



Introduction to Quantitative Geology

Lecturer: Ann-Kathrin Maier

Week 6 – Low-temperature thermochronology (II)



Last week

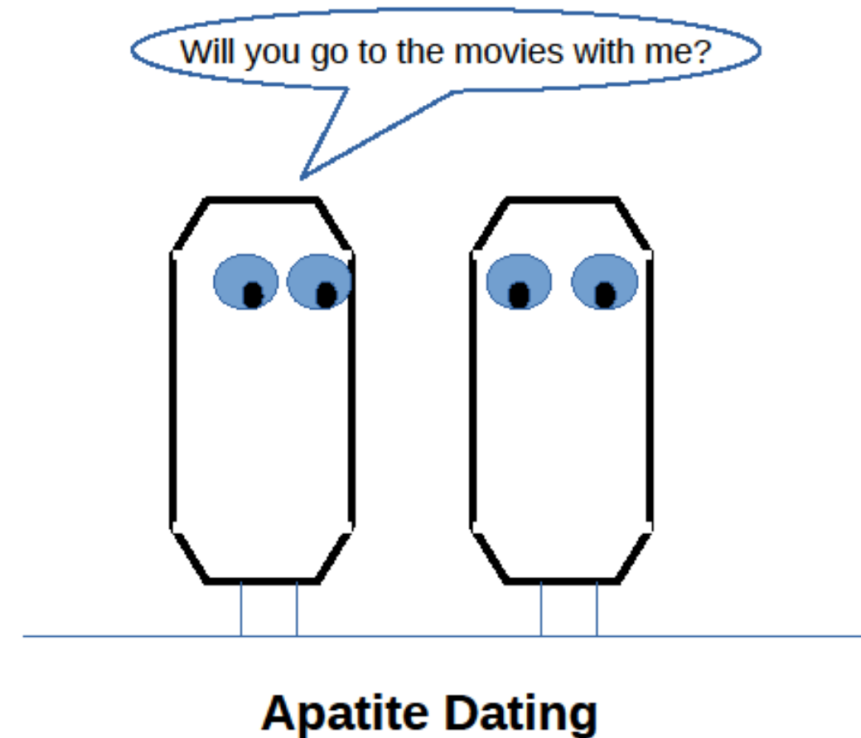
- **Rocks and ice as fluids**
- **Viscosity**
 - Definition
 - Viscous flow in a channel
 - Effects of temperature
 - Non-linear viscosity
- **Case study: Glaciers**





This week

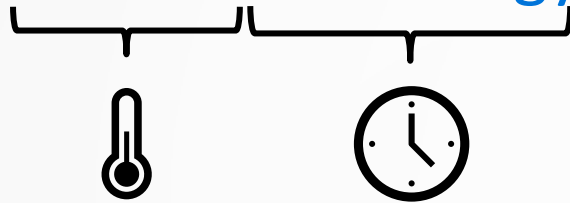
- **Low-temperature thermochronology**
 - Helium dating
 - Fission track dating
 - Argon dating
- **From rock to date**





Reminder: Thermochronology

Thermochronology



The science of inferring **thermal histories** of minerals and rocks.

Thermochronological ages

Interpreted as the time since the material cooled below a given temperature (**cooling ages**)

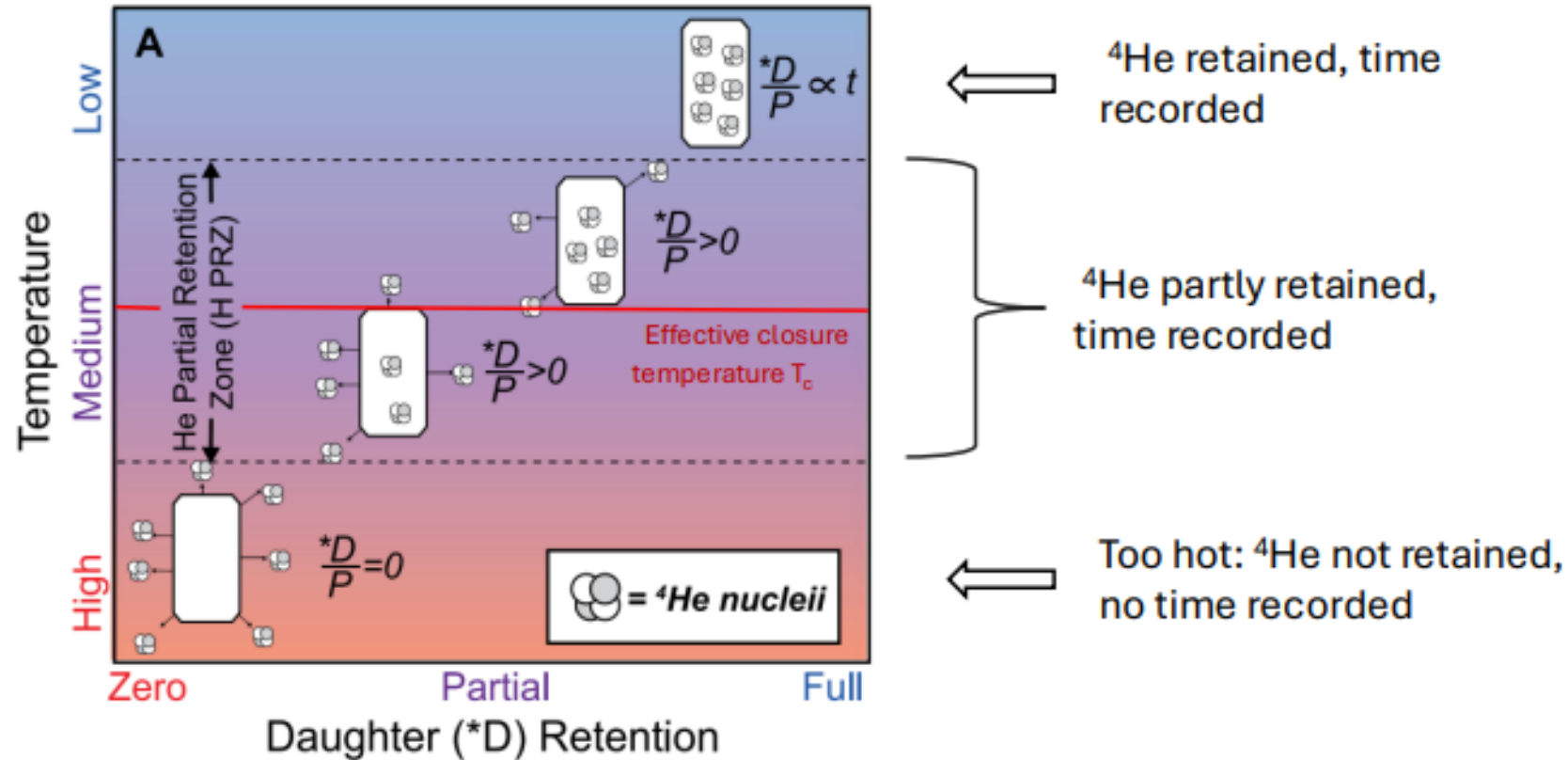
Thermochronometer

A radio-isotopic system consisting of:

- a radioactive parent
- a radiogenic daughter isotope or crystallographic feature
- the mineral in which they are found



Reminder: Effective closure temperature

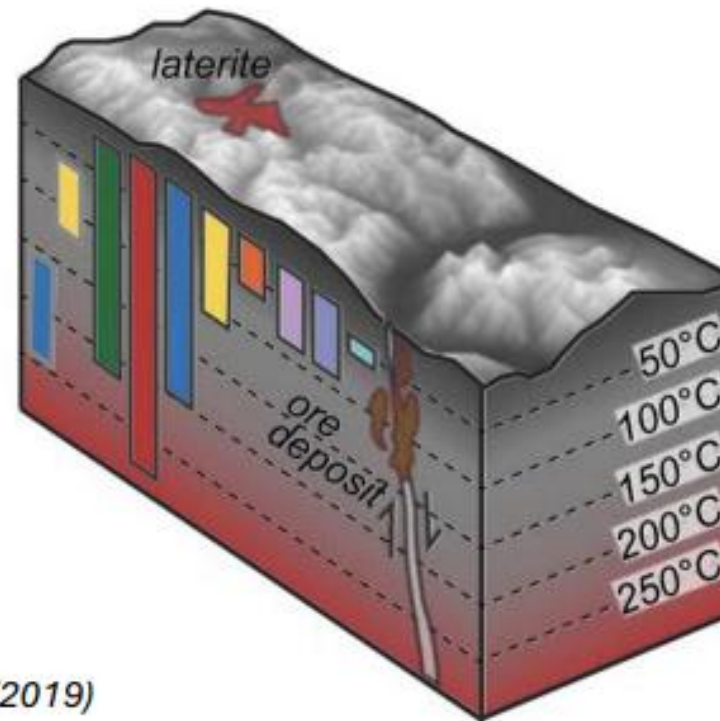
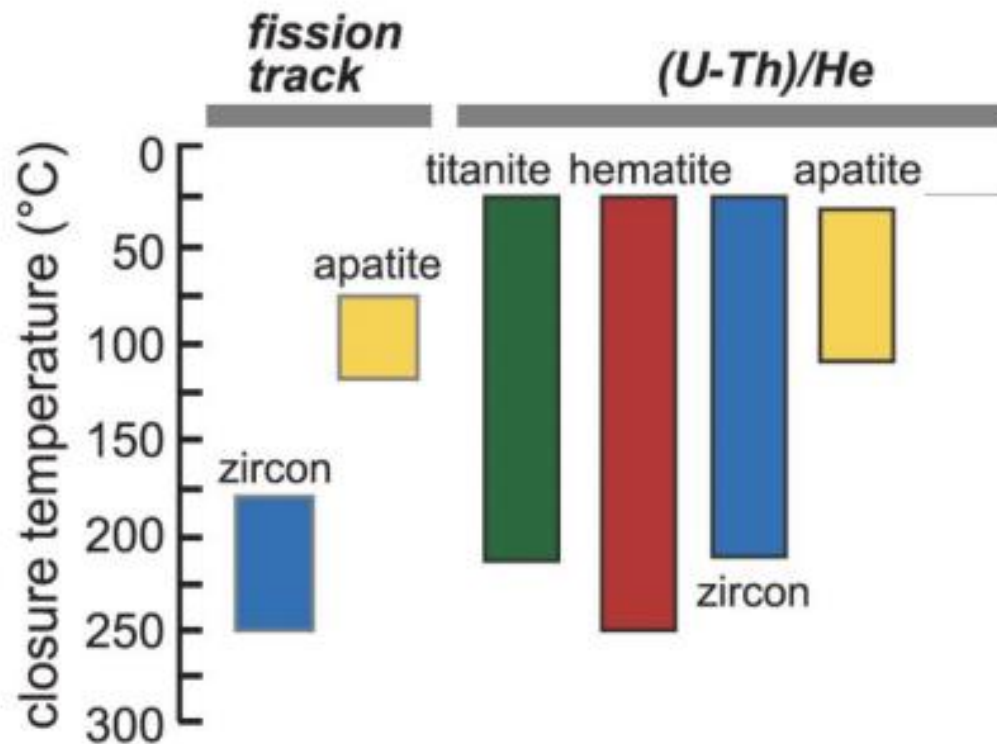


Closure temperature T_c :
"Temperature at the time corresponding to the apparent age"
(Dodson, 1973)

Flowers et al. (2022)



Reminder: Temperature sensitivities



different closure temperature ranges



different depths

Ault et al. (2019)



Why (low-temperature) thermochronology?

To investigate processes acting in the upper kilometres of the Earth's crust.



Andes: Climate and tectonic controls on topography



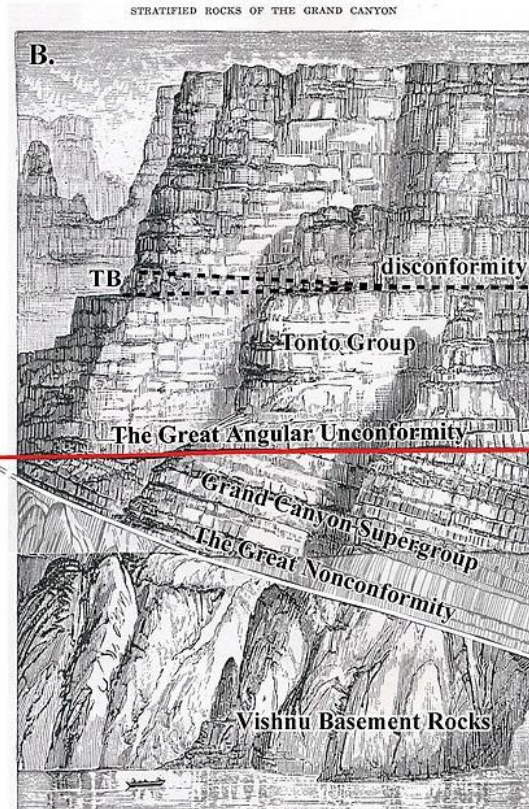
- River incision
- When did it start & why?
- How fast & how long?



- Endorheic altiplano
- How long will it persist?



The Great Unconformity: Missing time



USGS



Grand Canyon, Colorado, USA

- More time missing than recorded!
- Why?



Faults

History of fault activity?



[File:Kluft-photo-Carrizo-Plain-Nov-2007-Img 0327.jpg - Wikimedia Commons](#)

San Andreas Fault

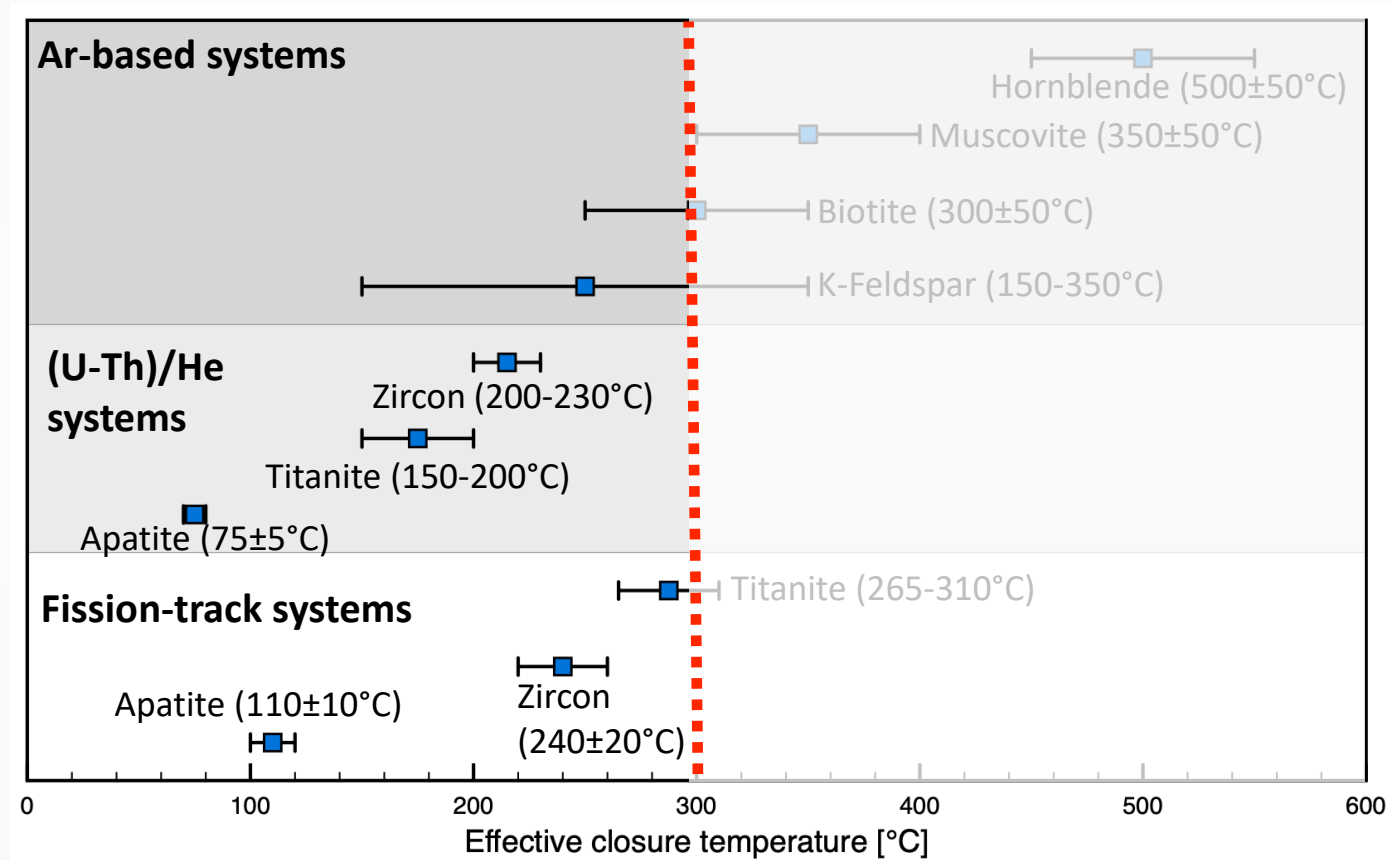


(Monash University)

Pseudotachylite



Low-temperature thermochronology

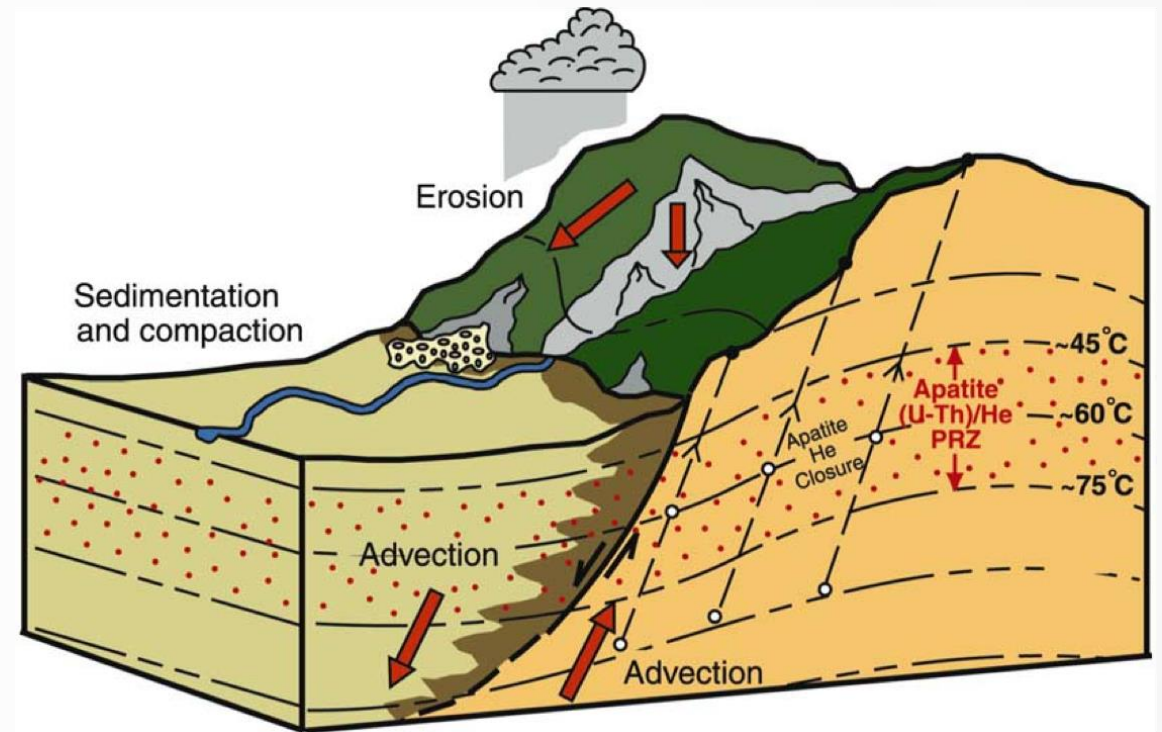


Low-T thermochronology uses thermochronometers with effective closure temperatures below ~300°C.



Why is thermochronology useful?

- Thermochronometers provide a constraint on the **time-temperature history** of a rock sample.
- In many cases, the age is the time since the sample cooled below the system-specific effective closure temperature.

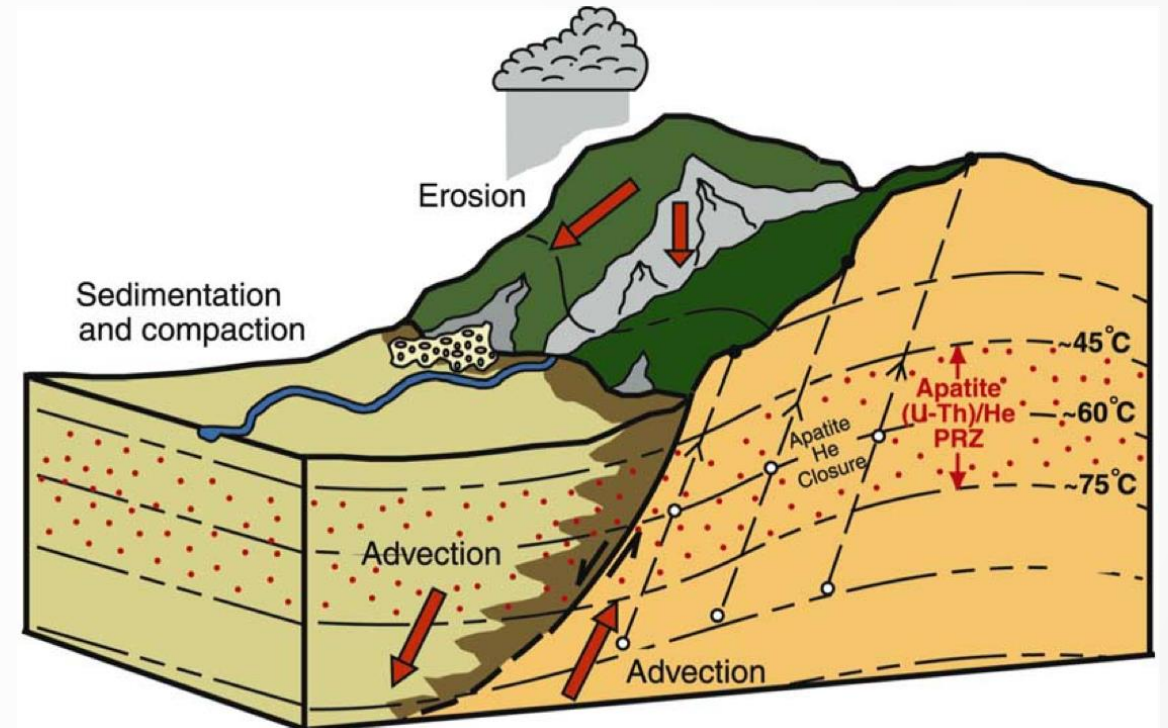


Ehlers and Farley, 2003



Why is thermochronology useful?

- Temperatures to which thermochronometers are sensitive generally occur at **depths of 1 to >15 km.**
 - **Ages are typically 1 to 100's of Ma**
- Record **long-term cooling** through the **upper part of the crust**

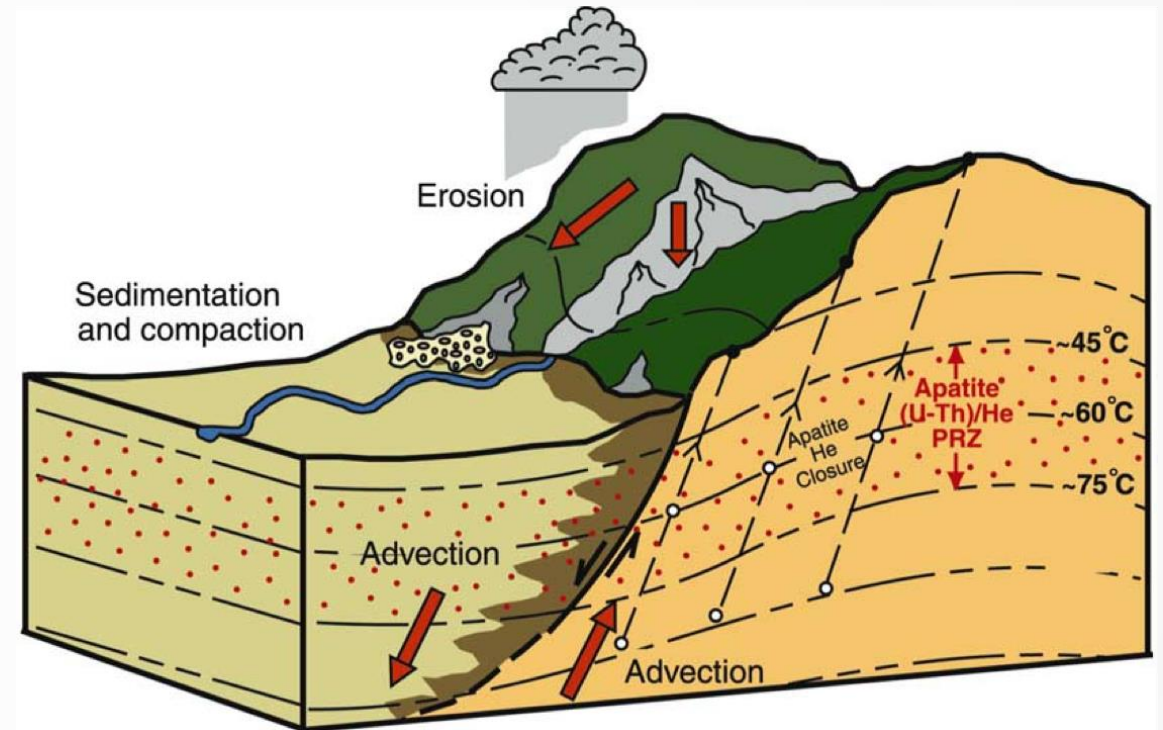


Ehlers and Farley, 2003



Why is *low-T* thermochronology useful?

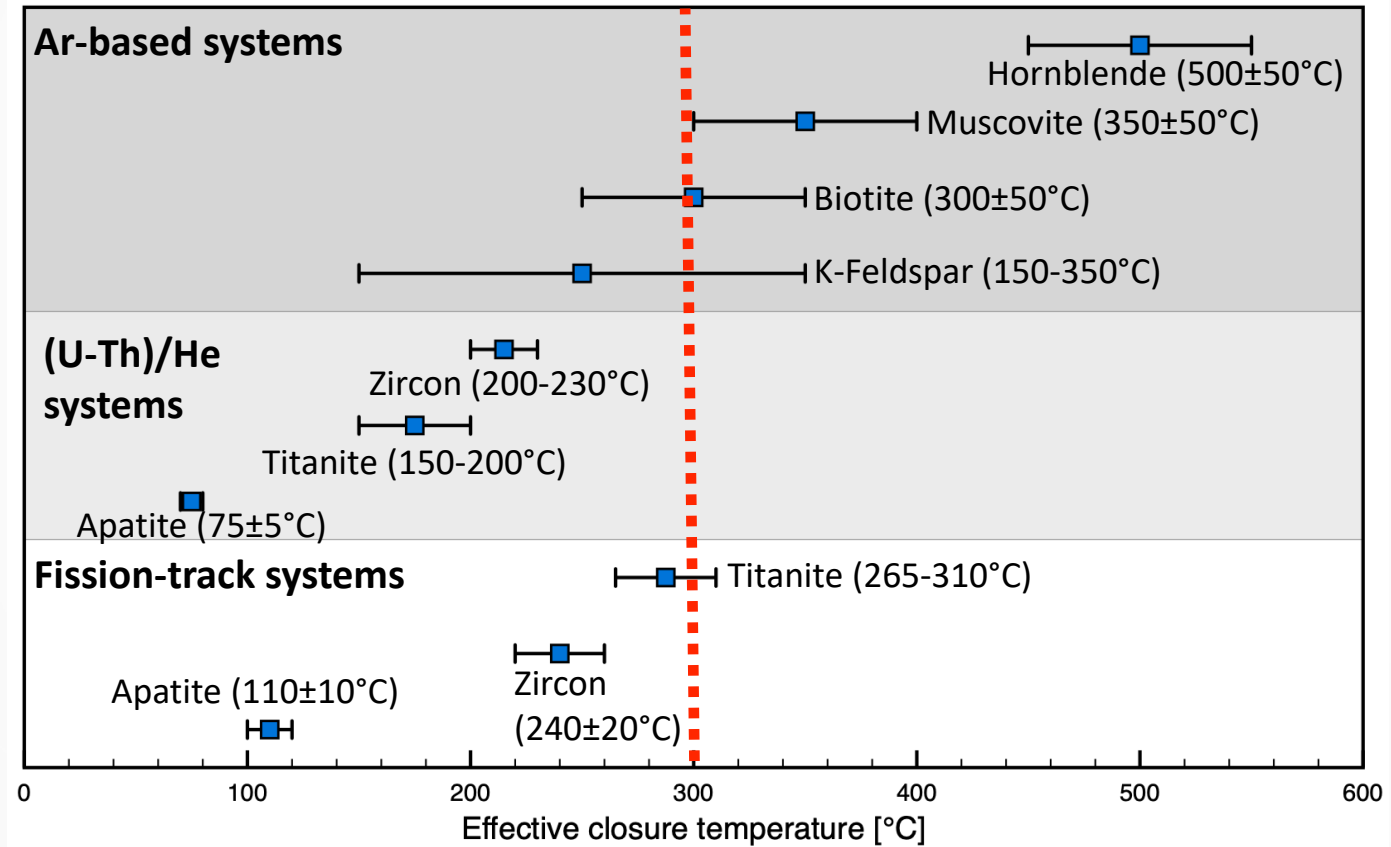
- Low-temperature thermochronometers: **Increased sensitivity to topography, erosional and tectonic processes!**



Ehlers and Farley, 2003



Common thermochronometers





Helium dating - (U-Th)/He method

- Ignoring the contribution of ^{147}Sm , we can say that the production of ^4He is

$$\begin{aligned}
 ^4\text{He} = & 8 \times ^{238}\text{U} (e^{\lambda_{238}t} - 1) \\
 & + 7 \times \frac{^{238}\text{U}}{137.88} (e^{\lambda_{235}t} - 1) \\
 & + 6 \times ^{232}\text{Th} (e^{\lambda_{232}t} - 1)
 \end{aligned}$$

where ^4He , ^{238}U and ^{232}Th are the present-day abundances of those isotopes, t is the He age and the λ values are the decay constants

Production of alpha particles by decay

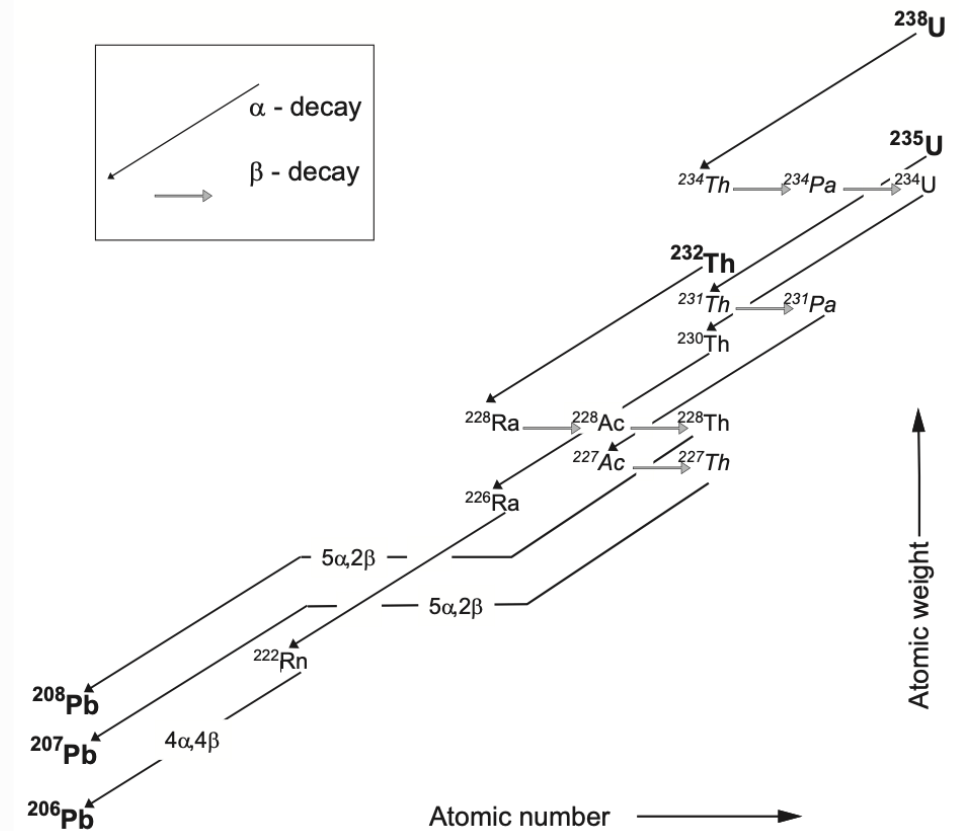


Fig. 3.3, Braun et al., 2006



Fission track dating

- **Fission-track dating** is based on measuring the **accumulation of damage trails in a host crystal** as the result of spontaneous fission of ^{238}U
- Fission splits the ^{238}U atom into two fragments that repel and damage the crystal lattice over the distance they travel

Spontaneous Nuclear Reaction

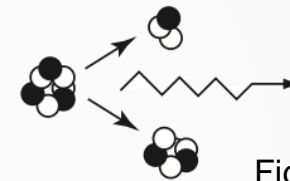
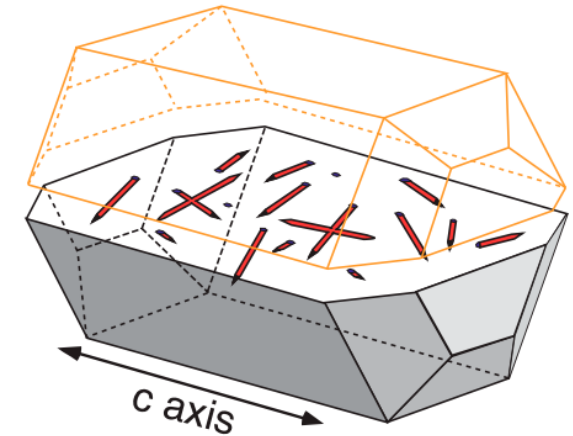


Fig 1.1, Braun et al., 2006



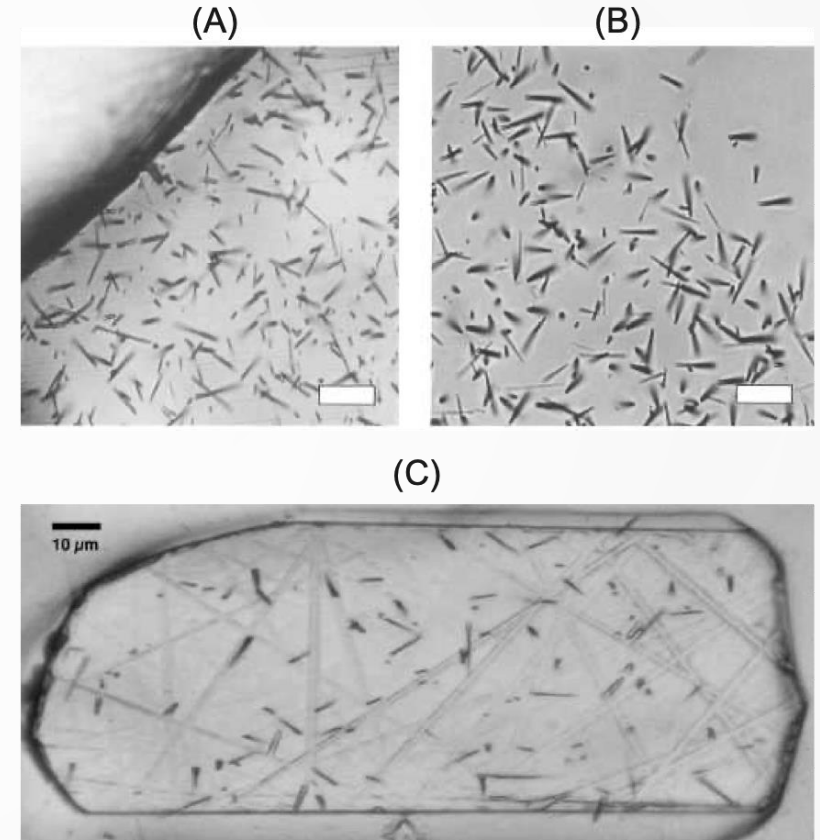
Kohn et al., 2024



Fission track dating

- **Fission-tracks: damage trails** in a host crystal resulting from spontaneous fission of ^{238}U
- Fission tracks repair, or **anneal**, at temperatures above T_c
- In apatite: fresh fission tracks are $\sim 16 \mu\text{m}$ long
- In Zircon: fresh fission tracks are $\sim 11 \mu\text{m}$ long

Etched fission tracks in apatite



Tagami and O'Sullivan, 2005

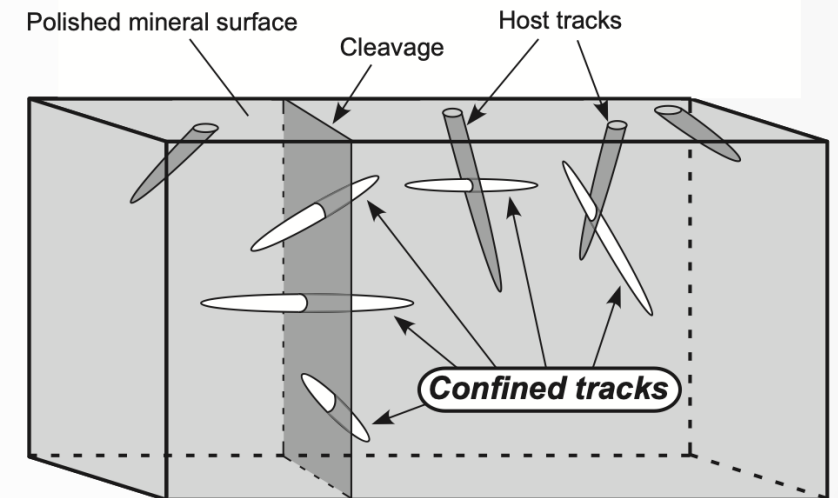


Fission track dating

- To be visible under a microscope, tracks must be chemically etched and enlarged
- The FT age can be calculated as

$$t = \frac{1}{\lambda_D} \ln \left(\frac{\lambda_D}{\lambda_f} \frac{N_s}{^{238}\text{U}} + 1 \right)$$

where λ_D is the ^{238}U decay constant, λ_f is the fission decay constant, N_s is the number of spontaneous fission tracks in the sample and ^{238}U is the number of ^{238}U atoms



Tagami and O'Sullivan, 2005



Argon dating - $^{40}\text{Ar}/^{39}\text{Ar}$ method

- Argon dating is based on the decay of ^{40}K to radiogenic ^{40}Ar
- $^{40}\text{Ar}/^{39}\text{Ar}$ dating is used on white micas, biotite, K-feldspar and amphiboles



Rob Lavinsky, [File:Muscovite-Albite-122837.jpg](https://commons.wikimedia.org/wiki/File:Muscovite-Albite-122837.jpg) - Wikimedia Commons

Muscovite



Argon dating - $^{40}\text{Ar}/^{39}\text{Ar}$ method

- Step 1: **Irradiate a sample (and standard) with fast neutrons** to produce ^{39}Ar from ^{39}K in the sample
- Step 2: Degas the sample to measure the $^{40}\text{Ar}/^{39}\text{Ar}$ ratio.
- Step 3: Calculate the $^{40}\text{Ar}/^{39}\text{Ar}$ age as
$$t = \frac{1}{\lambda} \ln \left(1 + J \frac{^{40}\text{Ar}}{^{39}\text{Ar}} \right)$$

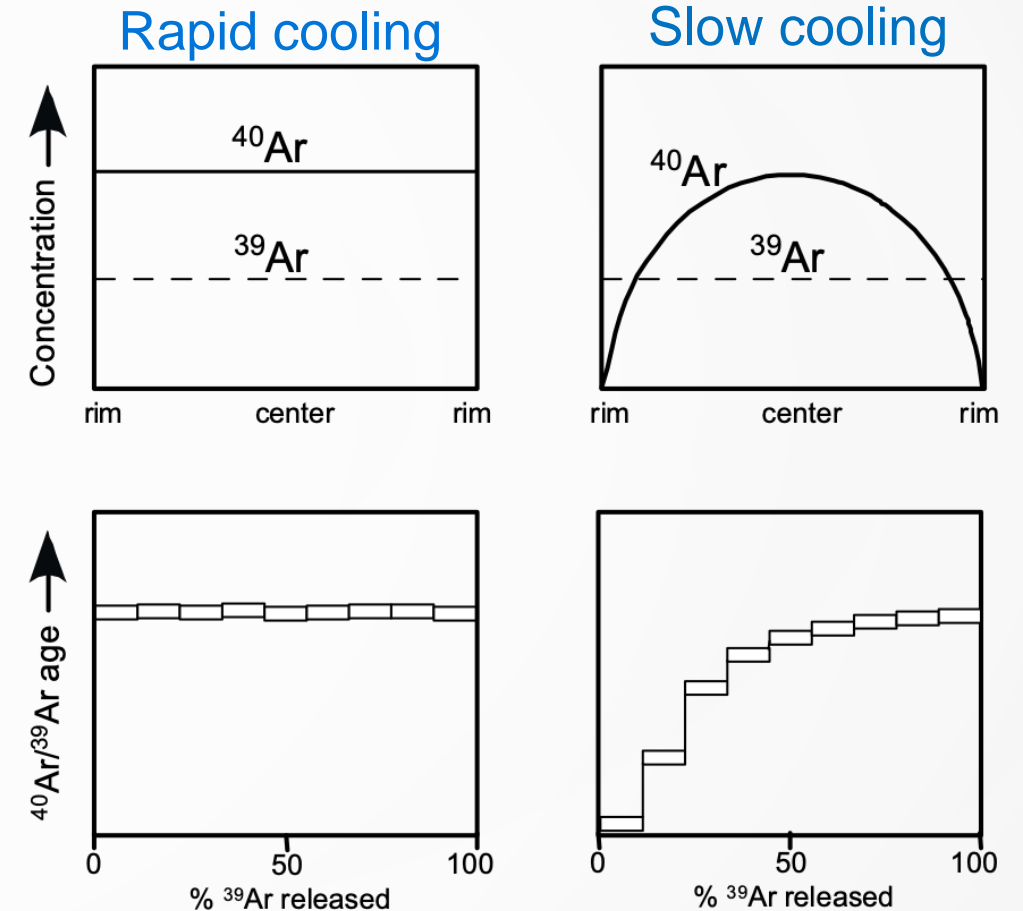
where λ is the **decay constant of ^{40}K** , $^{40}\text{Ar}/^{39}\text{Ar}$ is the **measured sample $^{40}\text{Ar}/^{39}\text{Ar}$ ratio** and J is the **irradiation factor**
$$J = \frac{e^{\lambda t} - 1}{^{40}\text{Ar}/^{39}\text{Ar}}$$

where t is a **known age for a standard** and $^{40}\text{Ar}/^{39}\text{Ar}$ is its **measured $^{40}\text{Ar}/^{39}\text{Ar}$ ratio**



Argon dating - Step heating

- **Stepwise heating** of samples to gradually release Ar as the sample temperature increases
- ^{40}Ar distribution in the sample is a function of the sample cooling history



Harrison and Zeitler, 2005



Argon dating – Age spectra

- a) Flat age spectra indicate rapid cooling of a rock sample (at time t_1)
- b) Curved spectra with lower concentrations initially either indicate partial reheating of the sample at time t_2 or slow cooling from t_1 to t_2
- c) Unexpected higher Ar concentrations near the rim of the grain: “Excess” Ar may have been taken up from surrounding minerals

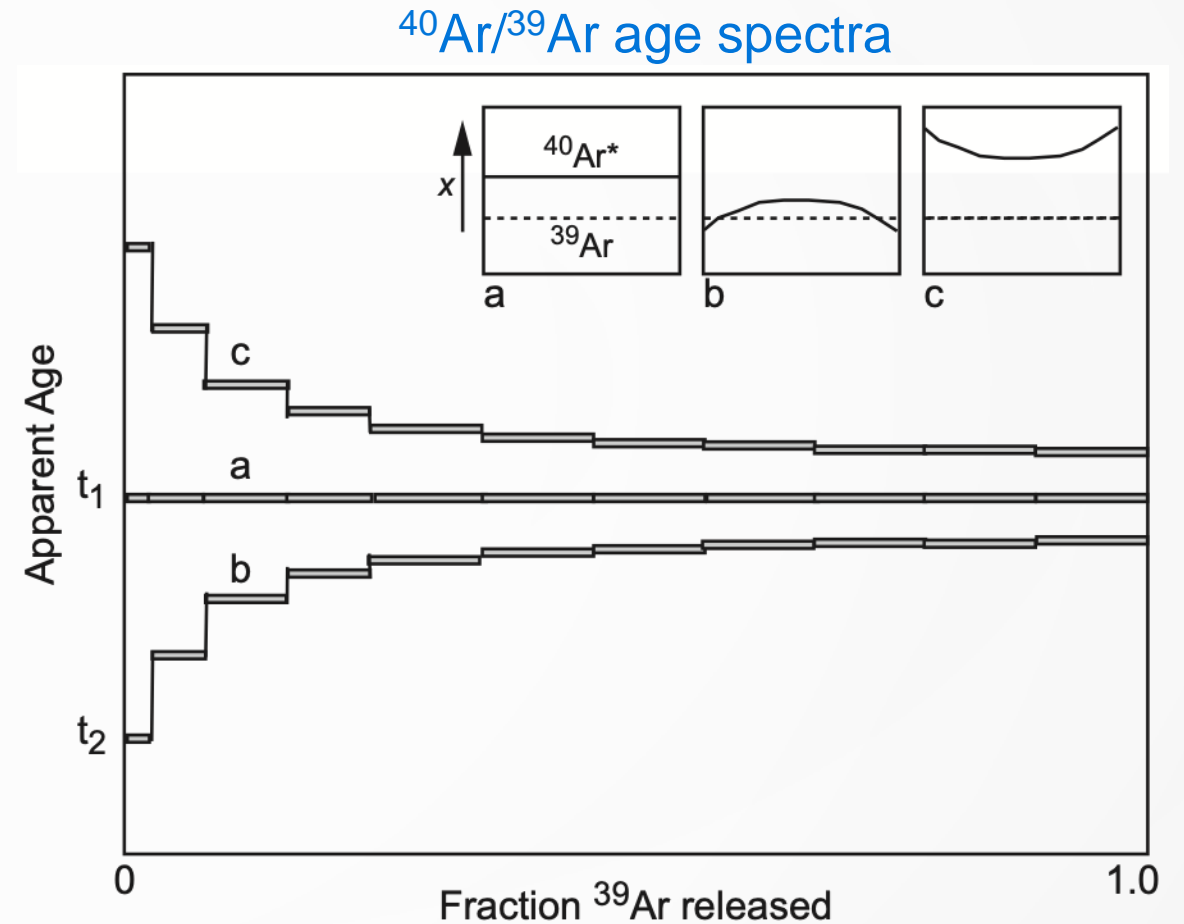


Fig. 3.1, Braun et al., 2006



Helium dating: From rock to date



Step 1: Find a rock



Helium dating: From rock to date



Step 2: Break the rock



Helium dating: From rock to date



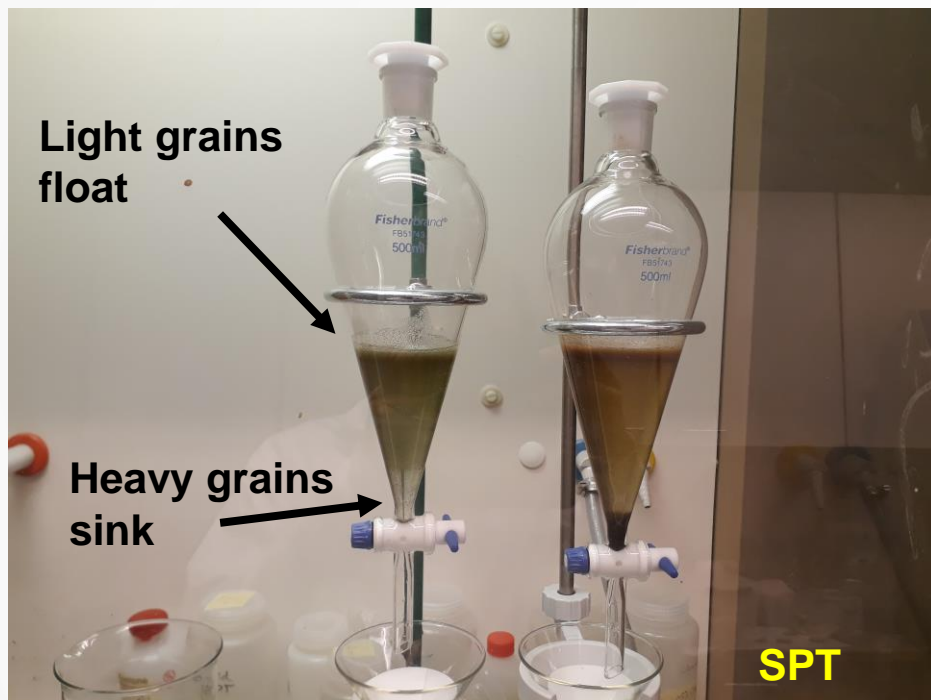
Step 3: Sieving



Step 4: Magnetic separation



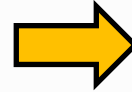
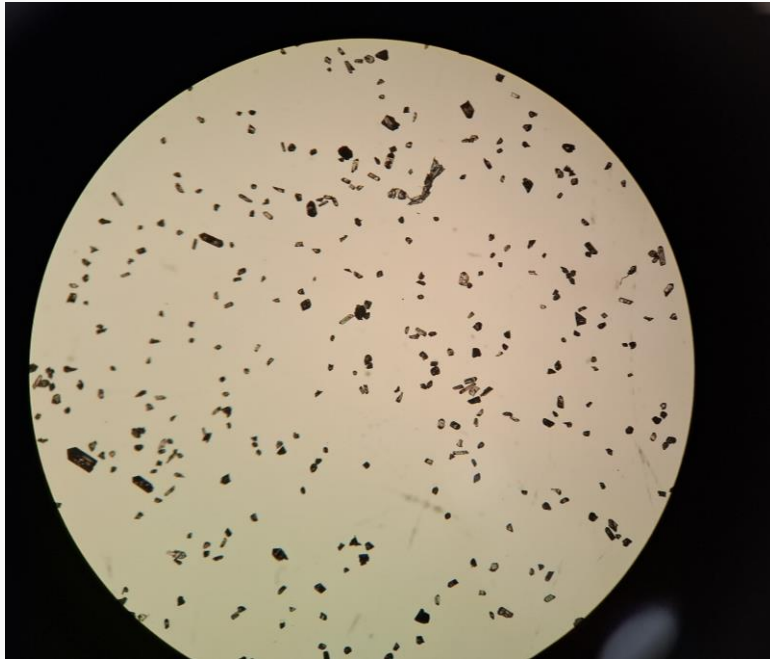
Helium dating: From rock to date



Step 5: Separation by density in "heavy liquids"



Helium dating: From rock to date



Step 6: Find grains for dating
(This can take several hours!)



Helium dating: Grain selection criteria

- Selected mineral grains for dating should be euhedral, homogeneous, free of inclusions and fractures, and $> 60 \mu\text{m}$.
- Why does the crystal form matter?
 - Alpha particles travel $\sim 20 \mu\text{m}$ when created and may be ejected from or injected into the sample crystal
 - We can correct for this!

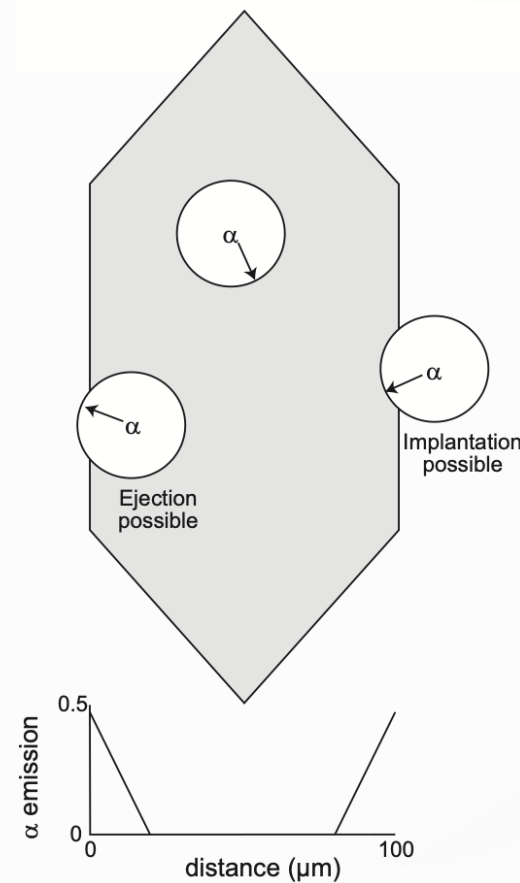
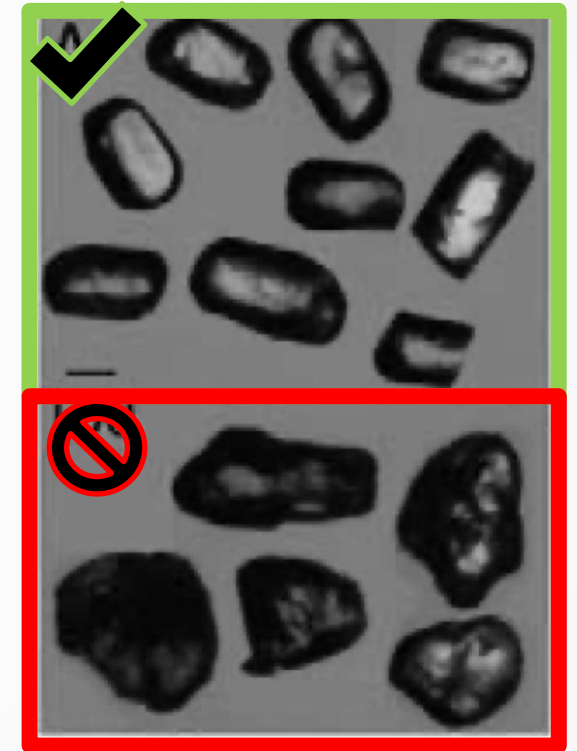


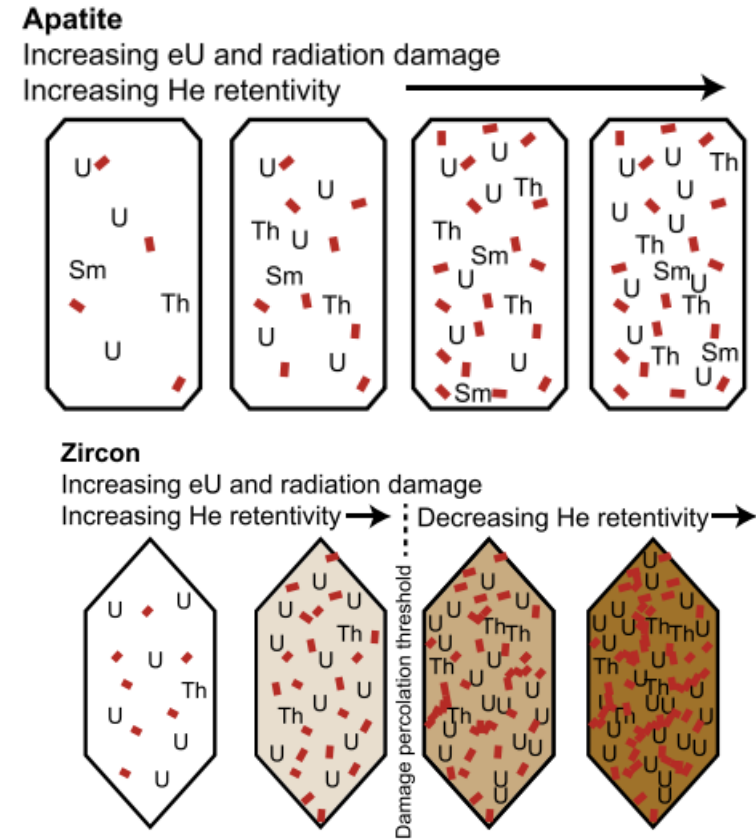
Fig. 3.4, Braun et al., 2006



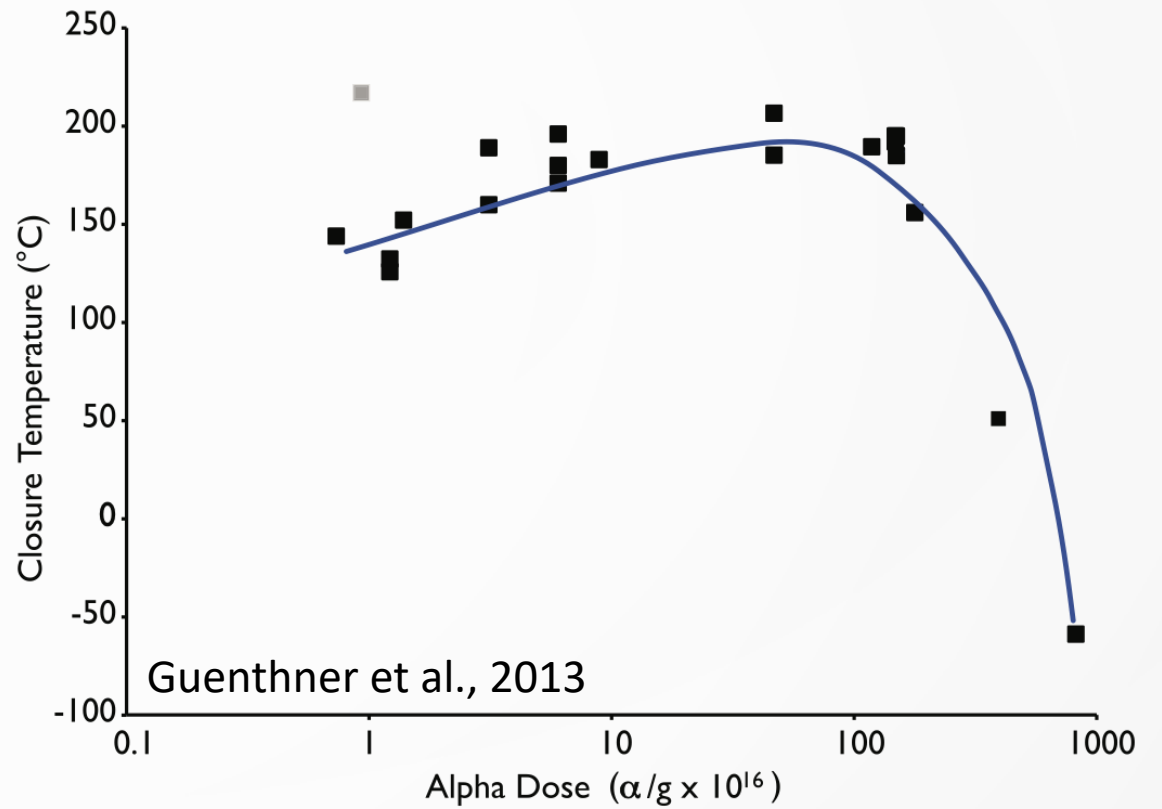
Ehlers and Farley (2003)



Another complication: Radiation damage

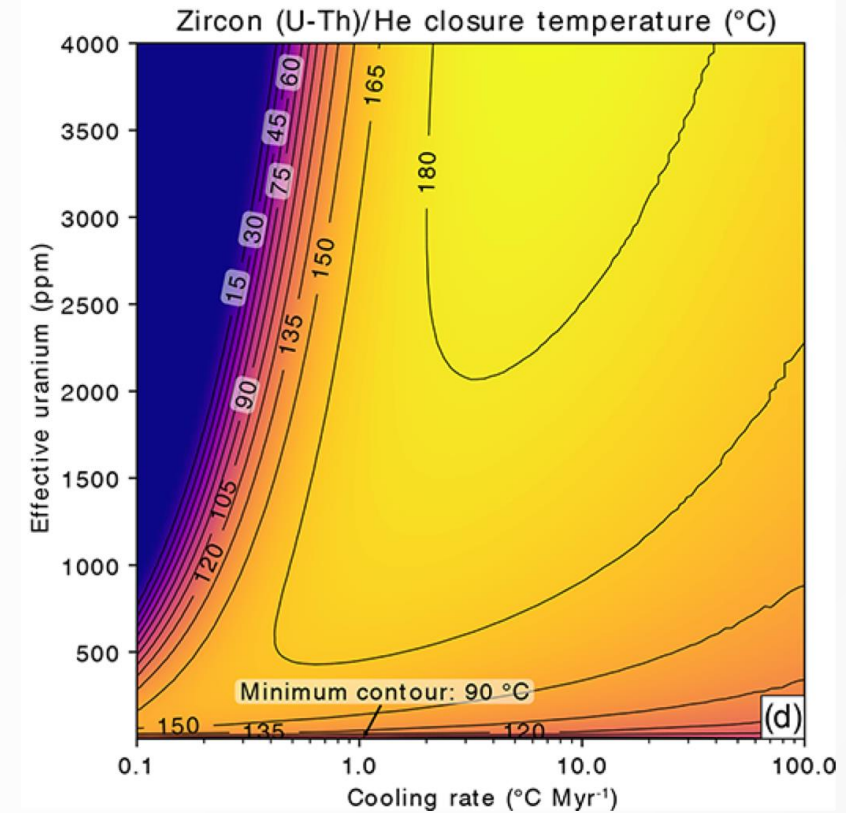
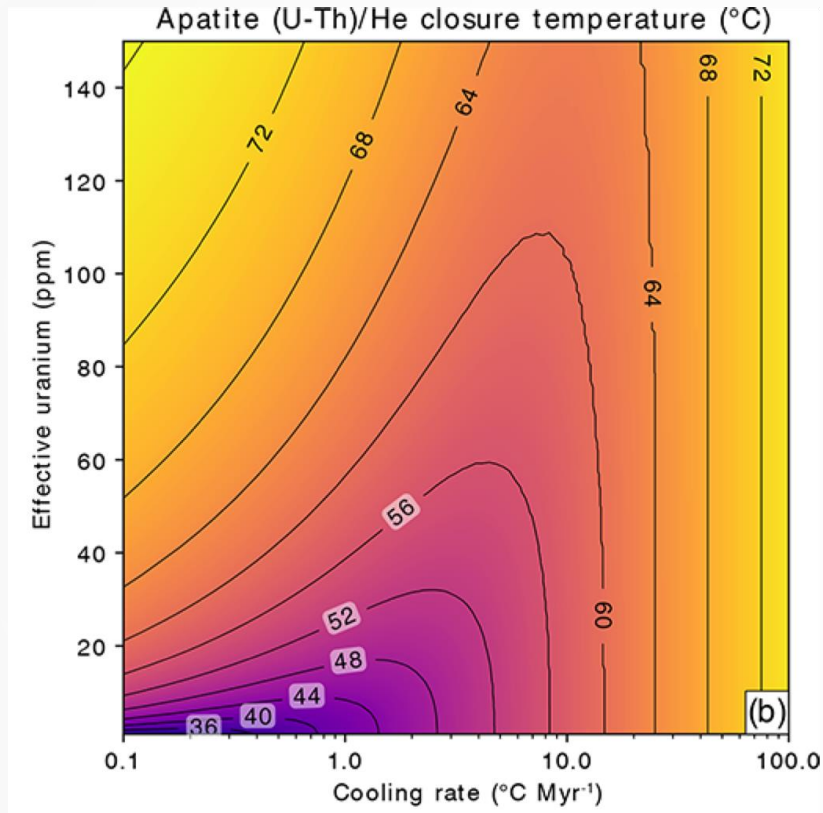


Flowers et al. (2022)





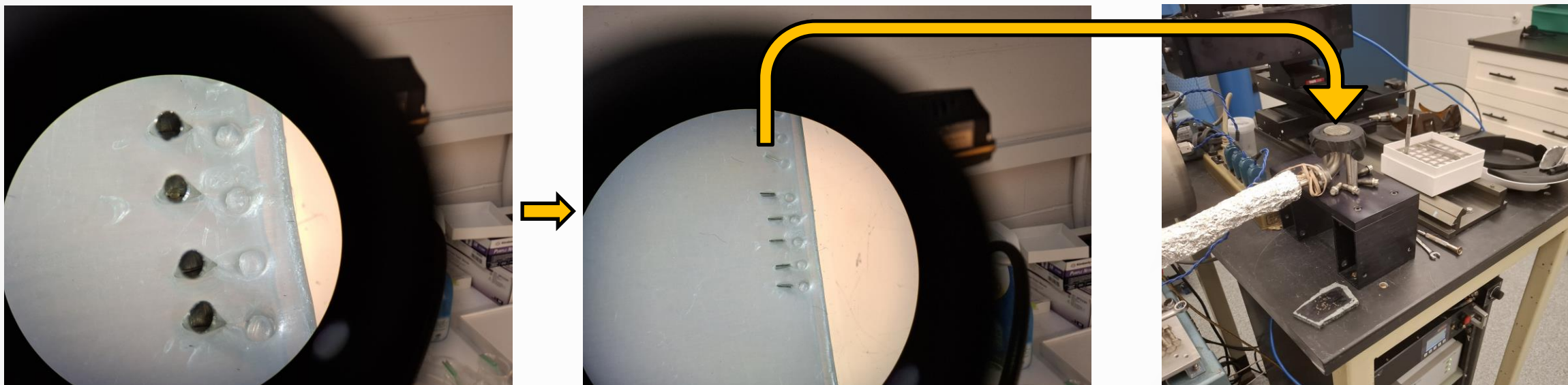
Radiation damage



Whipp et al., 2022



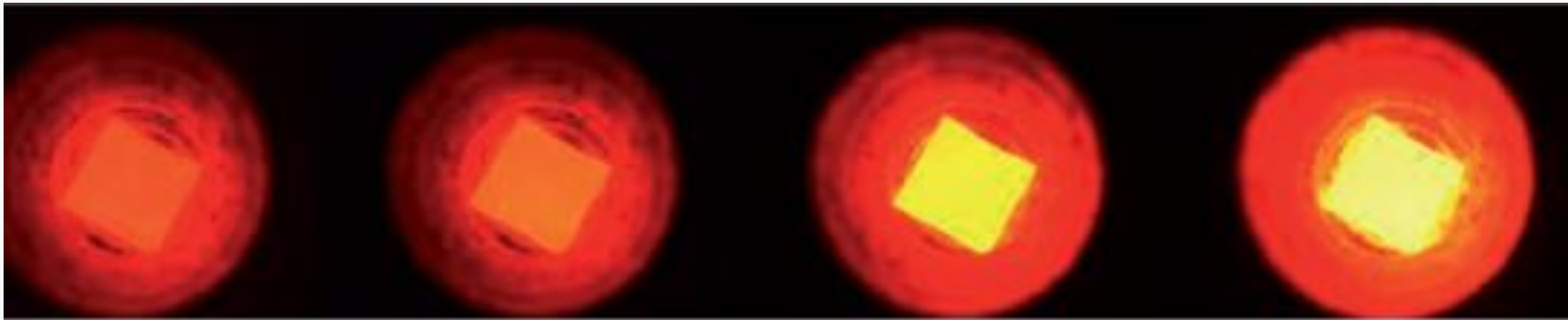
Helium dating: From rock to date



Step 7: Prepare grains for dating



Helium dating: From rock to date

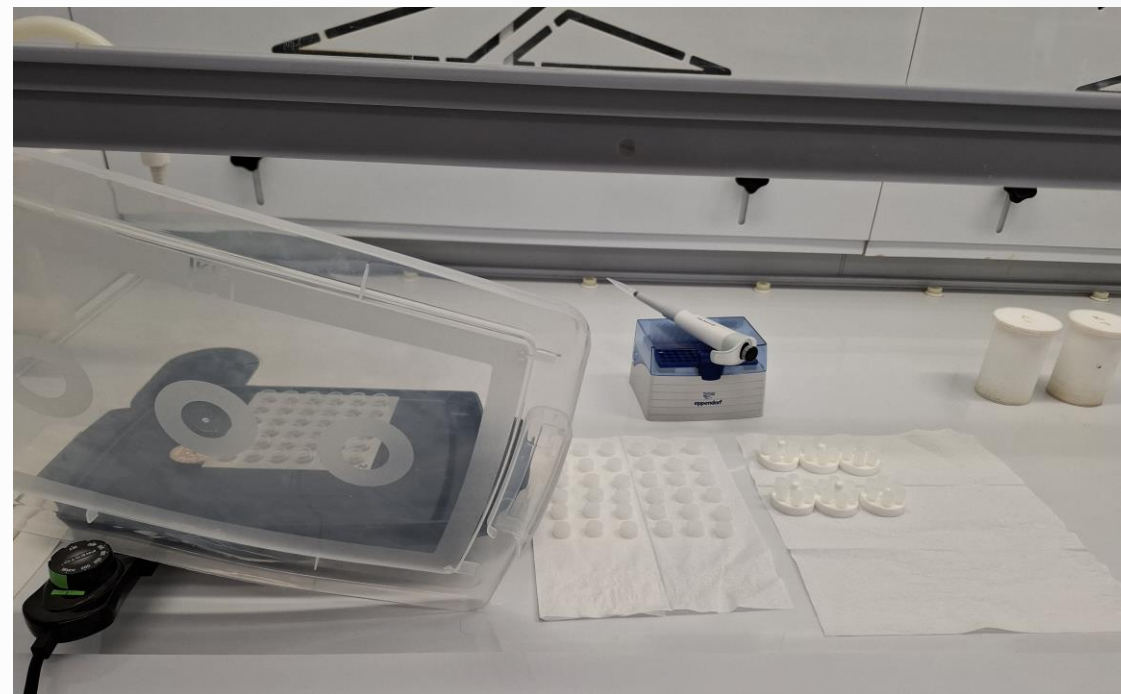
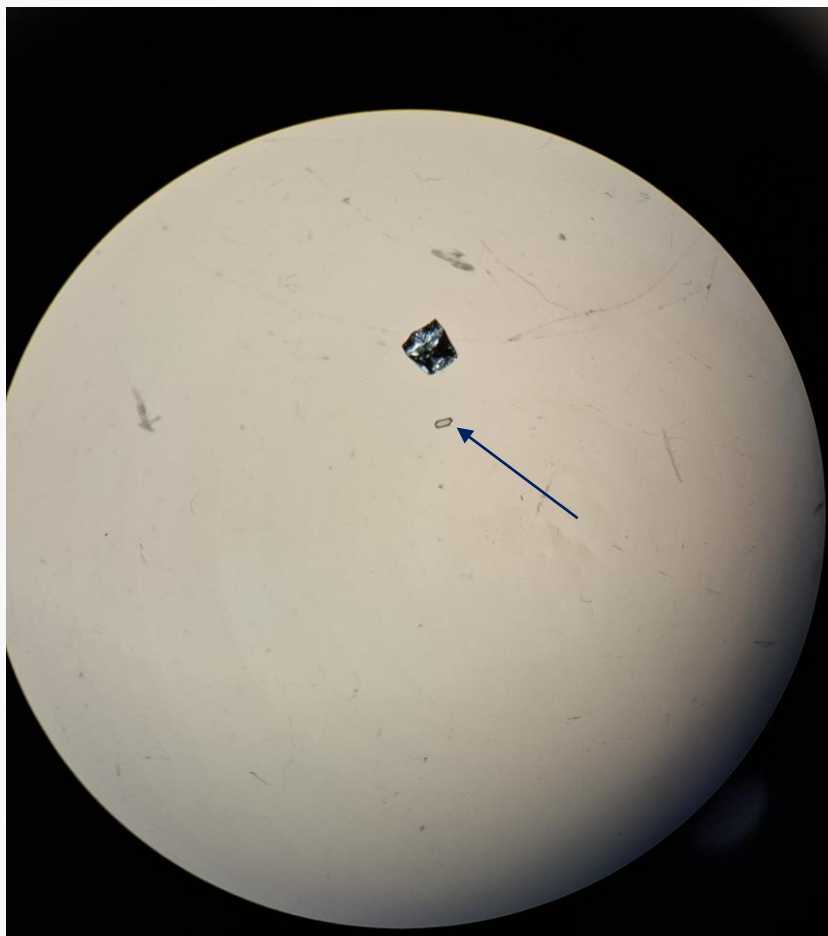


Gautheron et al. (2021)

Step 8: Degassing the sample and measuring helium



Helium dating: From rock to date



Step 9: Preparing the sample for ICP-MS

Step 10: Measuring U, Th and Sm



Helium dating: From rock to date

$${}^4\text{He} = 8 \times {}^{238}\text{U}(e^{\lambda_{238}t} - 1) + 7 \times \frac{{}^{238}\text{U}}{137.88}(e^{\lambda_{235}t} - 1) + 6 \times {}^{232}\text{Th}(e^{\lambda_{232}t} - 1) + 1 \times {}^{147}\text{Sm}(e^{\lambda_{147}t} - 1)$$

U decay Th decay Sm decay

↑ ↑ ↑ ↑

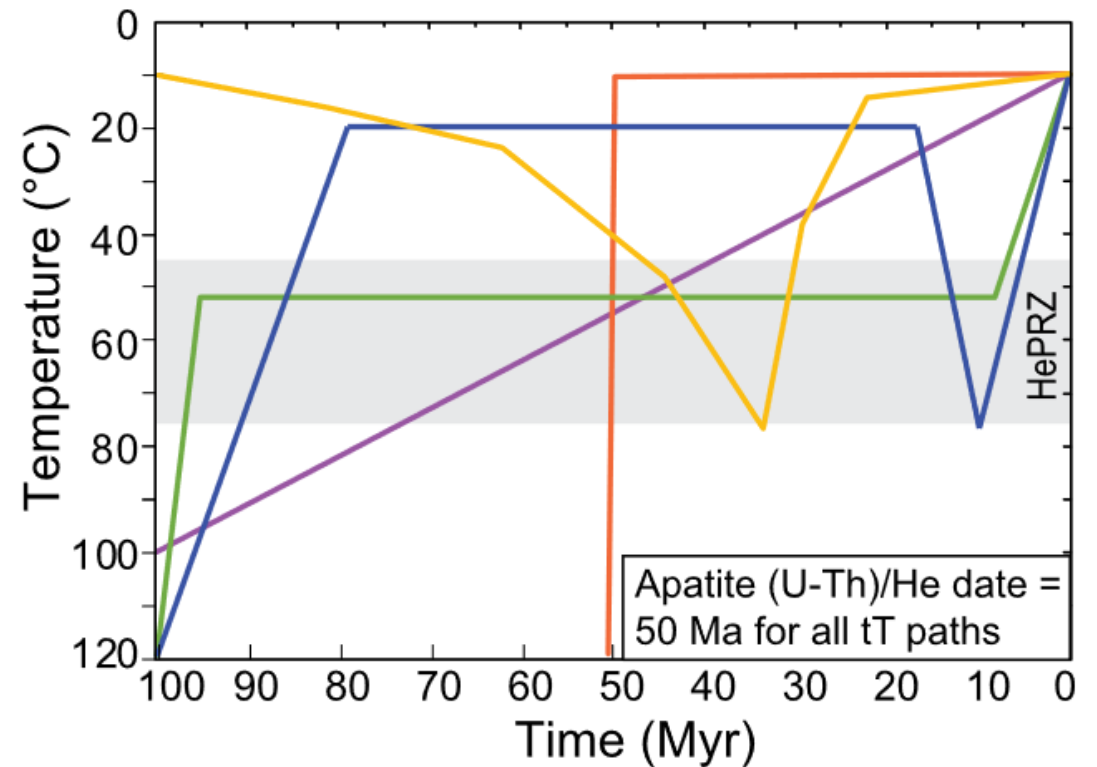
measure measure measure measure

Step 11: Calculating the (U-Th)/He date



Exercise 6: Building a thermochronology model!

- We need numerical models to figure out the thermal history our thermochronometer ages recorded.
- You will use this model for your final report.
- **Due: 10 Dec. at 12:15**



Flowers et al. (2022)



References

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