The Age of the Earth and the Planets

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Talk structure

- Historical ideas about the age of the Earth
- The use of radioactive isotopes as geological chronometers
- The main systems used in cosmochronology: Rb-Sr, Sm-Nd, Re-Os, K(Ar)-Ar, U(Pb)-Pb
- The age of the Earth, Moon and Mars

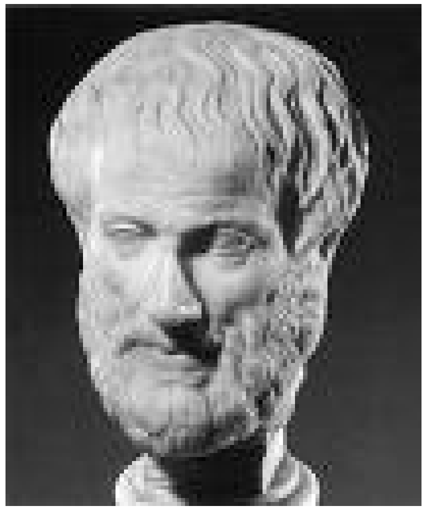
Next lecture- timescales in the protoplanetary disk

Historical ideas about the age of the Earth -1

- There were many ideas in the ancient world about how and when the Earth formed:
- In Japan, the oldest historical book, called Kojiki, written in Narazidai (712 AD) talks about two gods, Izanaginomikoto and Izanaminomikoto who made the Japanese islands a long time ago.
- Hindus believed in cosmic cycles of destruction followed by periods of renewal. Each cycle lasts 4,320,000 years, and there have been 100,000 cycles.
- The Babylonian Chaldean people believed that the Earth emerged from Chaos more than 2 million years ago.

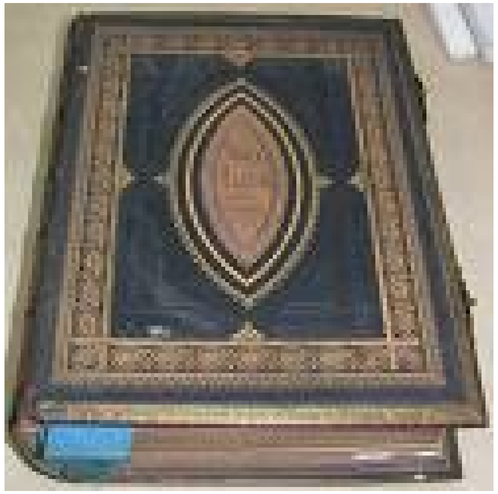
Ancient Greeks

Demokritus- believed everything was made from indestructible atoms



Aristotle- believed the universe had no beginning or end

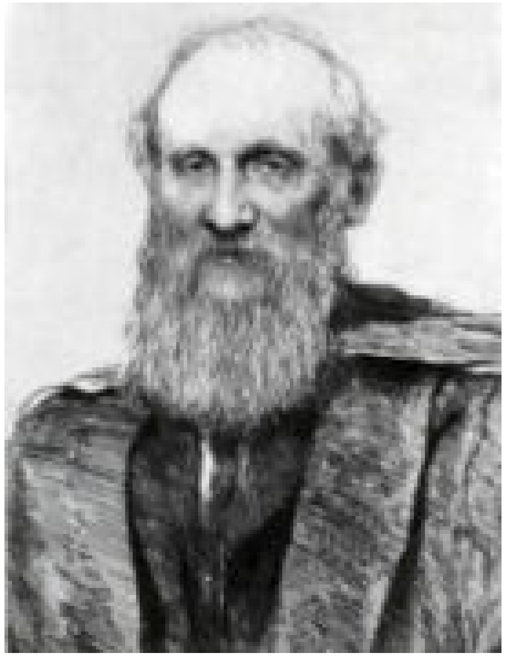
The Bible



- Many estimates have been made based on interpretations of the Bible, the first being Theophilus of Antioch (ca. 115-180). He calculated that the Earth had been created 5,698 years ago (5529 B.C.).
- These interpretations fell out of favour during the Age of Enlightenment (18-19th century) but are becoming more popular especially in the USA (Young Earth Creationists)

Historical ideas about the age of the Earth -2

- Amount of salts in the sea was used by Joly in 1889 to calculate an age of 70 million years.
- Kelvin calculated the age of the Earth from cooling rate calculations- but got a very young age- between 20 million and 400 million years old.
- Finally, in 1895, Henri Becquerel discovered radioactivity. It was soon realized that the energy from radioactive decay was enough to keep the planet hot, so the Earth could be older than Kelvin calculated. Radioactivity can also be used to make accurate age dates….



William Thompson (Lord Kelvin)

Rutherford proposed that he could determine the age of a rock sample by measuring its concentration of helium. He dated a rock in his possession to an age of 40 million years by this technique. Rutherford wrote,

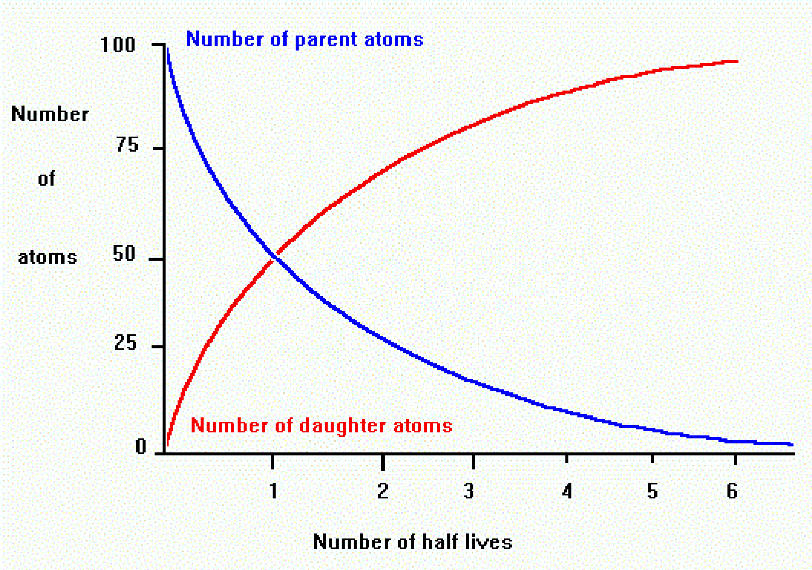
“I came into the room, which was half dark, and presently spotted Lord Kelvin in the audience and realized that I was in trouble at the last part of my speech dealing with the age of the earth, where my views conflicted with his. To my relief, Kelvin fell fast asleep, but as I came to the important point, I saw the old bird sit up, open an eye, and cock a baleful glance at me! Then a sudden inspiration came, and I said, 'Lord Kelvin had limited the age of the earth, provided no new source was discovered. That prophetic utterance refers to what we are now considering tonight, radium!' Behold! the old boy beamed upon me”

Age dating using radioactive decay

$$N = N_0 e^{-\lambda t}$$

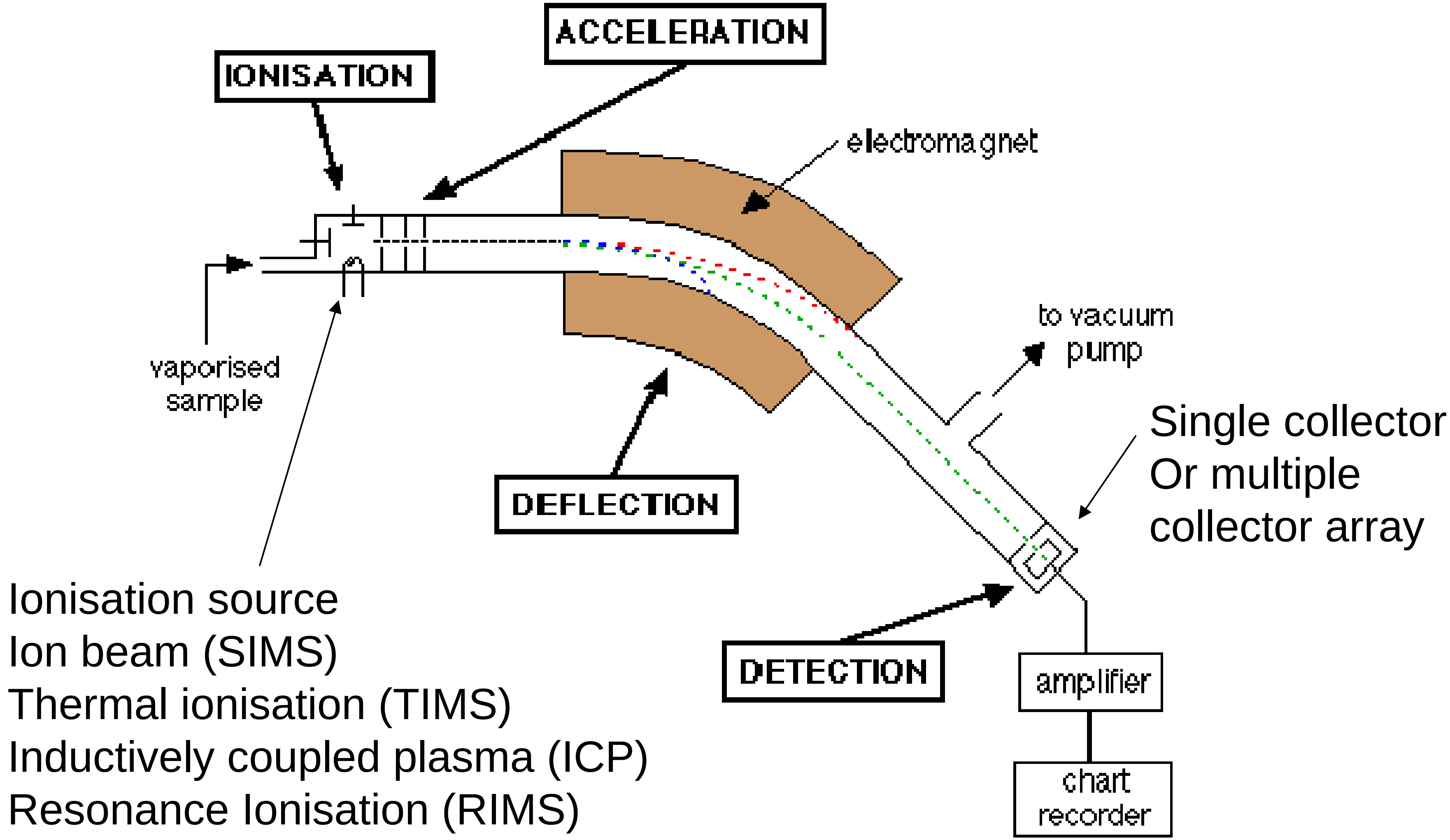
N= Current number of atoms
N_0 = Initial number of atoms
λ = a constant for this decay system
t = time

D = No-N
 = $Ne^{\lambda t}$-N
 = $N(e^{\lambda t}-1)$
D= number of daughters



λ is related to the 'half-life' of the system:

$$t_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$$



ACCELERATION
IONISATION
electromagnet
vaporised sample
to vacuum pump
Single collector
Or multiple
collector array
DEFLECTION
DETECTION
amplifier
chart recorder
Ionisation source
Ion beam (SIMS)
Thermal ionisation (TIMS)
Inductively coupled plasma (ICP)
Resonance Ionisation (RIMS)

Age dating using radioactive decay

- **Isotope variations can be measured as delta values:**

$$\partial = \left(\frac{R_{sample}}{R_{std}} - 1 \right) x1000$$

R = Isotope of interest/reference Isotope

Expressed as per mil (‰)

Scale goes from –1000 per mil to +∞

Epsilon units are also used ($\varepsilon = \delta$ x 10) or ppm (δ x 1000), but these are not standard units

Ideally….

–Ratio of Parent: Daughter should be large

–Minerals with ranges in parent/daughter ratios co-exist

–Closed system

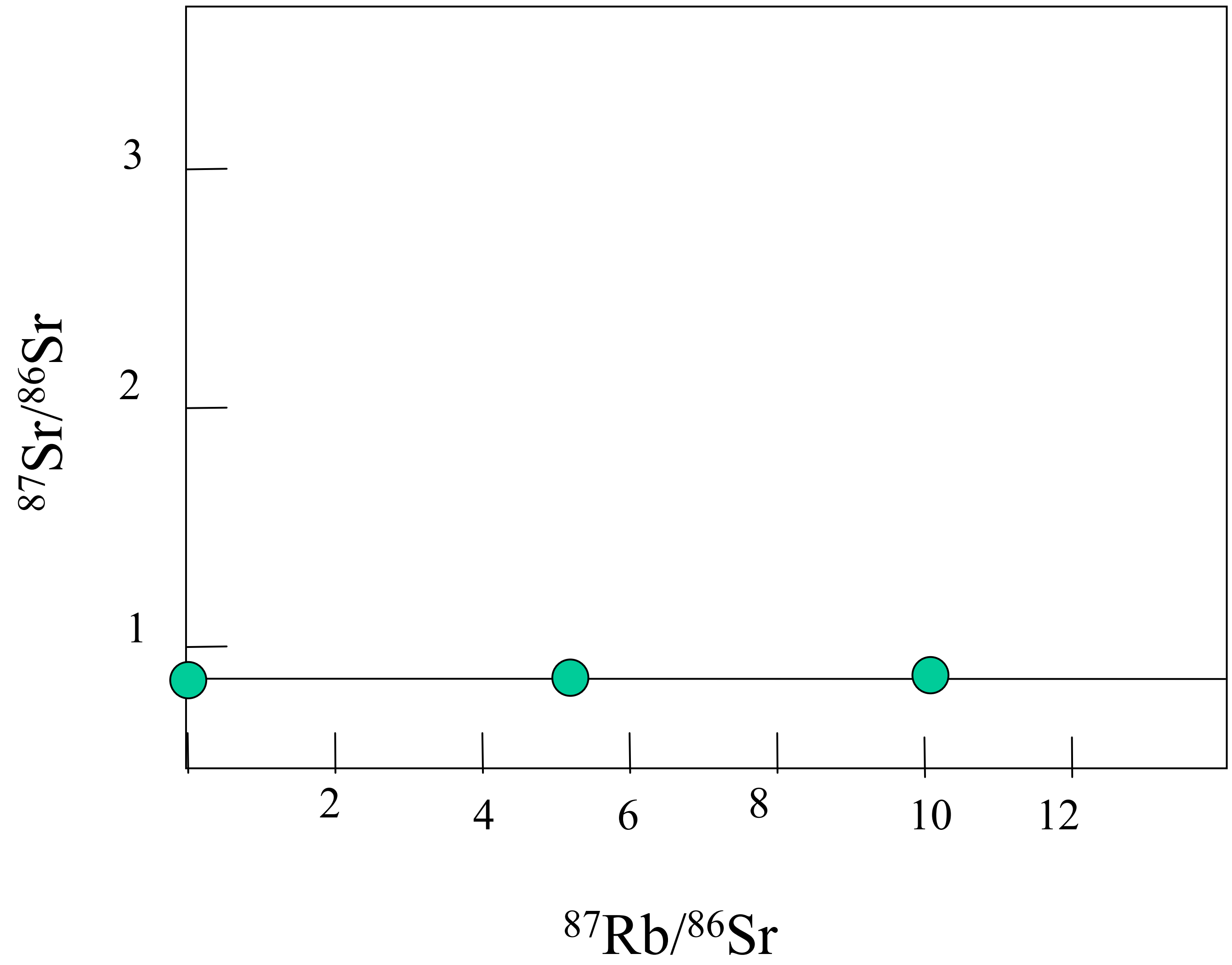
–Isotopic composition of the parent and daughter should be homogeneous at closure time

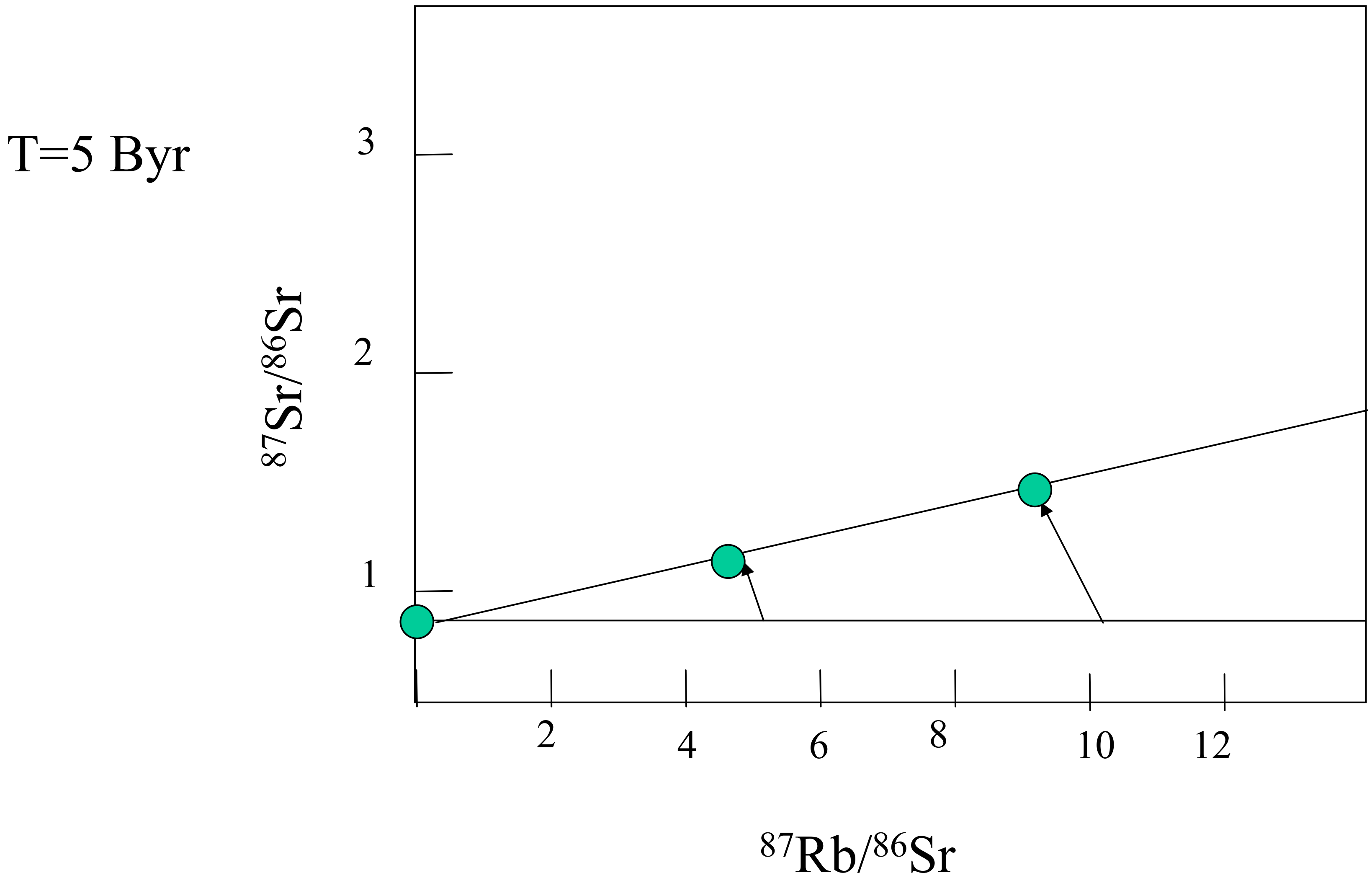
–**The measured time is the period since the closure temperature was reached- this is different for each system. This may be crystallisation time or a metamorphic age**

Commonly Used Long-Lived Isotopes in Cosmochronology

Parent Isotope	Stable Daughter Product	Half-Life (Gyr)
Potassium-40	Argon-40	1.25
Rubidium-87	Strontium-87	48.8
Samarium-147	Neodymium-143	106
Rhenium- 187	Osmium- 187	43.0
Thorium-232	Lead-208	14.0
Uranium-235	Lead-207	0.7
Uranium-238	Lead-206	4.5

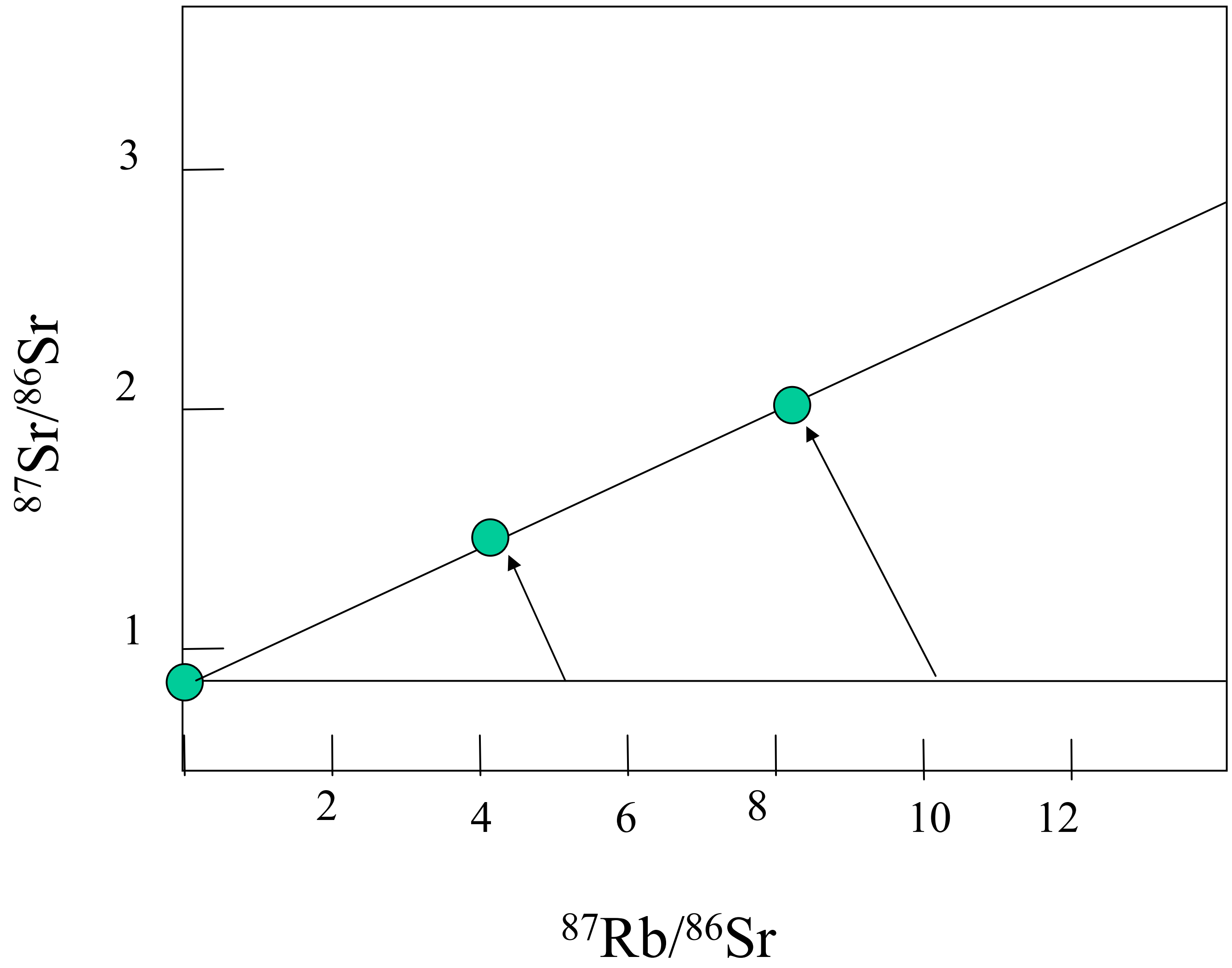
T=0



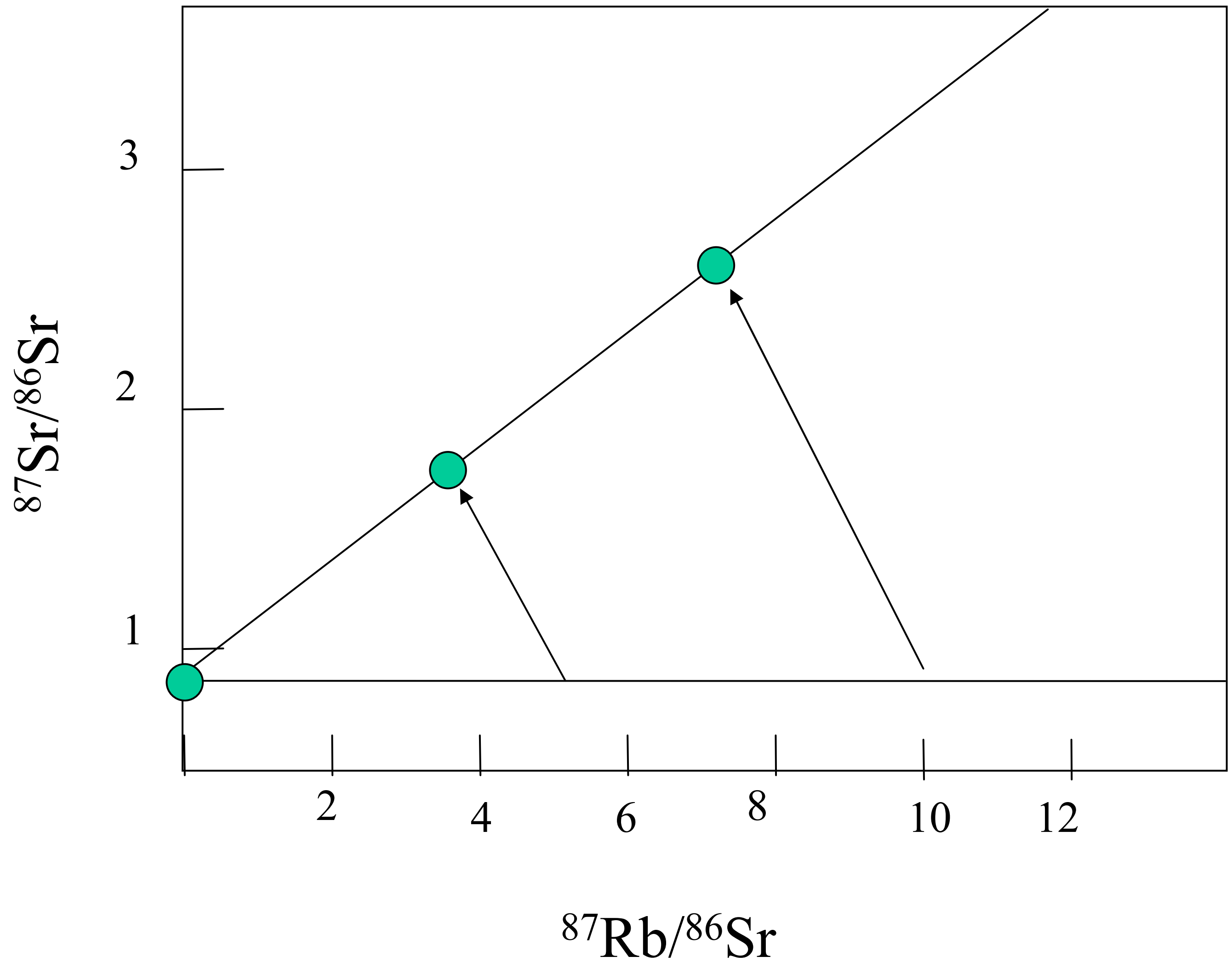


T=5 Byr
3
2
1
87Sr/86Sr
2
4
6
8
10
12
87Rb/86Sr

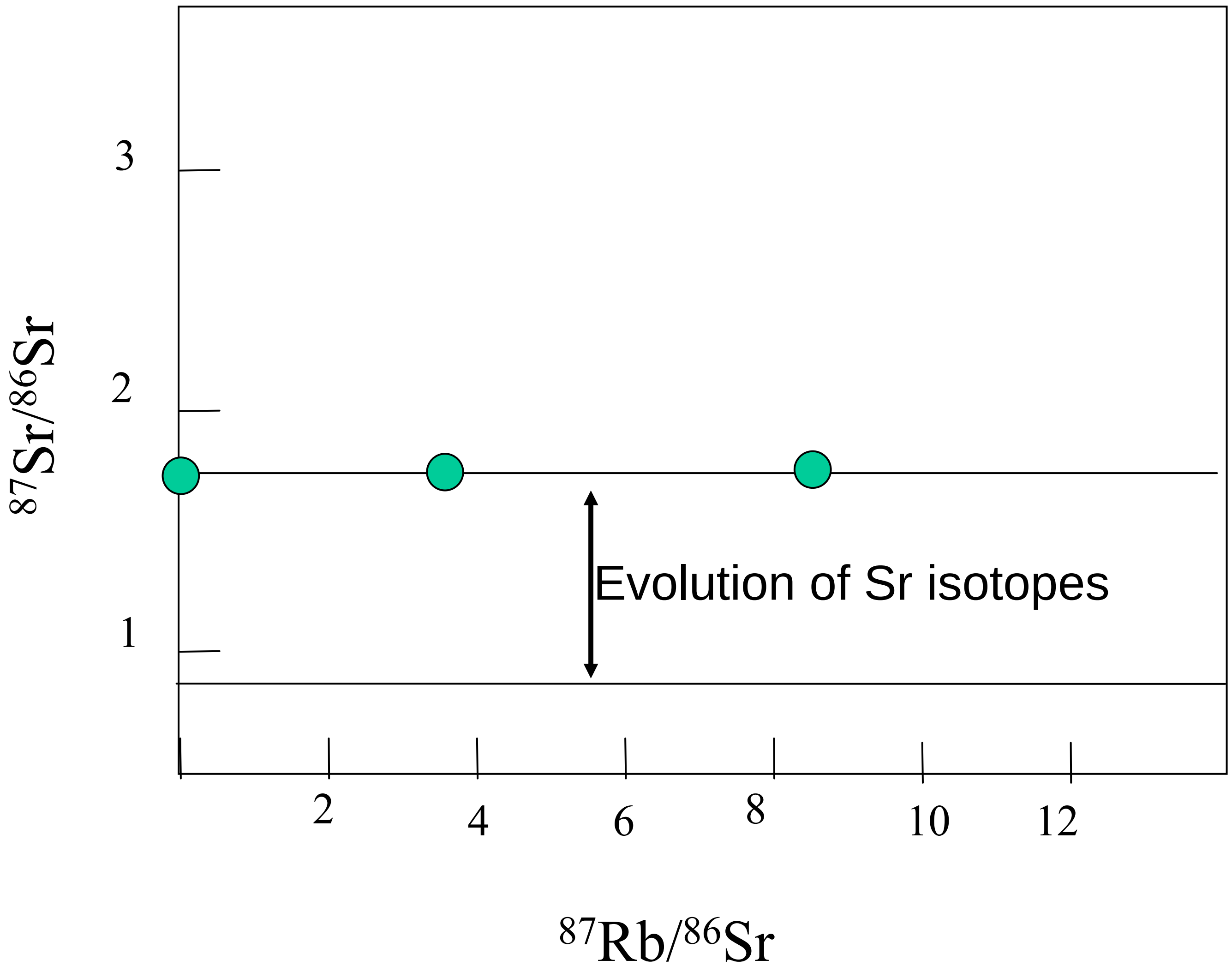
T=10 Byr



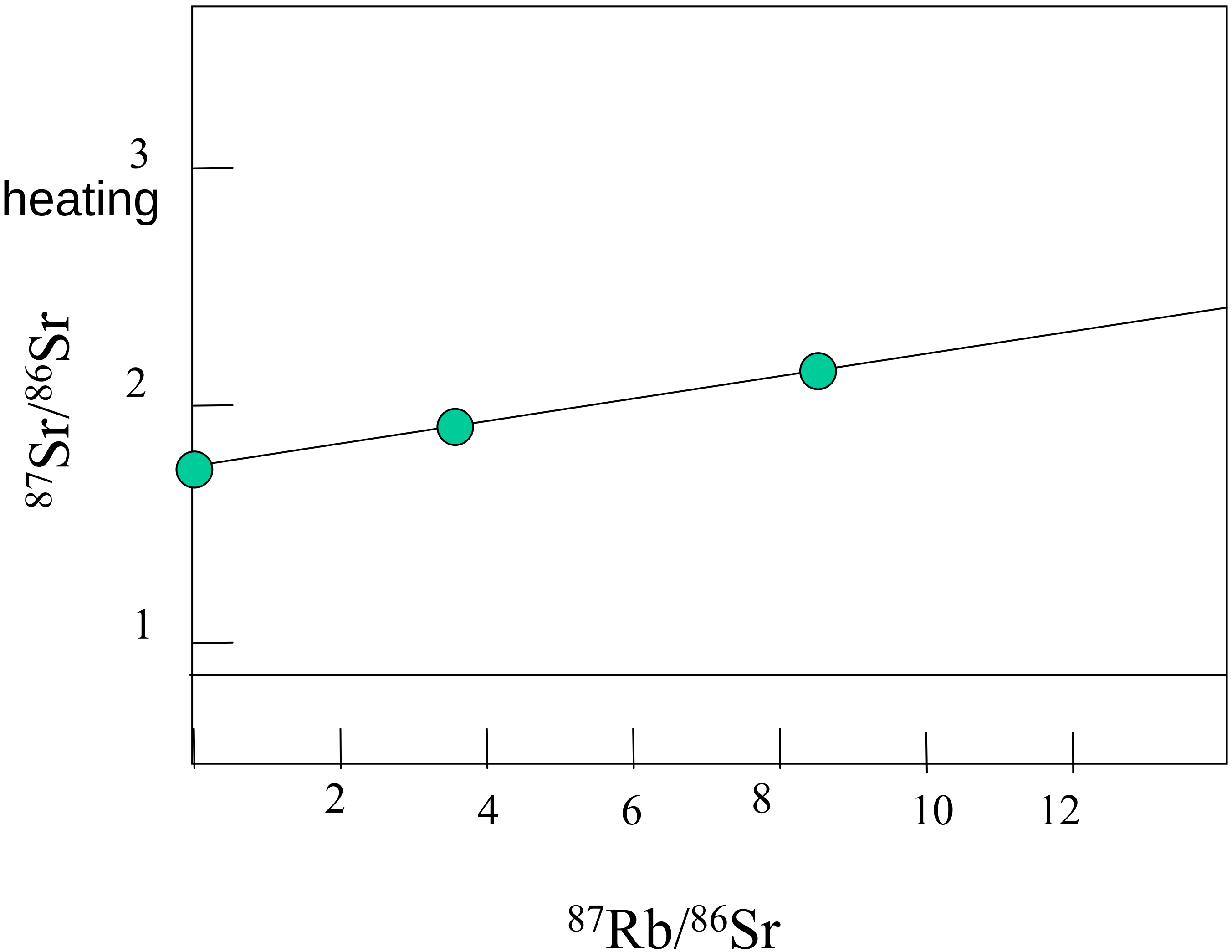
T=20 Byr



Reheating



Evolution after heating



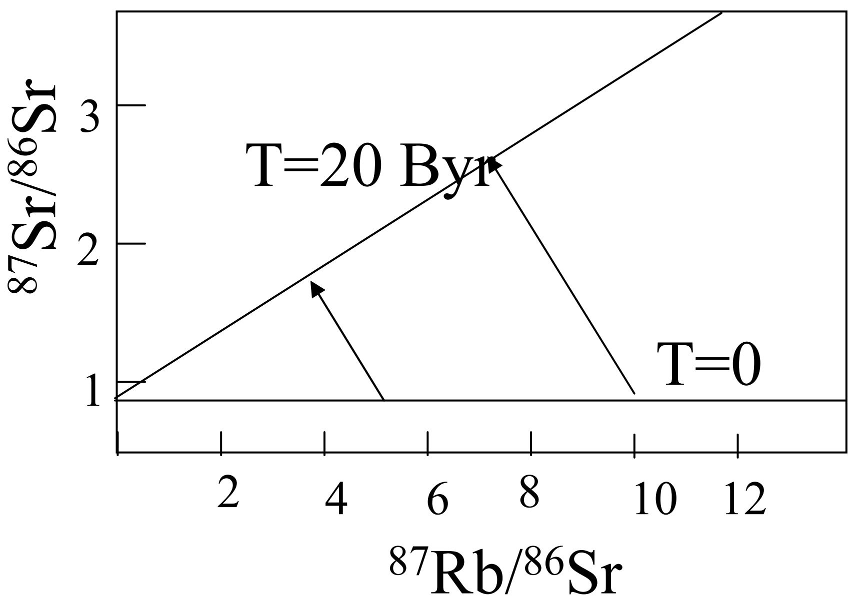
Rb-Sr dating

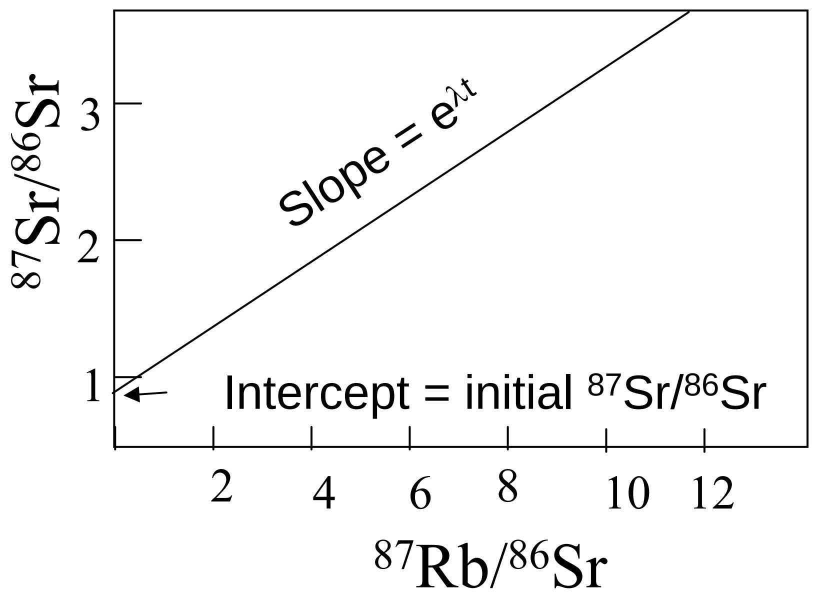
^{87}Rb decays to ^{87}Sr by beta decay

$$N = N_0 e^{-\lambda t} \qquad \mathbf{D = N(e^{\lambda t}-1)}$$

$$^{87}Sr = {}^{87}Sr_0 + {}^{87}Rb\left(e^{\lambda t} - 1\right)$$

$$\frac{^{87}Sr}{^{86}Sr} = \frac{^{87}Sr}{^{86}Sr}_0 + \frac{^{87}Rb}{^{86}Sr}\left(e^{\lambda t} - 1\right)$$

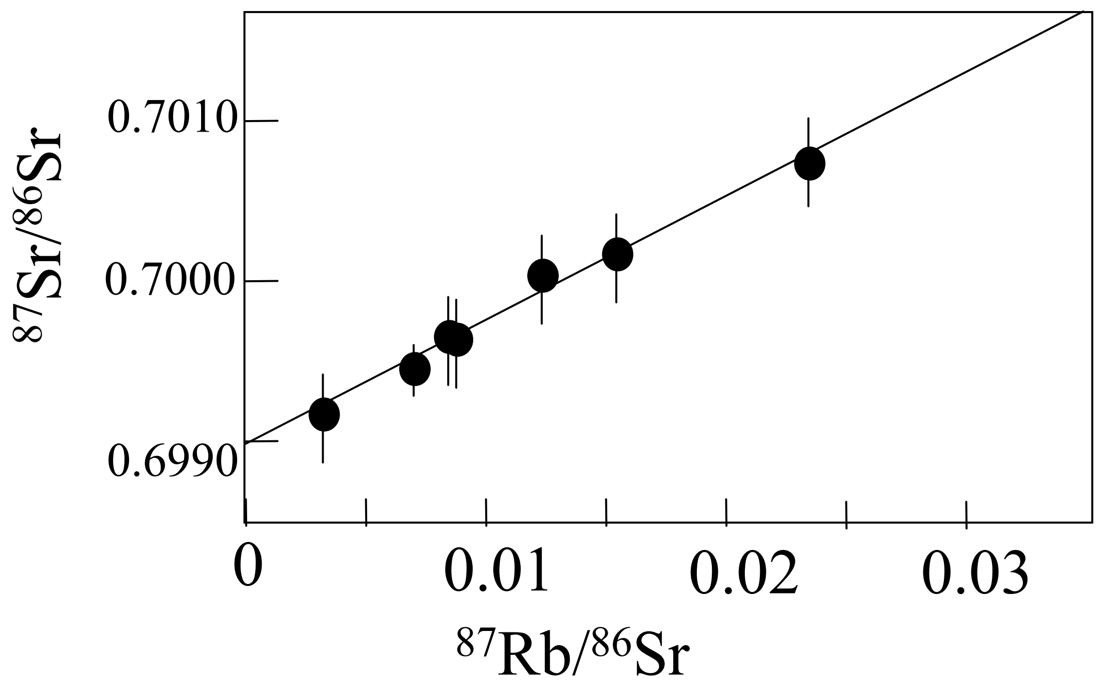




Sr and Rb geochemistry

Sr has similar chemistry to Ca: enriched in plagioclase and carbonates
Rb alkali element –volatile.

Rb-Sr diagram for eucrites.
(Papanastassiou et al., 1969.)



Intercept= ~0.6990-
“BABI”
More primitive intercepts have now been determined (ADOR, Allende)

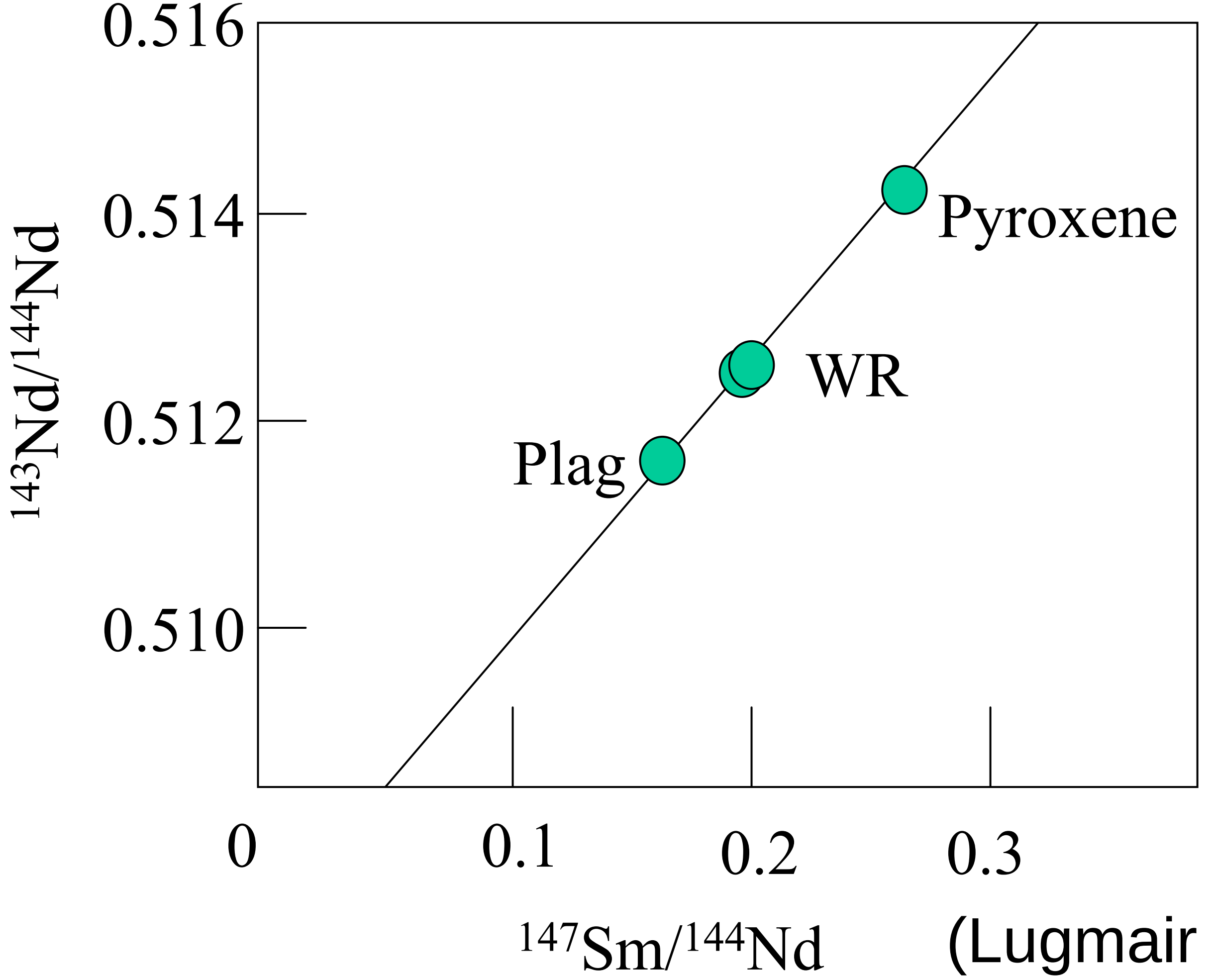
Rb-Sr in planetary science

- Accurate, has yielded good ages for many chondrites and their components
- Not so good where mobilisation of elements has occurred
- Not so good for many achondites, that tend to have lower bulk Rb/Sr than chondrites and show disturbance.
- In this case, Sm-Nd may be better- less easily mobilised elements involved.

Sm-Nd geochemistry

- Sm and Nd are both rare earth elements (REEs) and so have similar geochemical behaviour
- Both refractory elements, both incompatible
- Sm partitions more favorably into mafic minerals
- Felsic rocks have high Sm and Nd, and low Sm/Nd

Sm-Nd results from Juvinas
-Age is 4560±80 Myr



(Lugmair et al., 1975)

K-Ar dating (and Ar-Ar)

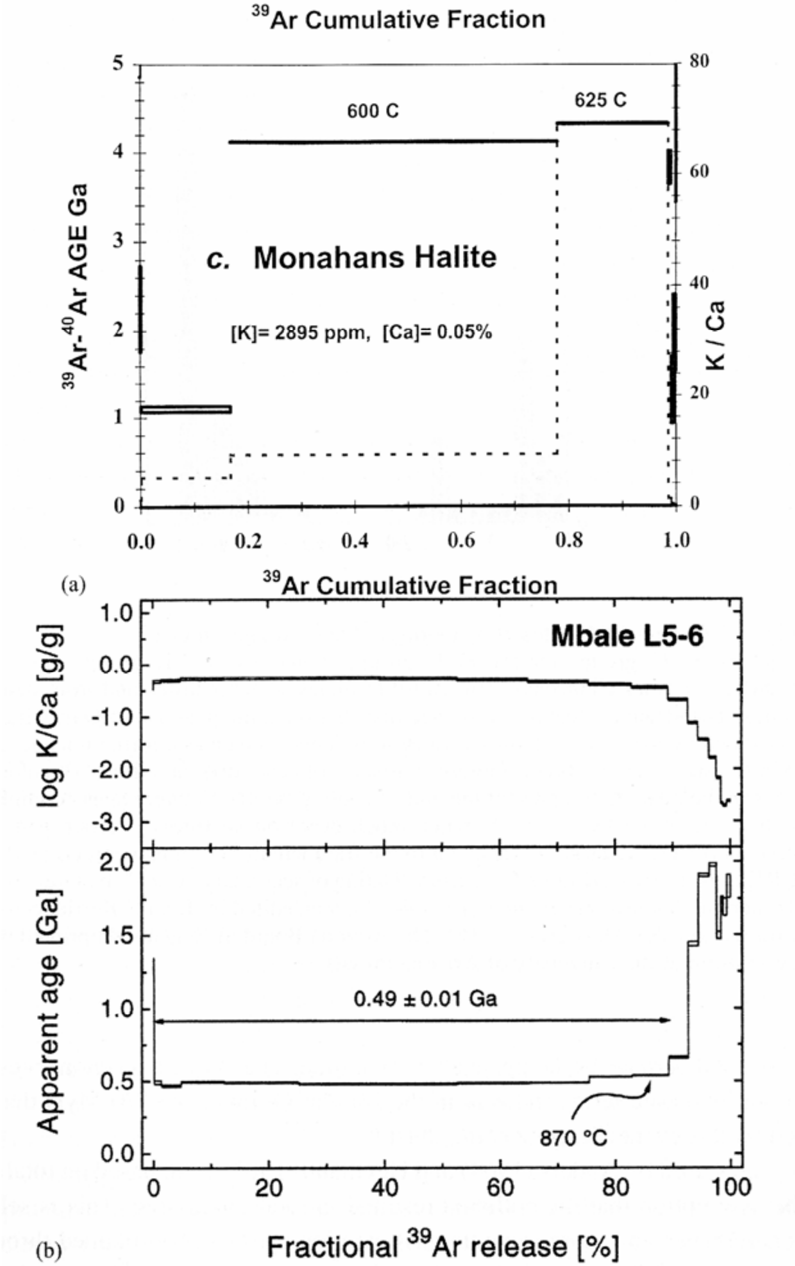
^{40}K decays to ^{40}Ar.
A relatively simple system because typically there is essentially no initial argon in igneous samples

- $^{40}Ar/^{36}Ar = (^{40}Ar/^{36}Ar)_0 + {}^{40}K/^{36}Ar\ (e^{\lambda t}-1)$

^{40}K can be converted to ^{39}Ar by irradiation, then:

- $^{40}Ar/^{36}Ar = (^{40}Ar/^{36}Ar)_0 + {}^{39}Ar/^{36}Ar\ C(e^{\lambda t}-1)$
  - C is a constant that depends on the irradiation efficiency

  Both K and Ar are volatile- Ar is not a rock-forming element. The system is very **easily reset** –good for dating, for example, impact events.



ig. 6.3 Ar release patterns of neutron-irradiated unshocked and shock-reheated hondrites.

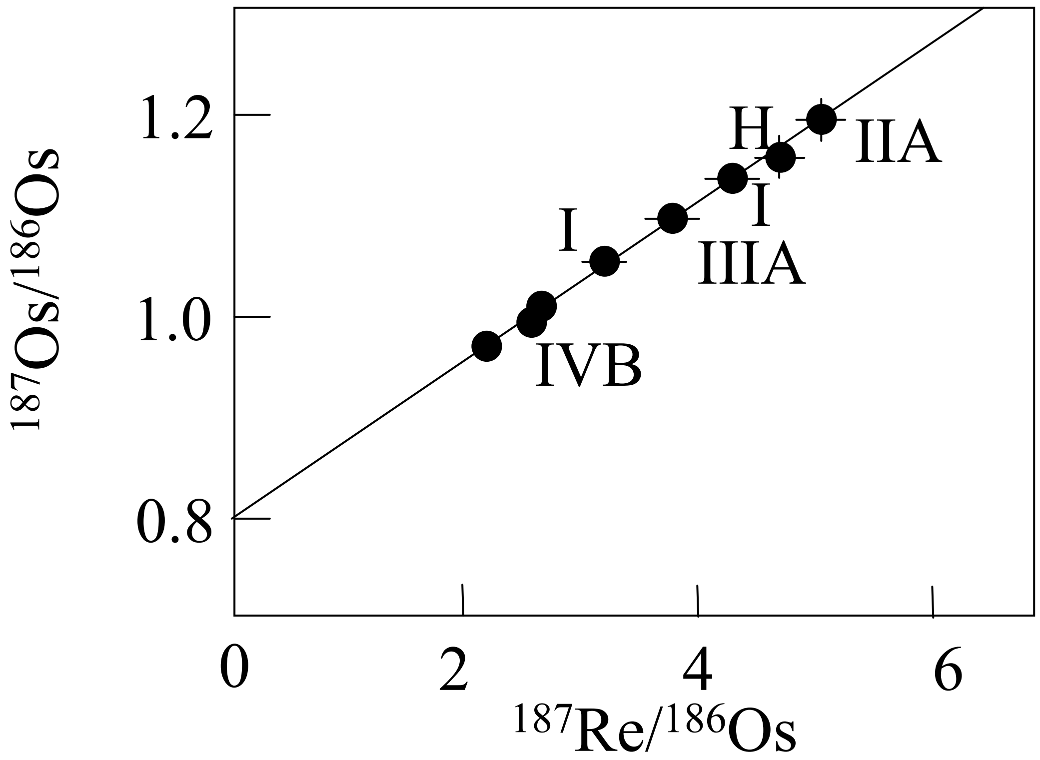
An example of an unshocked sample- halite that is 4.529±0.008 Gyr old

An example of a shocked sample- age apparently increases in final steps of experiment

From Hutchison, 2004 (see references therein)

Re-Os

- A *siderophile* system, therefore good for dating metal rich systems such as iron meteorites
- Re partitions into sulfides

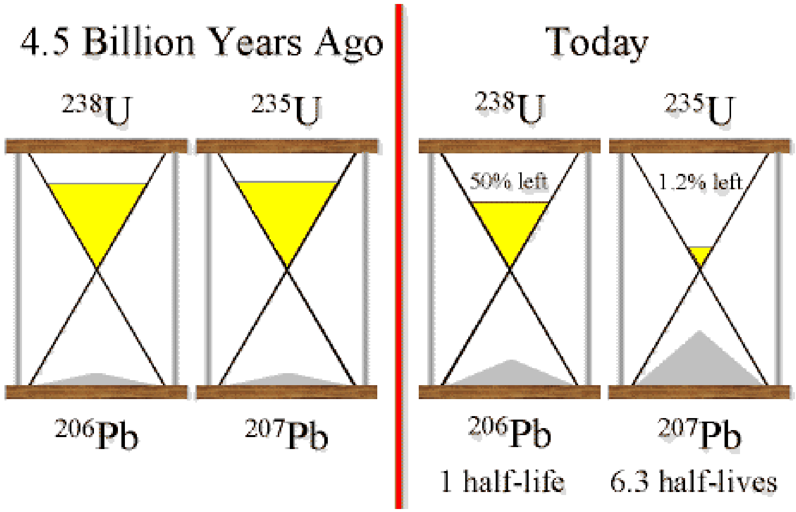


T = 4550 Myr

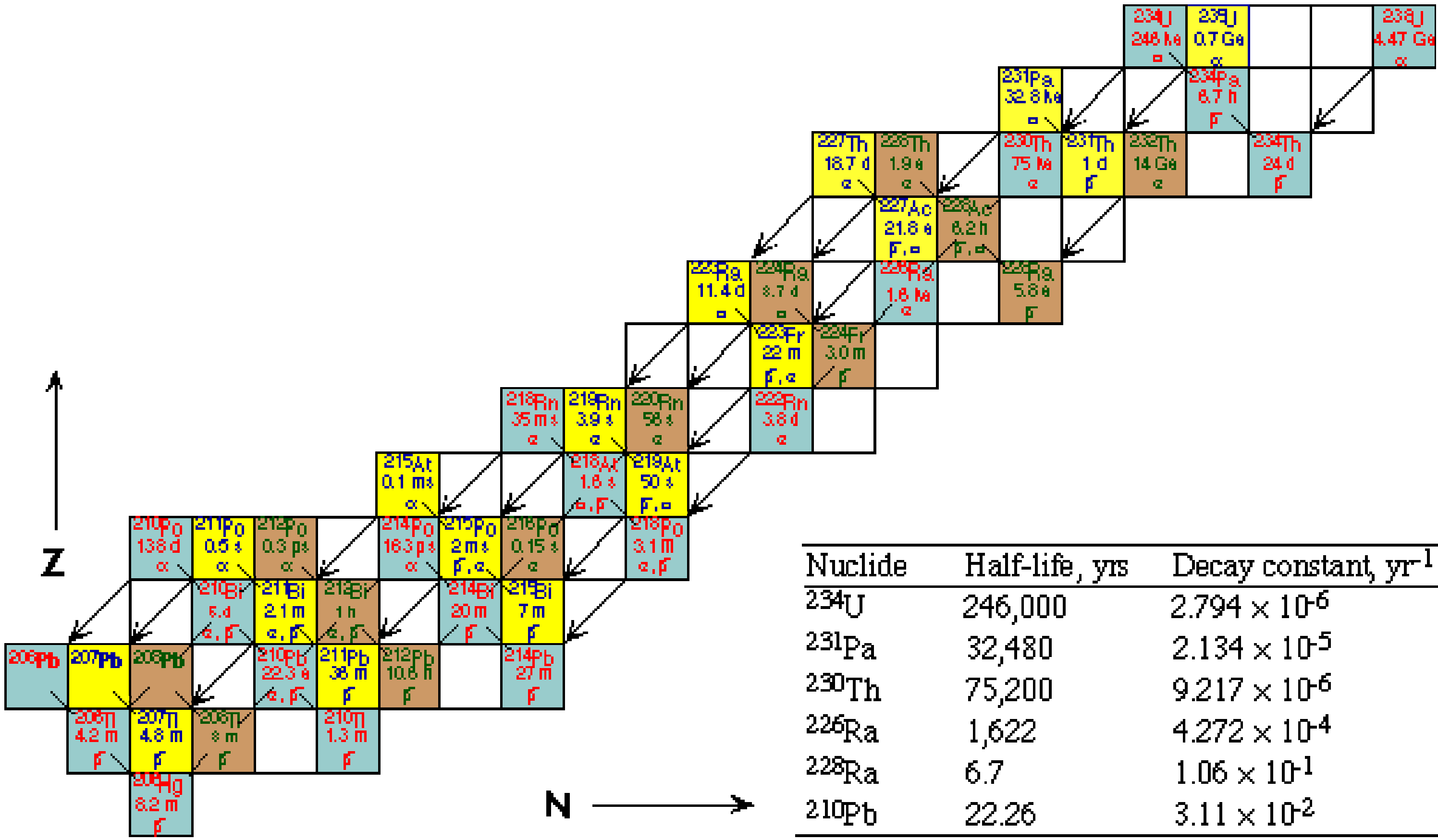
After Luck, 1980

Pb-Pb dating

- Decay sequence
- Suitable minerals- have high U/Pb ratios
- Problems of contamination, mobilization of Pb

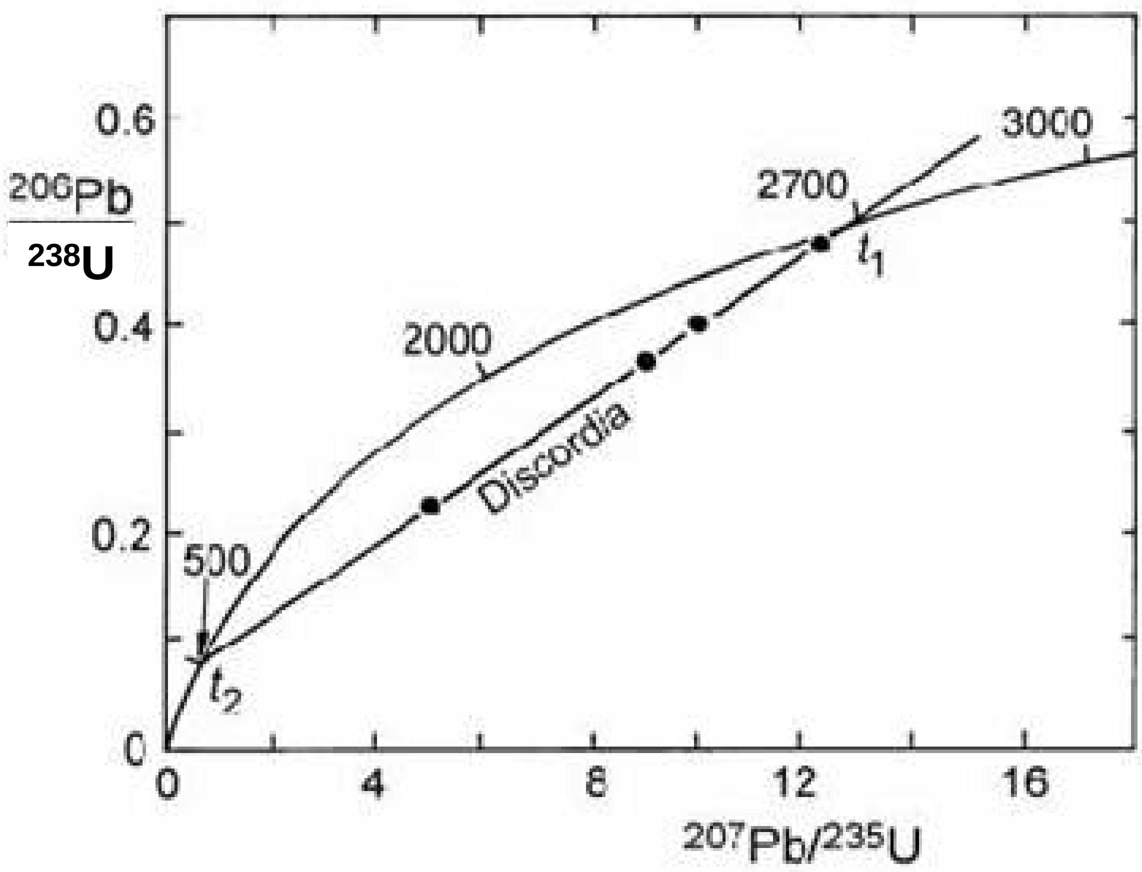


Uranium series decay

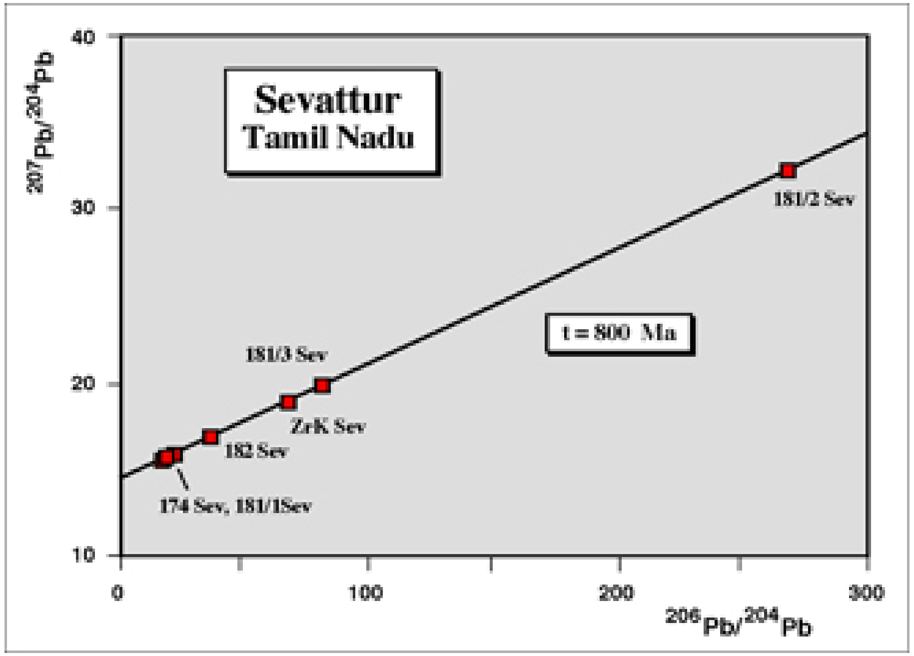


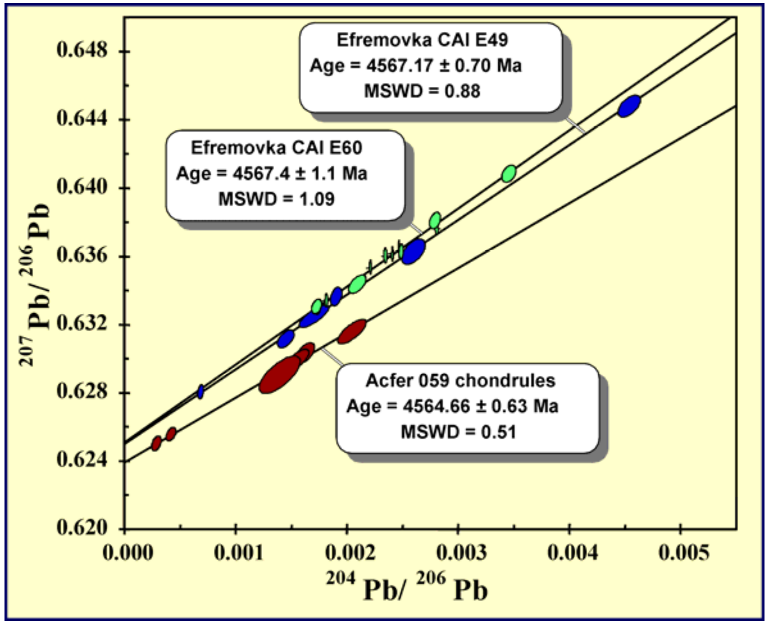
Nuclide	Half-life, yrs	Decay constant, yr^{-1}	Parent
^{234}U	246,000	2.794×10^{-6}	^{238}U
^{231}Pa	32,480	2.134×10^{-5}	^{235}U
^{230}Th	75,200	9.217×10^{-6}	^{238}U
^{226}Ra	1,622	4.272×10^{-4}	^{238}U
^{228}Ra	6.7	1.06×10^{-1}	^{232}Th
^{210}Pb	22.26	3.11×10^{-2}	^{238}U

“Concordia” Plot

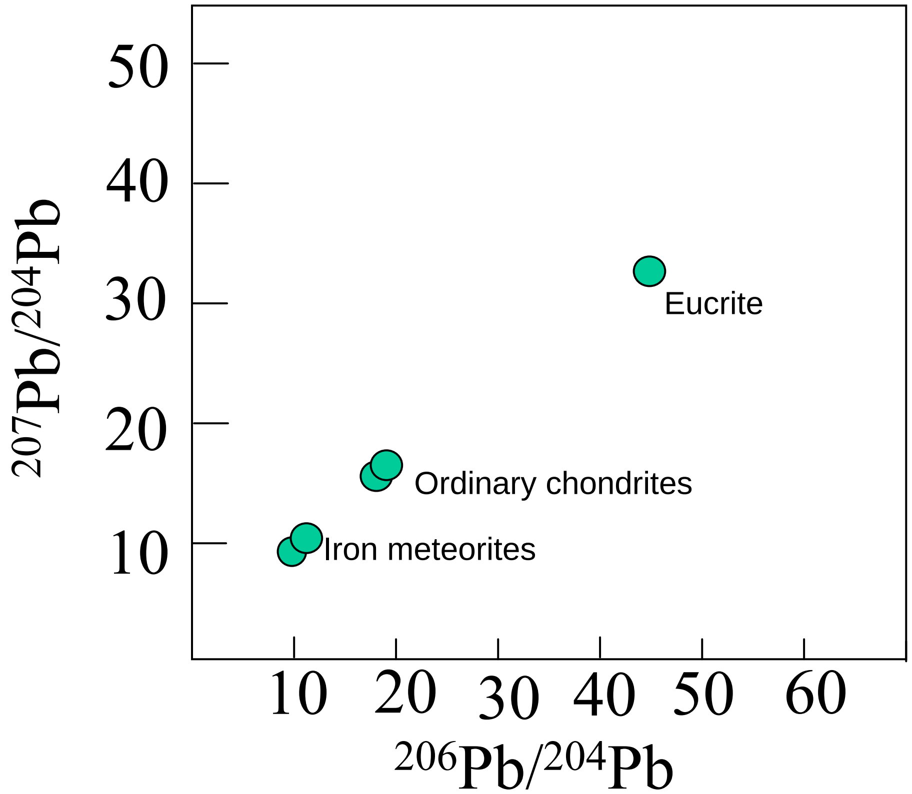


Different ways of plotting Pb-Pb isotope data



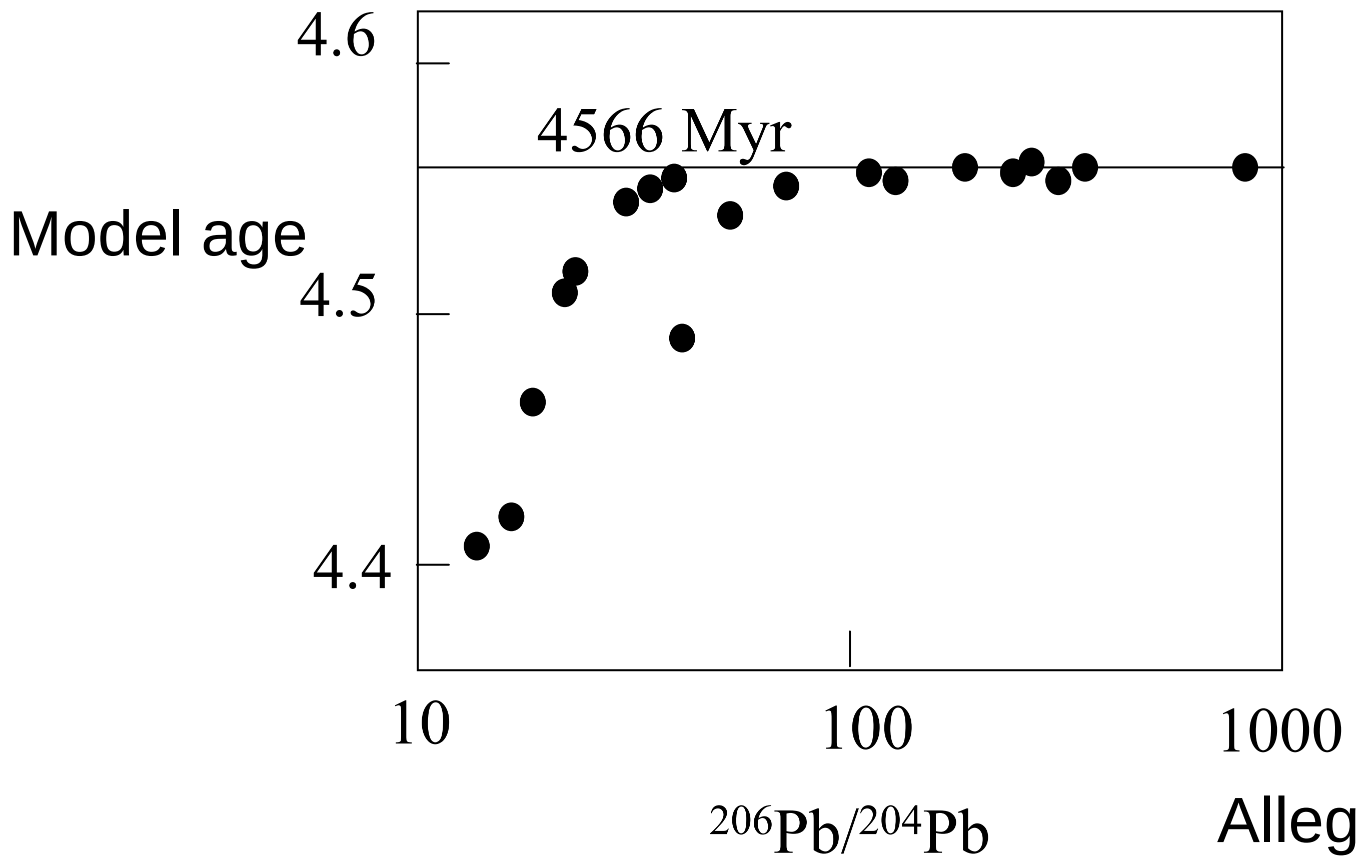


Age of Meteorites



Pioneering work by Clair Patterson (1956). He measured the lead isotope composition of several meteorites that produced an isochon corresponding to an age of 4.50±0.07 Gyr

Measurements of CAIs from Allende:



Allegre et al., 1995

Model ages based on $^{207}Pb/^{206}Pb$ give good data only for radiogenic samples.

Pb-Pb ages of meteorites

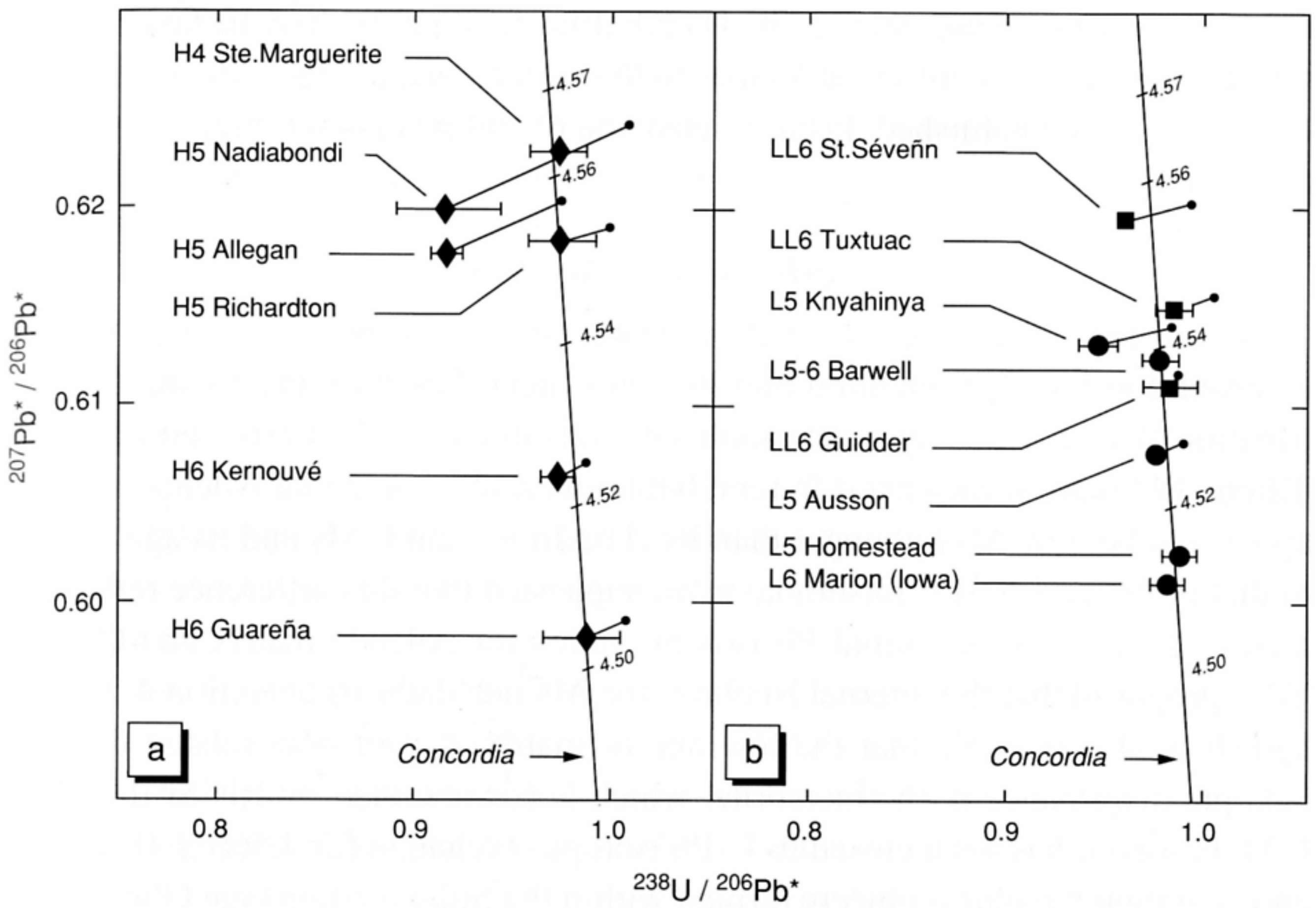
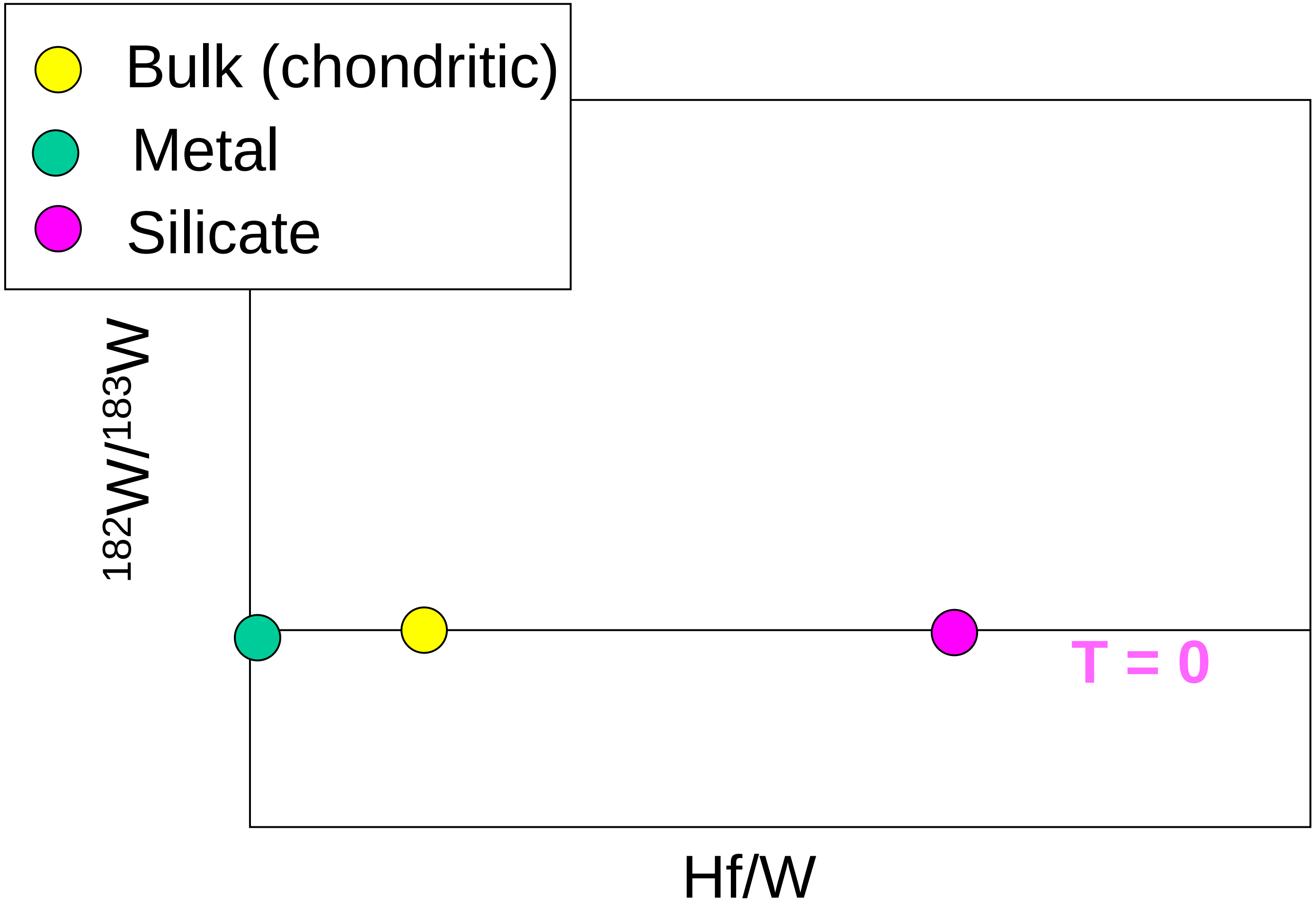


Fig. 6.6 U-Pb ages of separated phosphates of equilibrated ordinary chondrites.

Short-lived (extinct) radionuclides

First example – ^{182}Hf decays to ^{182}W with half life of ~9 Myr



Older samples = more ^{182}Hf on formation, steeper slope

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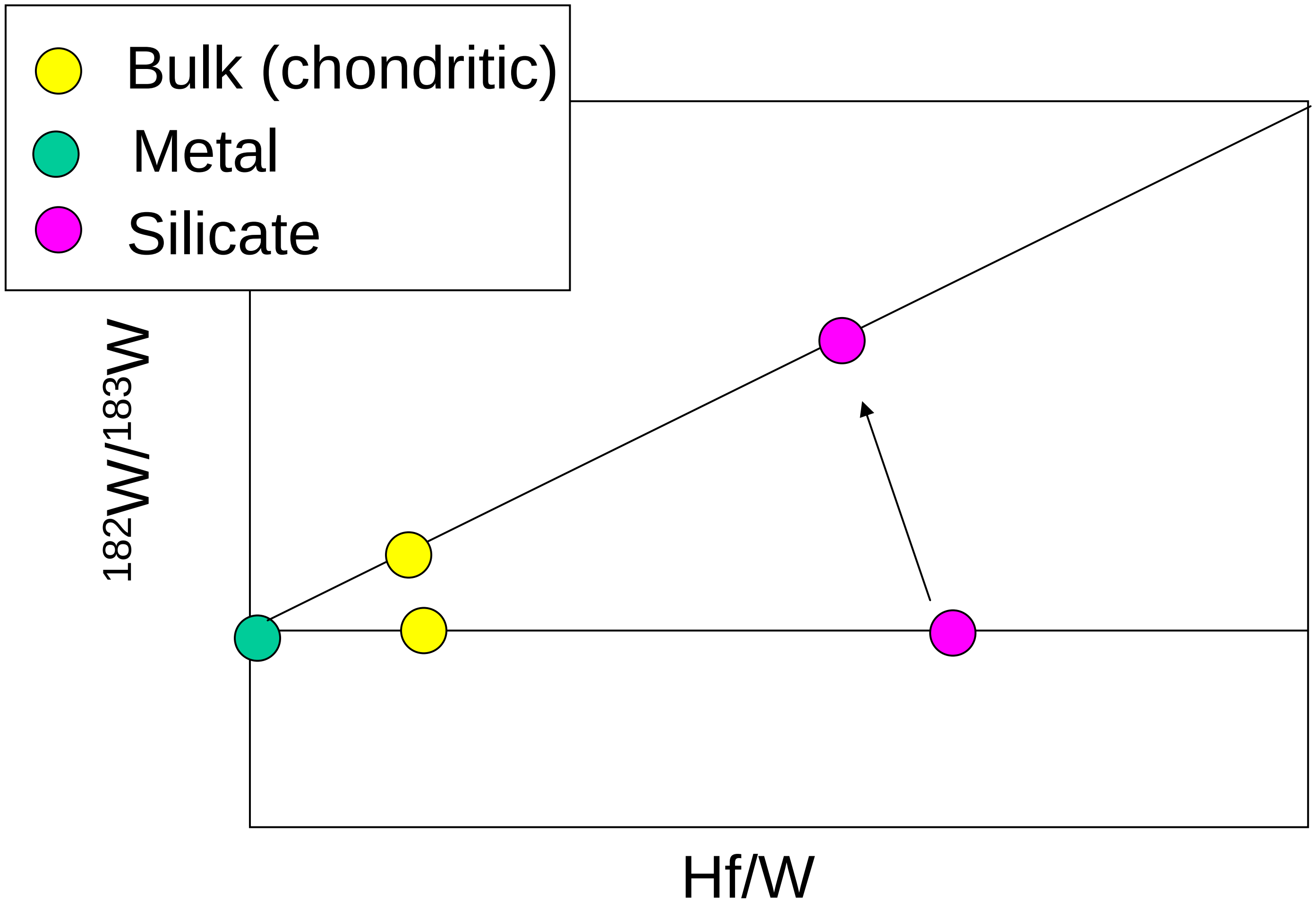

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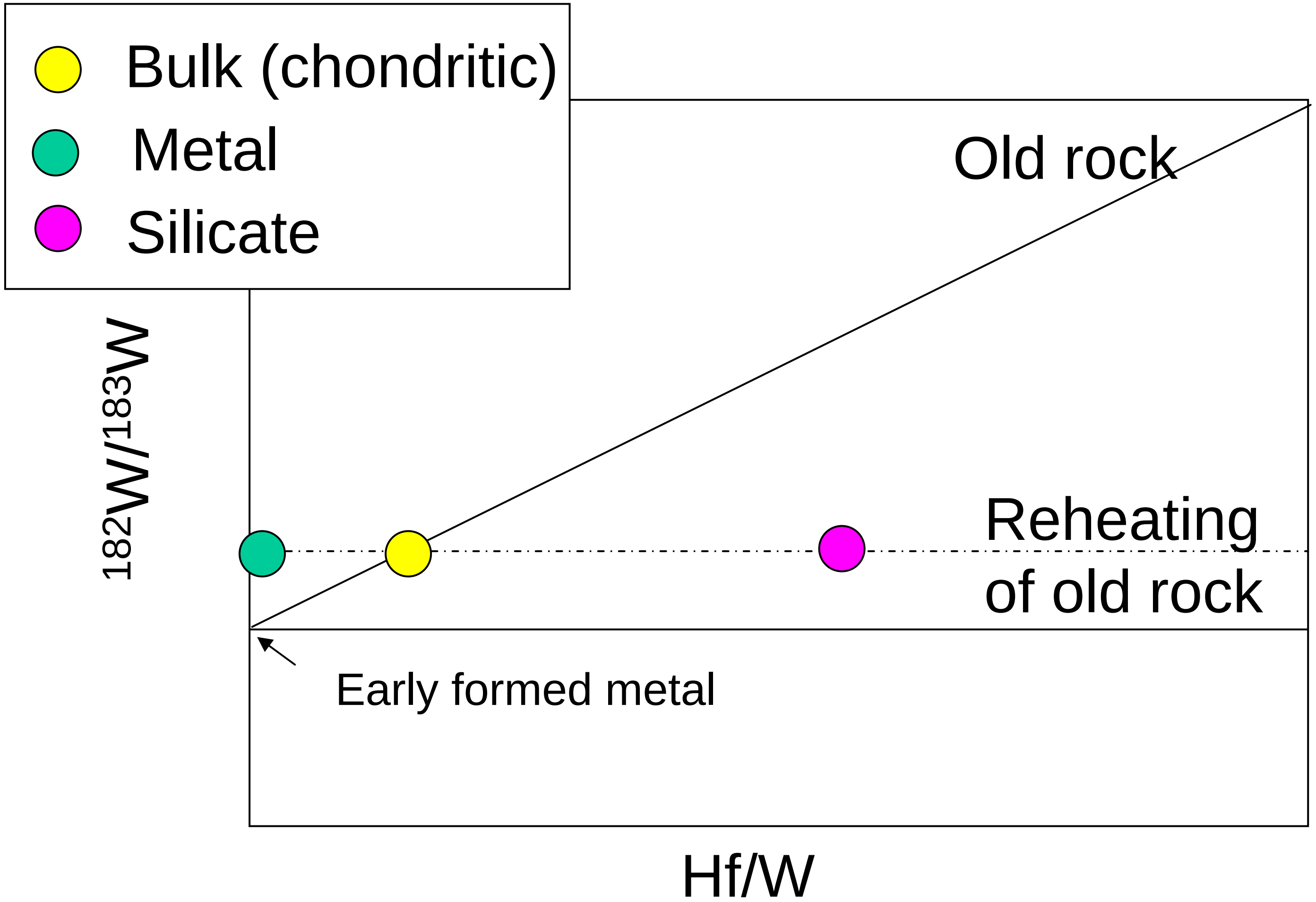
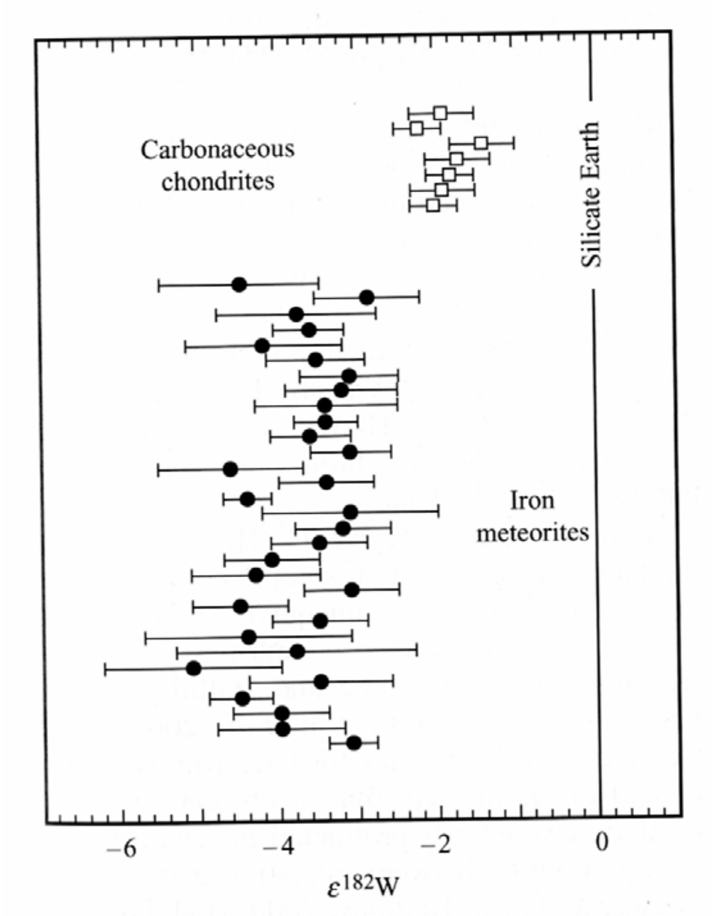


Older samples = more ^{182}Hf on formation, steeper slope

Age of the Earth



An excess of ^{182}W compared to carbonaceous chondrites and iron meteorites suggests that ^{182}Hf was still alive when Earth accreted – points to an early age.

See Halliday and Kleine, 2006.

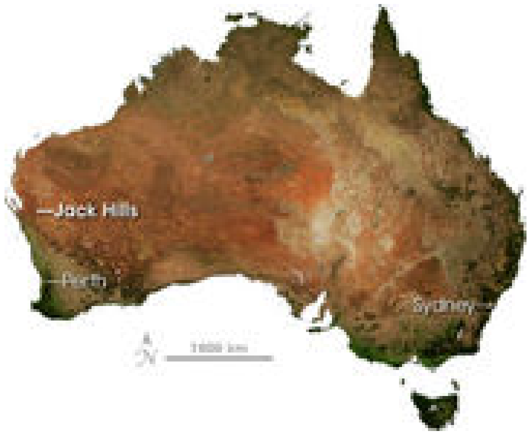
The Oldest Rocks on Earth

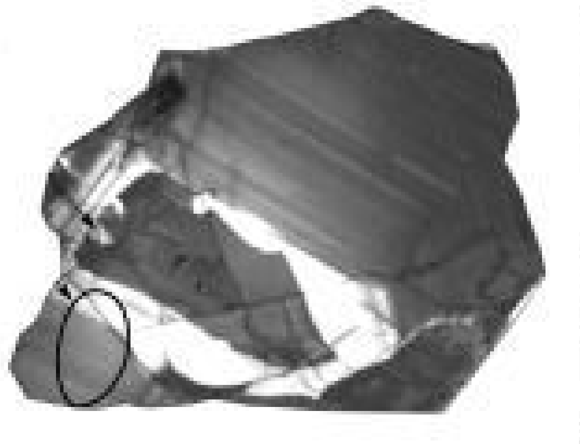
- ~3.75 Billion years old (W. Greenland).

Isua greenstone belt

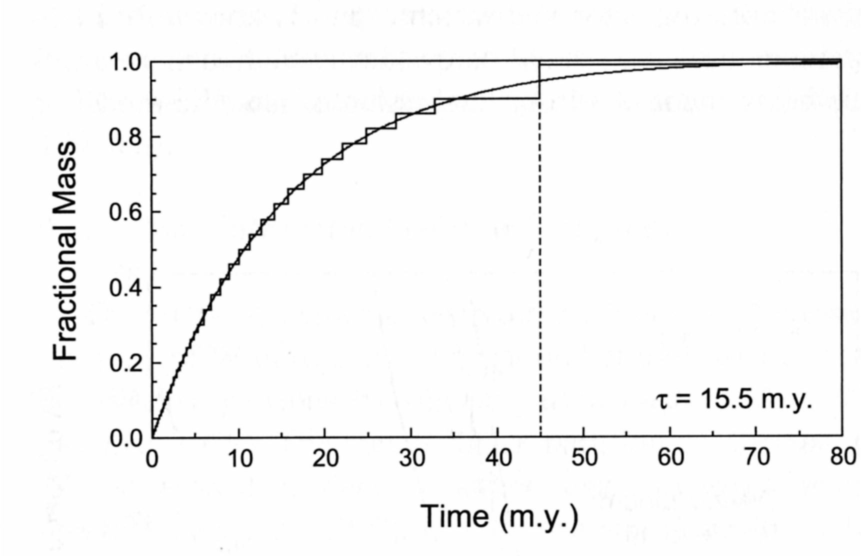
•Rocks of a similar age have recently been reported from Quebec- Cates and Mojzsis (2007)

Single minerals (zircons) can be older than rocks.
Oldest found in Jack Hills, Australia
Up to ~4.4 Gyr
Indicates differentiation and crust formation had occurred at this early stage

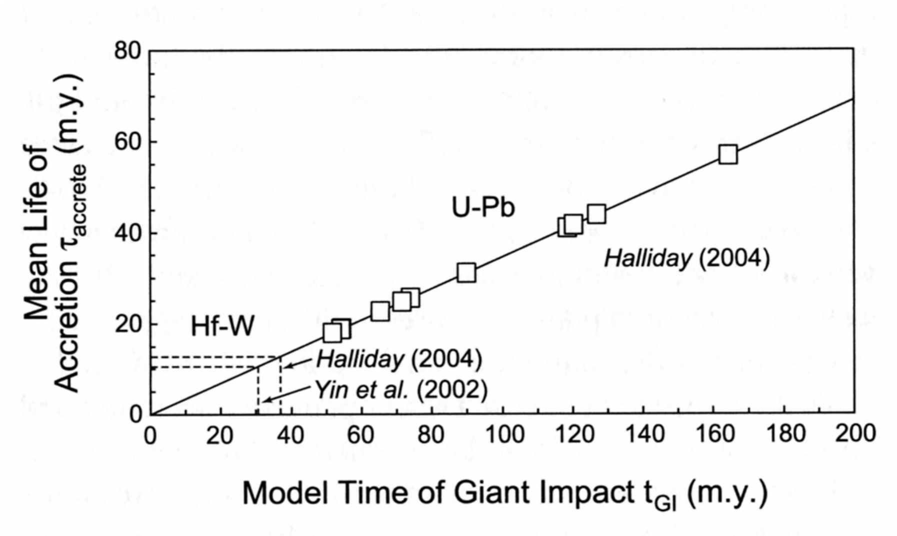




Age of the Earth 2



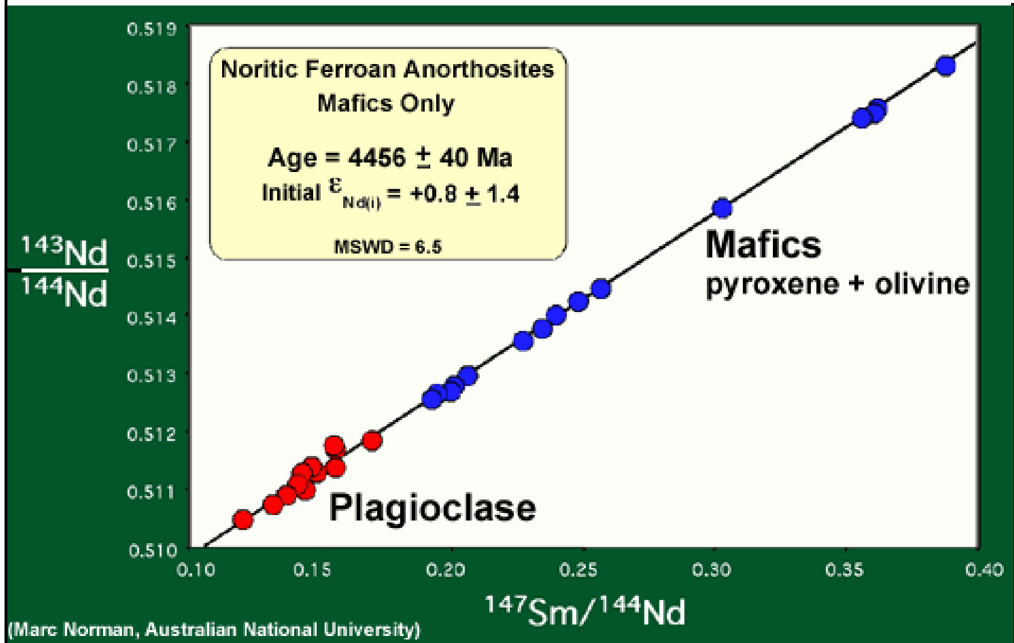
Model of the growth of the Earth from a series of impacts of differentiated objects. The growth rate decreases exponentially. Approximate mean life of accretion is the time taken to achieve 63% of final growth. (Halliday, 2004)

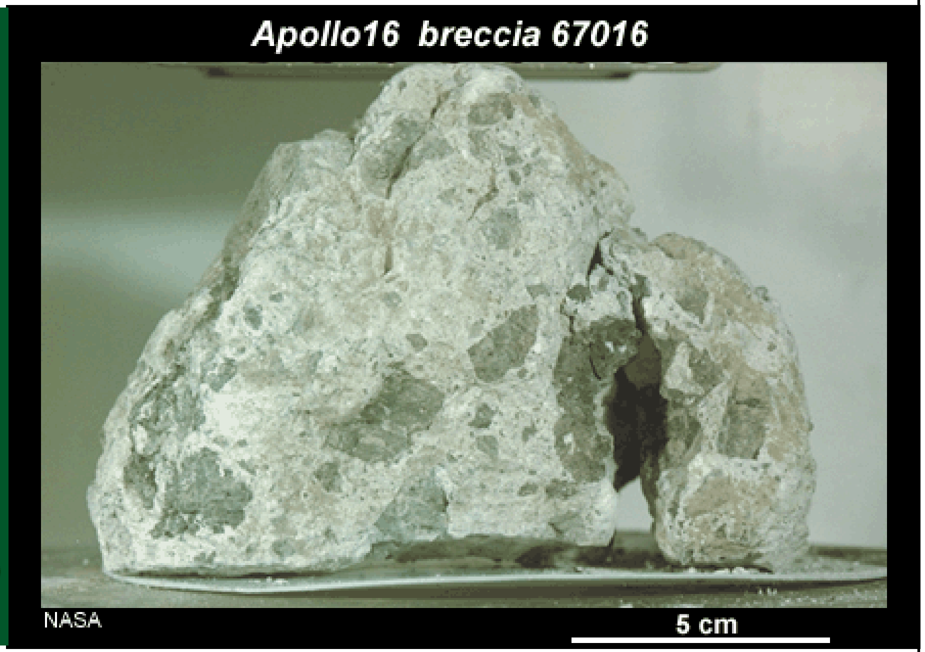


Calculated values for the Earth's mean life of accretion and the time of the giant impact. U-Pb give younger ages than Hf-W.
From Halliday and Kleine, 2006.

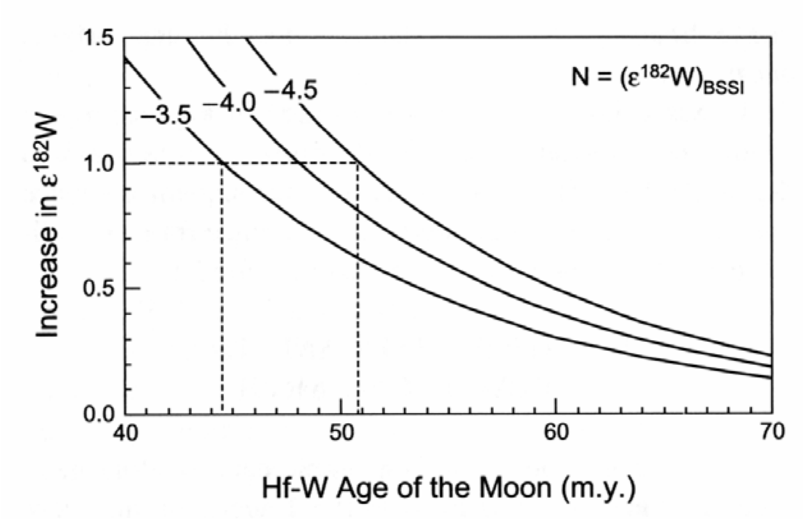
The oldest rocks on the Moon

- Anorthosite crust
- Approx 4.45 Gyr- 100 million years after formation of meteorites





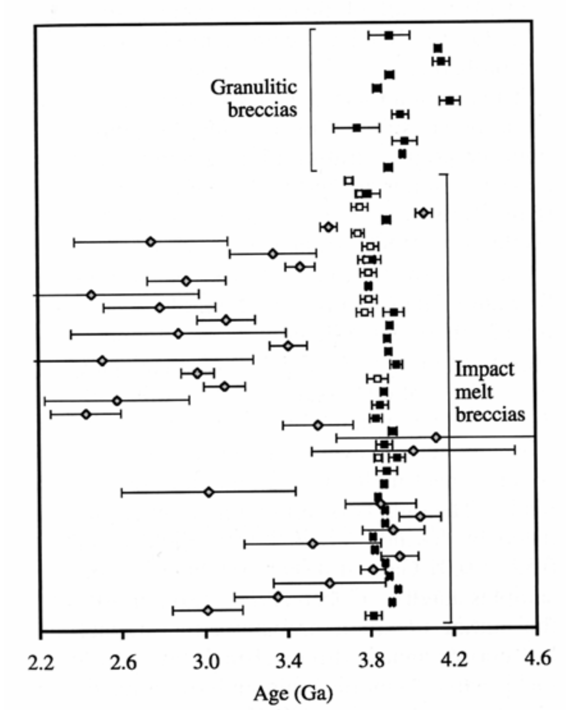
The Age of the Moon



The Hf-W age of the Moon is highly model dependent because of a contribution from cosmogenic ^{182}W.

Easier to interpret data from metal grains that are not affected by cosmogenic ^{182}W (no 181Ta) –age is 4.527 ± 0.010 billion years ago (Kleine et al. 2005)

Late Heavy Bombardment-
End of main stages of planetary accretion?

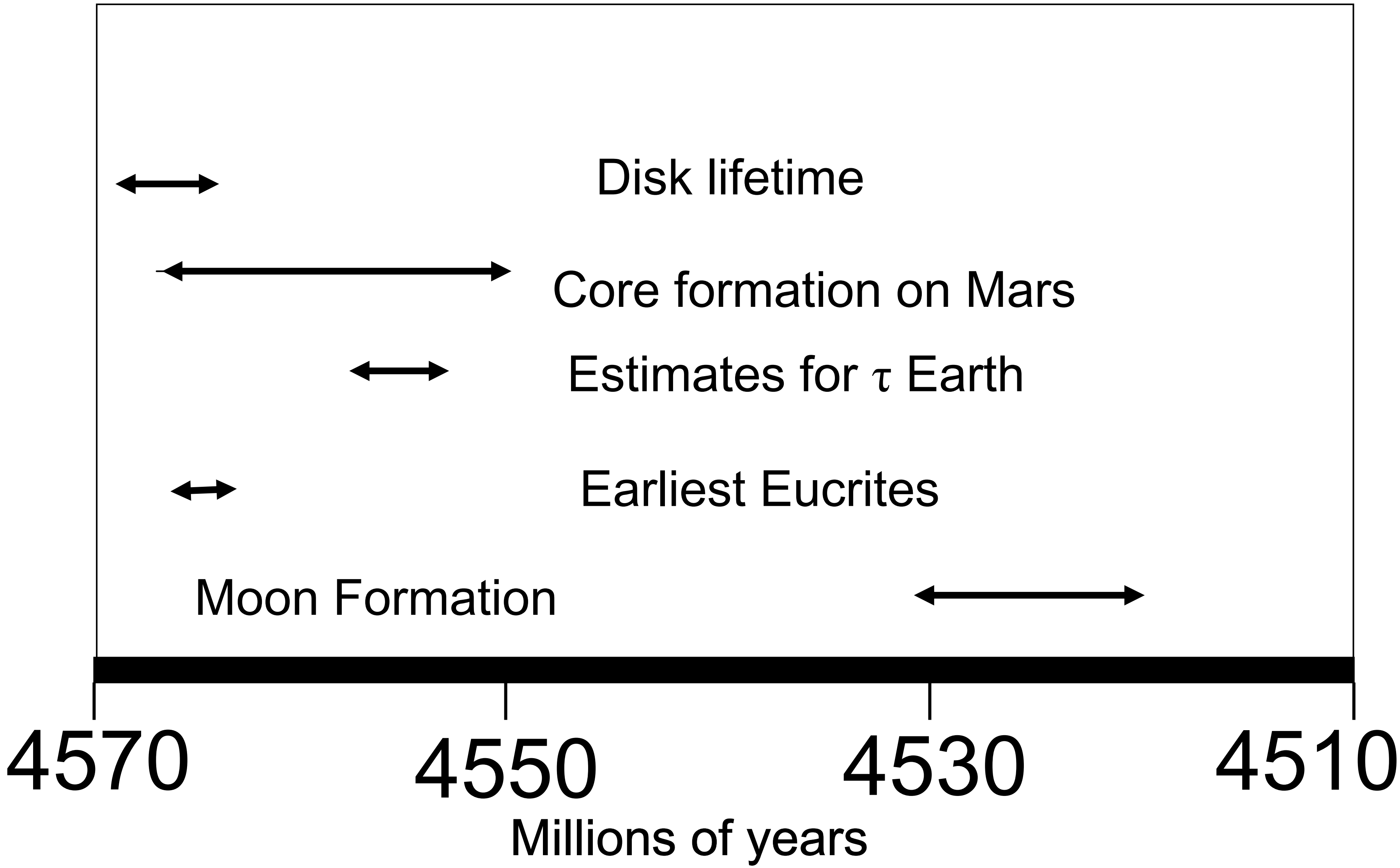


Ar –Ar ages of lunar breccias show a clustering of ages around 3.9 Gyr- a late heavy bombardment? (e.g. Warren, 2005)

Age of the Solar system 3. The oldest rock we have from Mars

- ALH84001- Sm-Nd age of ~4.5 Byr (Nyquist et al., 1995)
- Complex geological history

Summary figure of timescales



After Halliday and Kleine 2006

Conclusions

- The solar system is assumed to have formed from a disk such that the Sun and all the planets formed at approximately the same time
- This has been accurately dated using radioactive dating techniques.
- The most accurate of these is Pb-Pb dates, from which we have learnt that the oldest solids in the solar system are 4.567 billion years old
- In the next lecture, we will look at the timescales of processes that occurred immediately after the formation of these first solids.

References

General References:

Halliday A. and Kleine T. (2006) In: Meteorites and the Early Solar System.

Hutchison (2004). *Meteorites: A petrological and isotopic synthesis.* Cambridge University Press.

Russell S. et al., Meteorites and the Early Solar system 2. pp233-250.

Russell S. et al. The Origin of Short-lived isotopes. Trans. Roy. Soc.

Referred to in the text:

Allegre C. et al. (1995) *Geochimica Cosmochimica Acta* **59** 1445-1456.

Amelin, Y. et al., (2002) Pb isotopic ages of chondrules and CAIs. *Science* **297** 1678-1683.

Amelin Y. and Krot A. N. (2005) *LPSC* **XXXVI**, abstract #1247.

Cates and Mojzsis (2007) *Earth Plan. Sci. Lett*. **255** 9-21.

Halliday, A. (2004) *Nature* **427** 505-509.

Luck et al. (1980) *Nature* **283** 256-259.

Lugmair G. et al. (1975) *Earth Plan. Sci. Lett*. **27** 79-84.

Norman, M. D., Borg, L. E., Nyquist, L. E., and Bogard, D. D. (2003) *Meteoritics and Planetary Science,* **38**, 645-661.

Nyquist et al. (1995) Martians Young and Old… http://cmex.ihmc.us/MarsLife/LPI/nyqlxxvi.htm

Nyquist et al. (2001)Ages of martian meteorites http://seismo.berkeley.edu/~manga/nyquist.pdf

Papanastassiou D. and Wasserburg G.J. (1969) *Earth Plan. Sci. Lett.* **5** 361-376.

Patterson C. (1956) Age of the meteorites and the Earth. Geochim. Cosmochim. Acta 10 230-237.

Righter K. and Shearer, C. (2003) *Geochimica Cosmochimica Acta* **67** 2457-207.

Warren P. (2005) In: Meteorites Comets and Planets, Ed. A. M. Davis, Treatise on Geochemistry 1, Elsevier- Pergamon, Oxford.

Yin et al. (2004) *Nature* **418** 949-952.