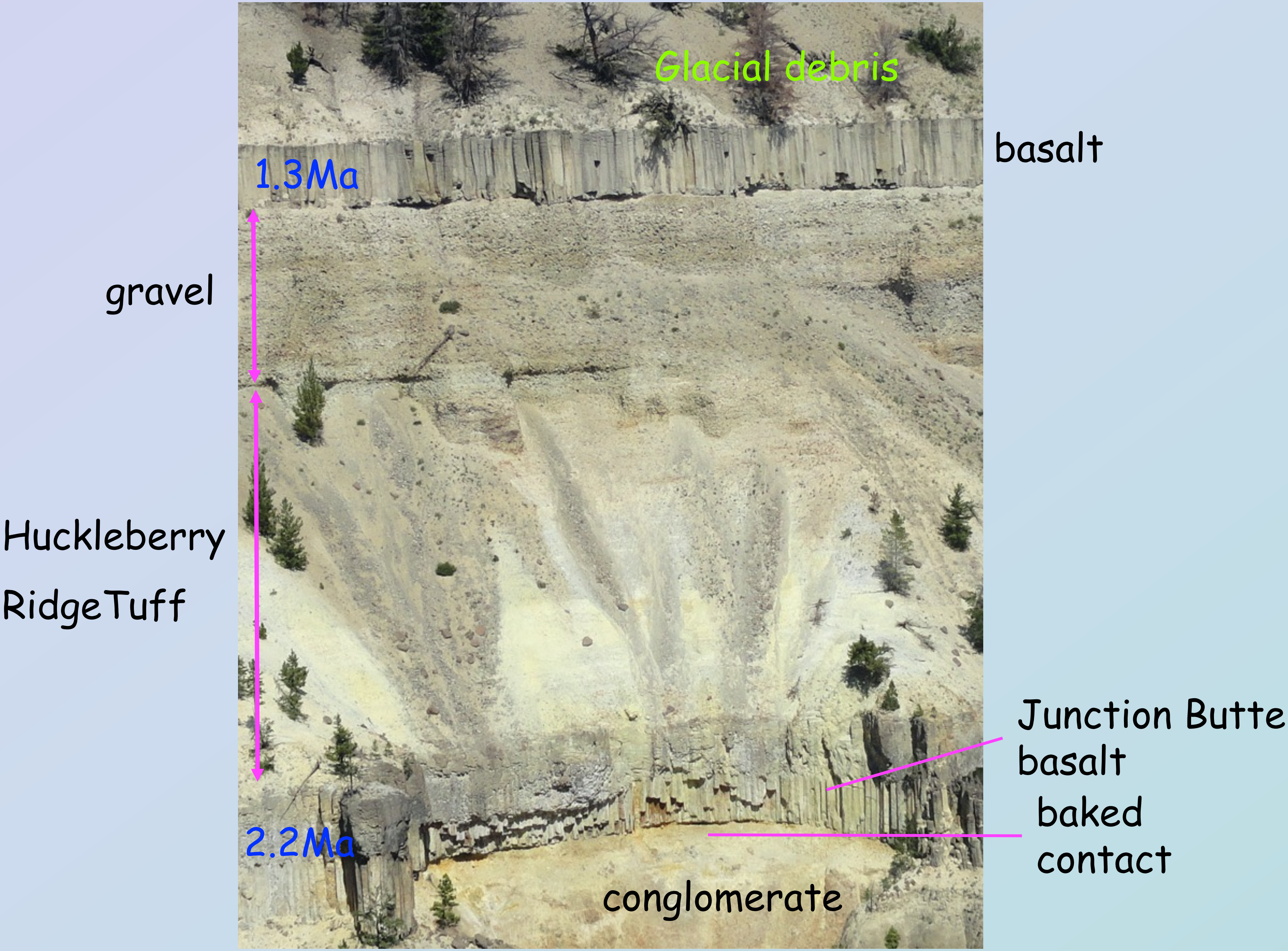
λ = decay constant

t = age of system

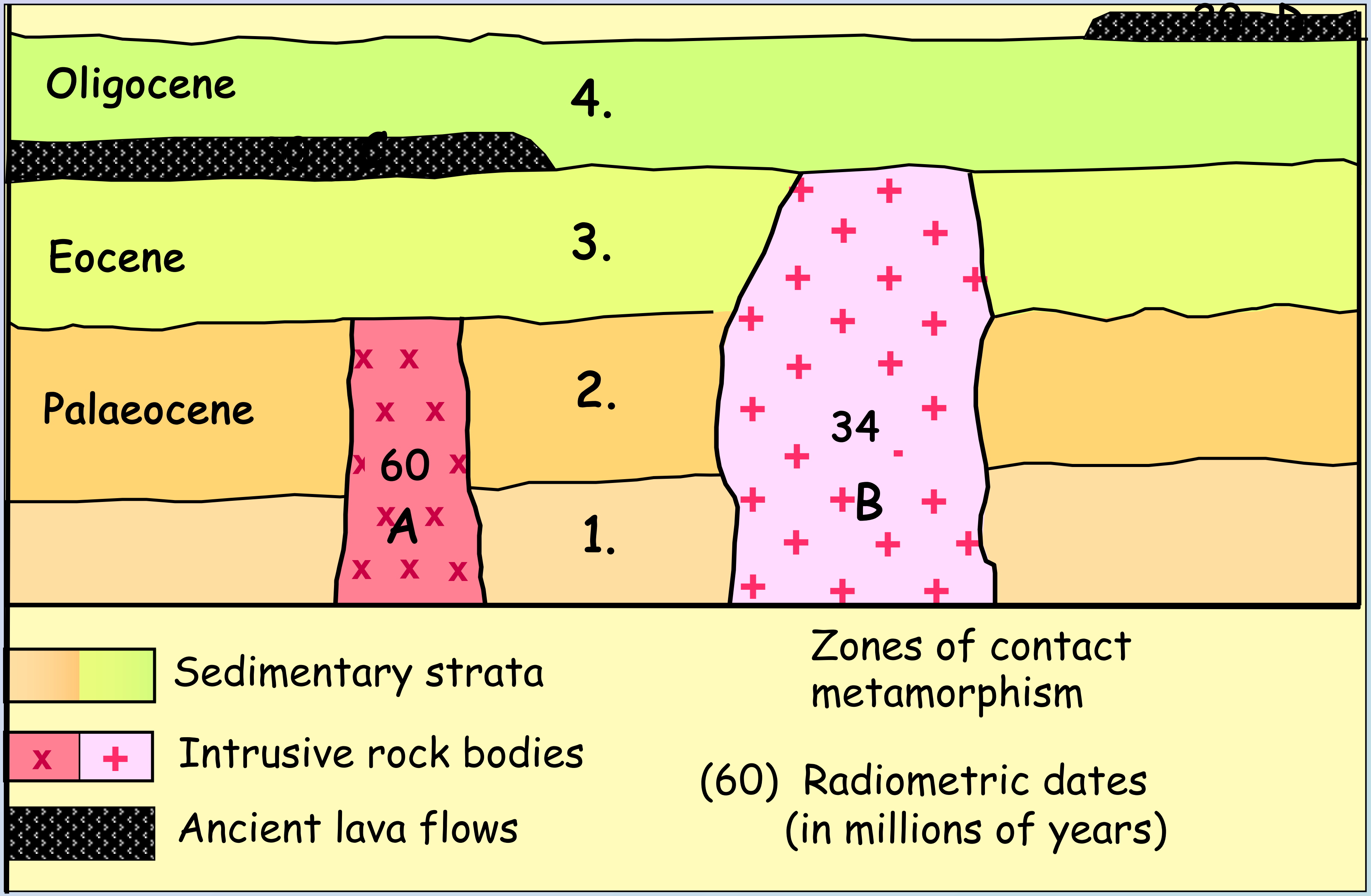
Calibrating the time scale

- Only certain rocks can be dated by radioactive dating methods
- most sedimentary rocks cannot be dated by radioisotope methods however, the geological timescale is based on accumulation of sedimentary material (metamorphic, igneous generally suitable)
- rocks ideal for dating do not always exist at the ideal position to calibrate the time scale
- these may be related to other rocks by the principles of stratigraphy and correlation
- many hundreds of thousands of measurements have been compiled to enable us to calibrate the relative time scale

Stratigraphic section at Yellowstone



Basalt dyke cross-cutting sedimentary rocks, Kew, Vic.



Stratigraphic relationships for relative dating

The Geological time scale

Eon	Era	Period	Age base (Ma)
PHANEROZOIC	Cainozoic	Quaternary	2
		Tertiary	65
	Mesozoic	Cretaceous	144
		Jurassic	206
		Triassic	250
	Palaeozoic	Permian	299
		Carboniferous	359
		Devonian	419
		Silurian	444
		Ordovician	488
		Cambrian	545
		PRECAMBRIAN (Super Eon)	4600

Geological time scale for Cenozoic era

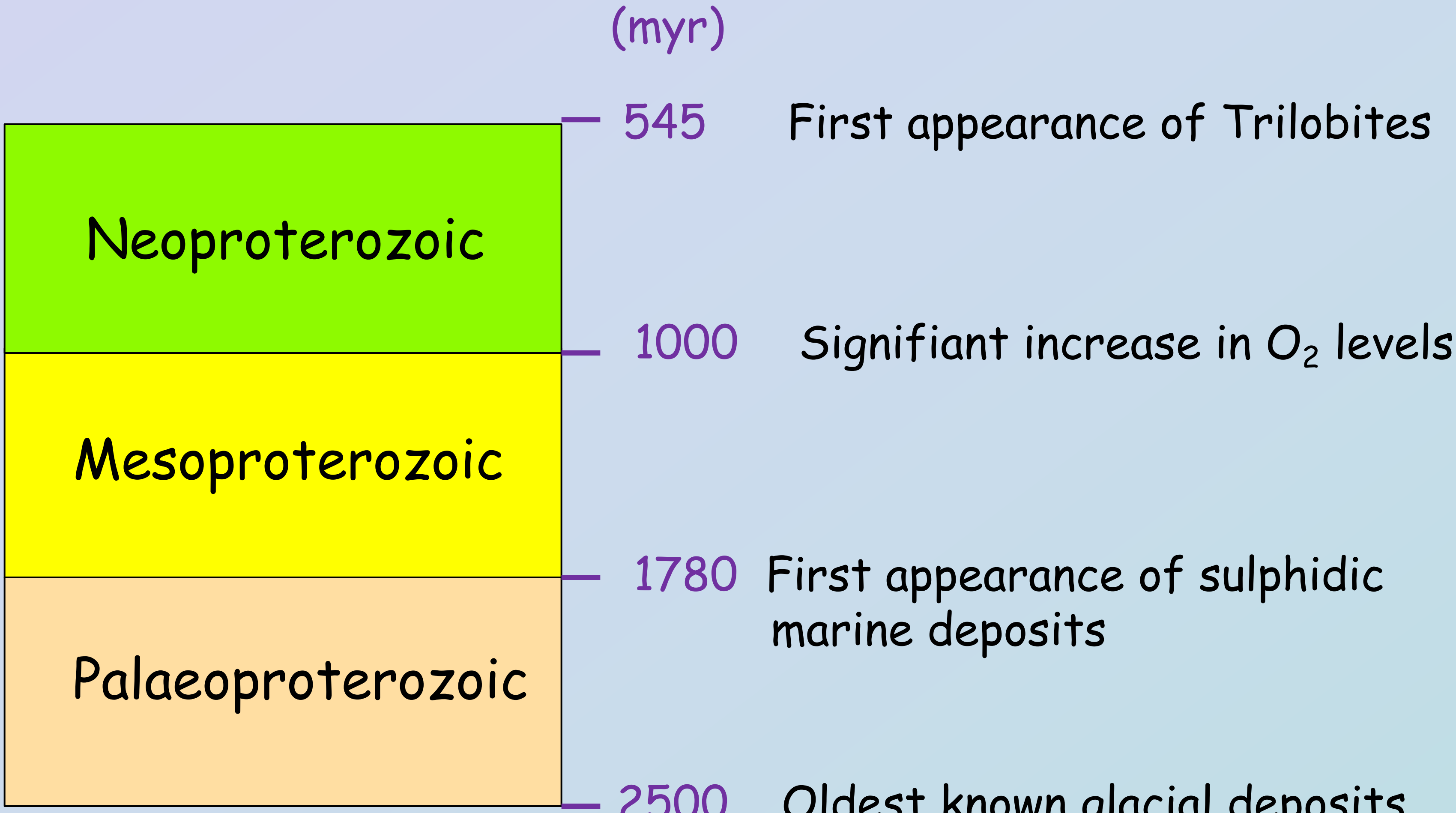
Era	Period		Epoch	(mya)
Cenozoic	Quaternary		Holocene	0.01
			Pleistocene	2.58
	Tertiary	Neogene	Pliocene	5.2
			Miocene	23.3
		Palaeogene	Oligocene	35.4
			Eocene	56.5
			Palaeocene	65

Subdividing the Precambrian Super Eon

EON	AGE AT BASE (Ma)
Phanerozoic	545
Proterozoic	2500
Archaean	4000
Hadean	4600

Ma = mega anum (million years)

Eras of the Proterozoic eon



(myr)

Neoproterozoic

Mesoproterozoic

Palaeoproterozoic

545 First appearance of Trilobites

1000 Signifiant increase in O_2 levels

1780 First appearance of sulphidic marine deposits

2500 Oldest known glacial deposits