Introduction to Quantitative Geology

Lesson 6.1

Low-temperature thermochronology

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Goals of this lecture

- Define **low-temperature thermochronology**
- Introduce three common types of low-temperature thermochronometers
    - **Helium dating** (The (U-Th)/He method)
    - **Fission-track dating** (The FT method)
    - **Argon dating** (The $^{40}Ar/^{39}Ar$ method)

What is low-temperature thermochronology?

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

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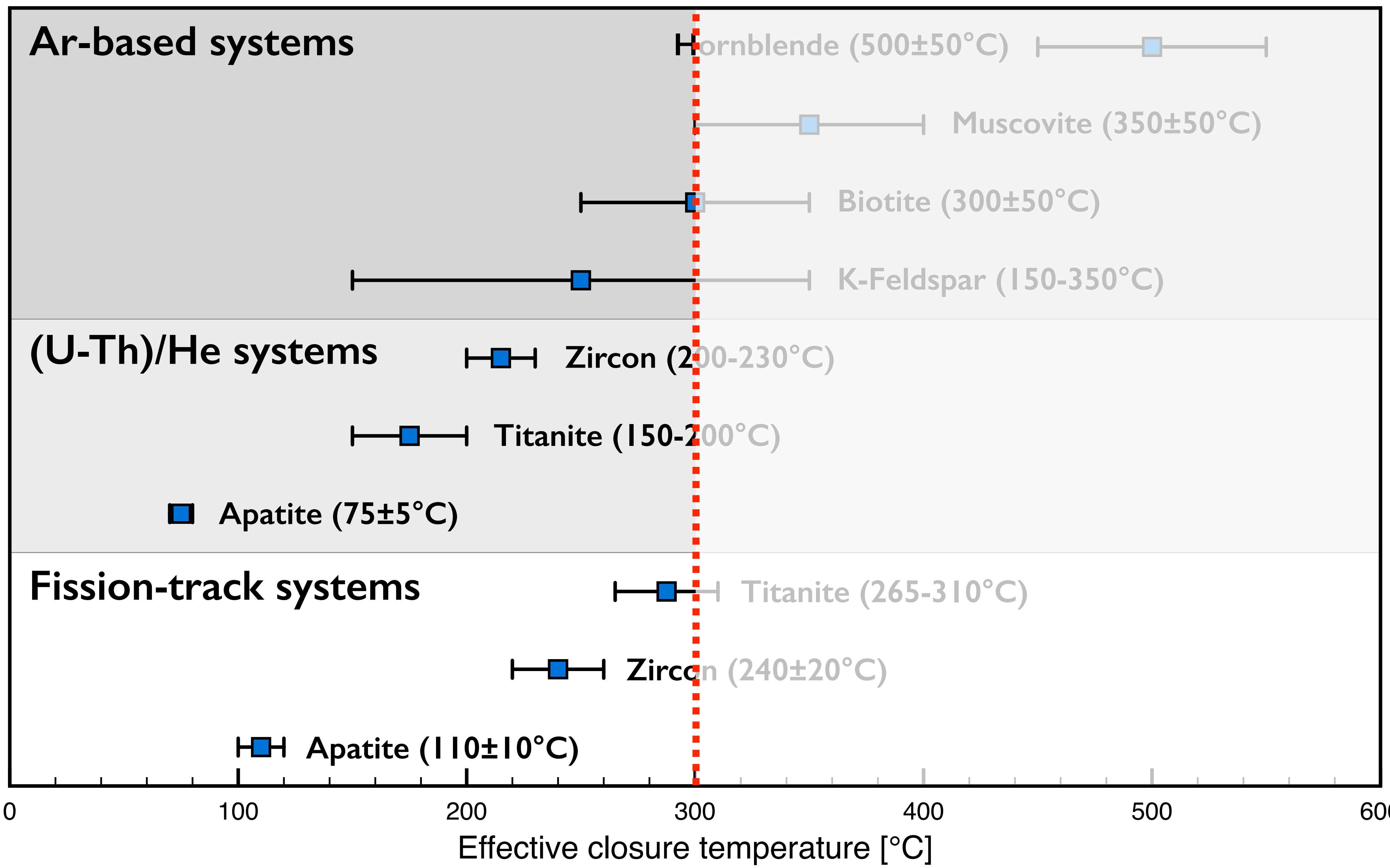
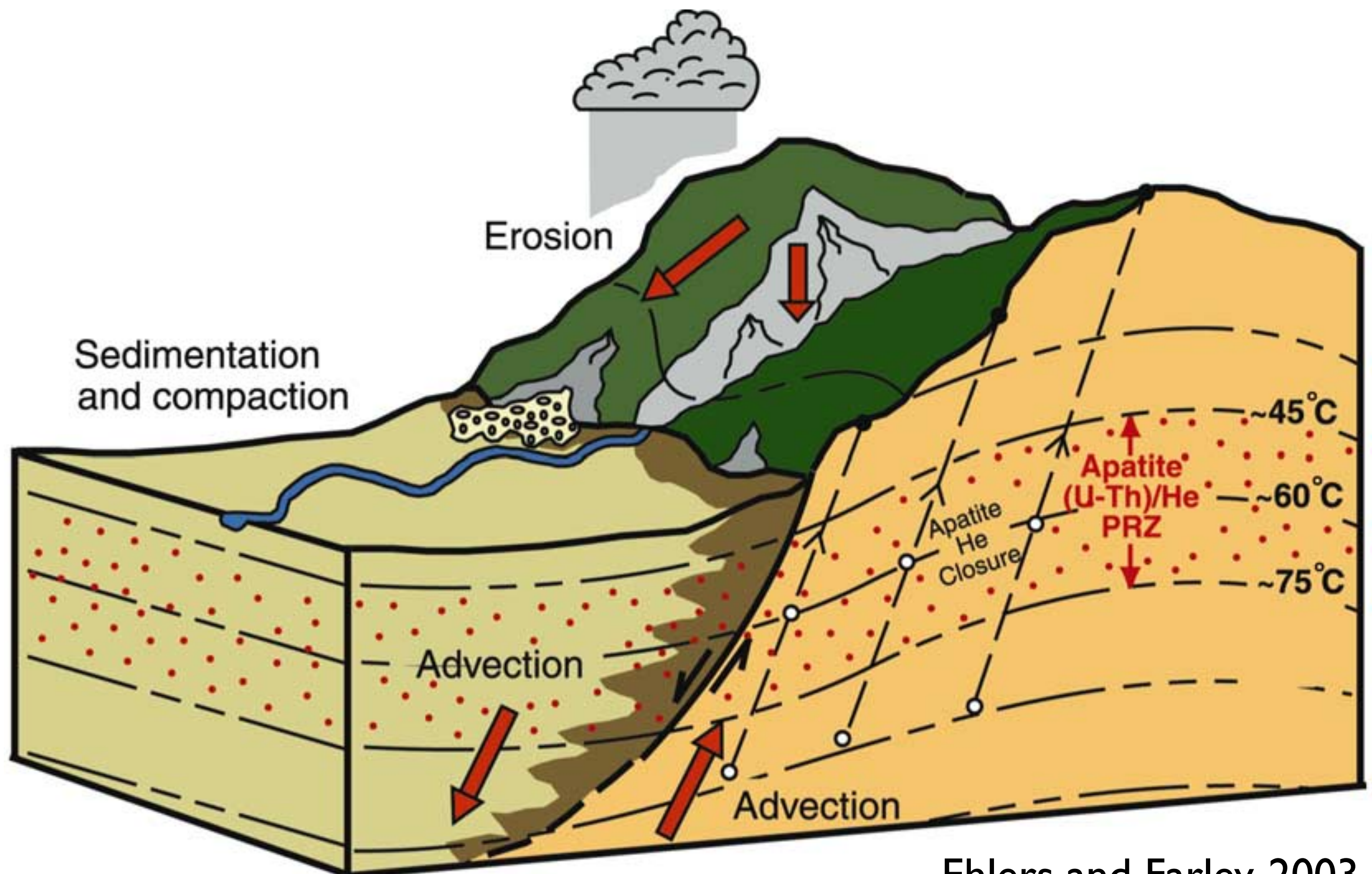
What is low-temperature thermochronology?



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

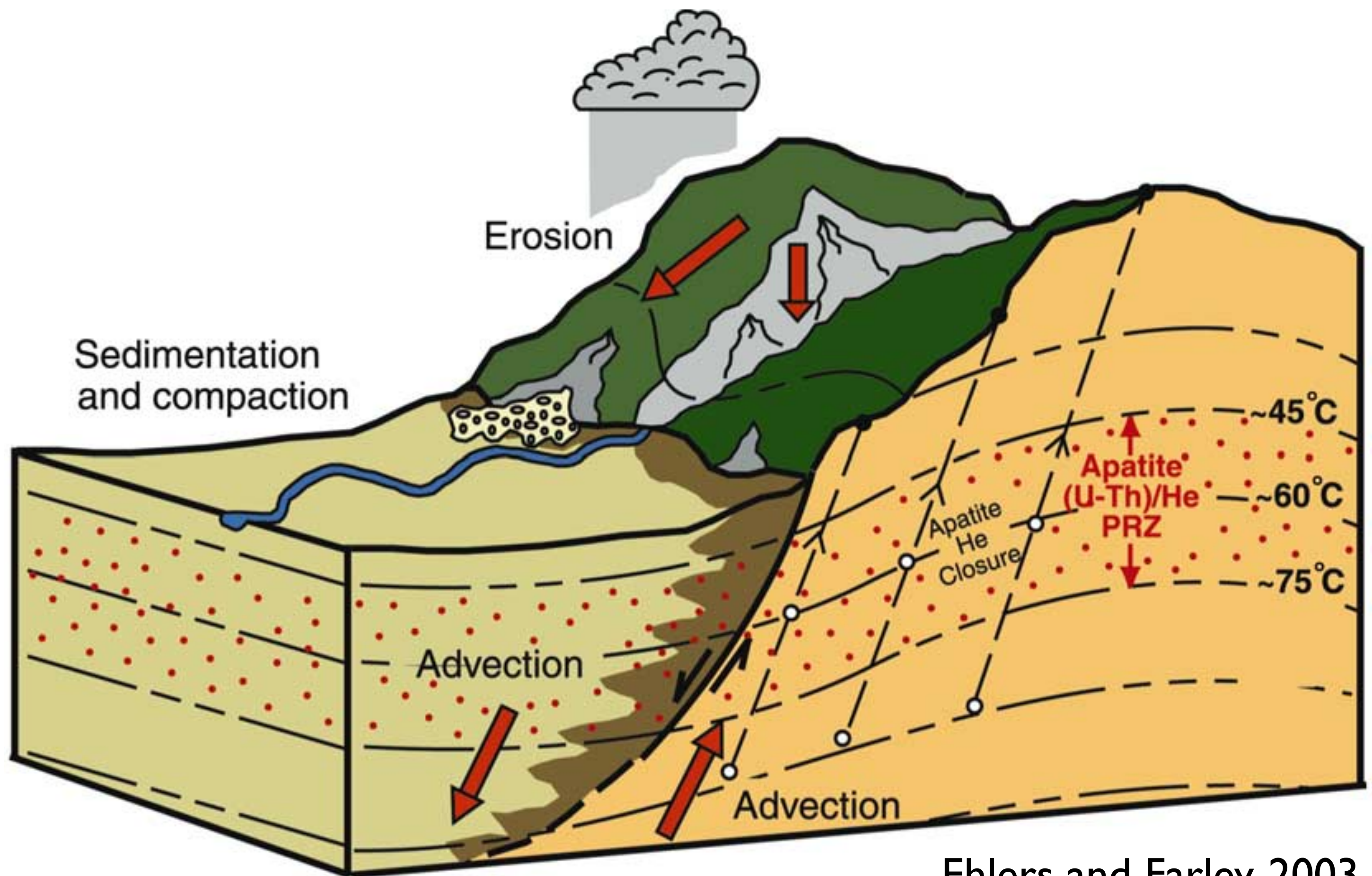
Why is thermochronology useful?



Ehlers and Farley, 2003

- Thermochronometer ages 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

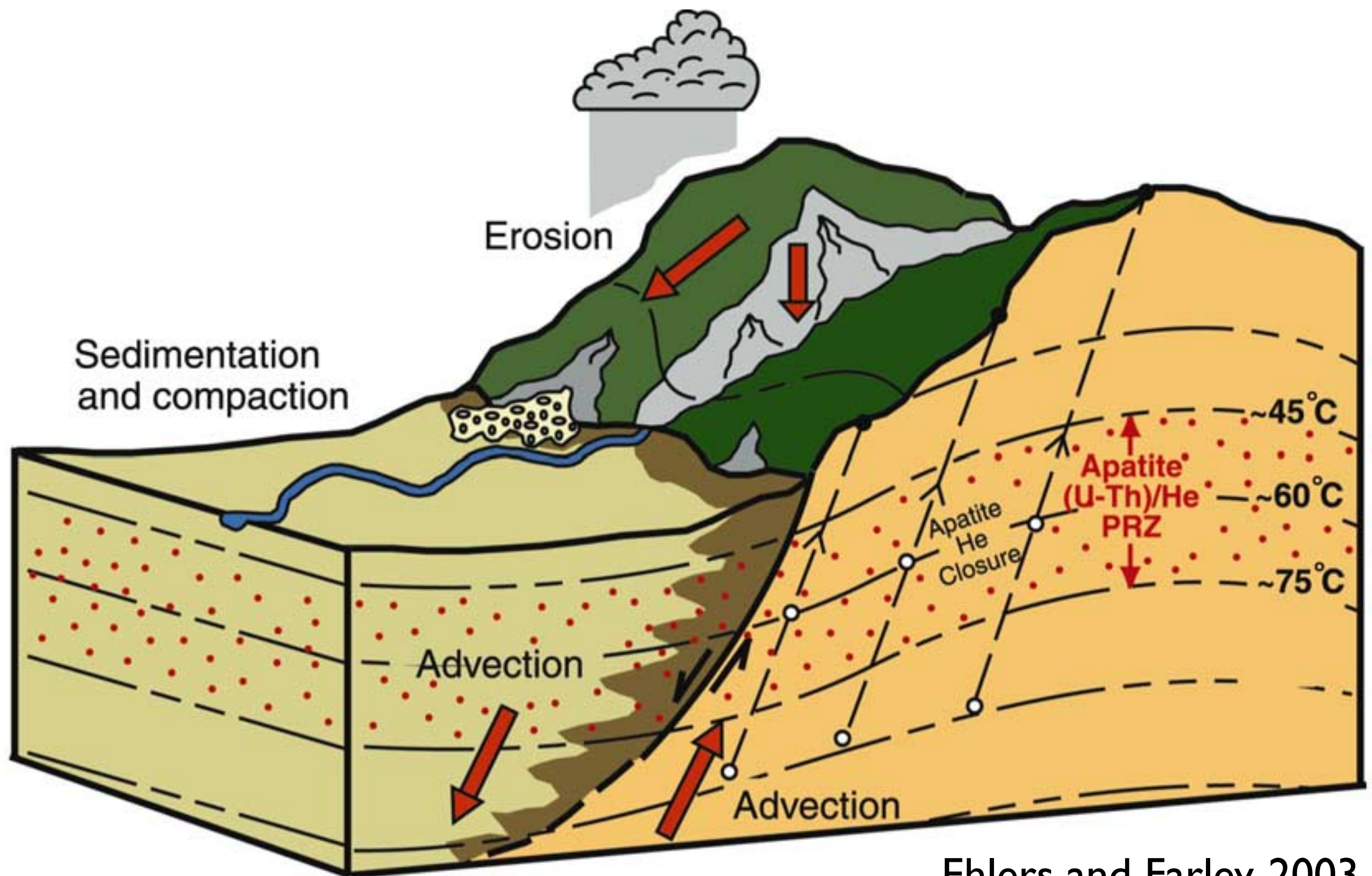
Why is thermochronology useful?



Ehlers and Farley, 2003

- Because the temperatures to which thermochronometers are sensitive generally occur at depths of 1 to >15 km and ages are typically 1 to 100's of Ma, they record long-term cooling through the upper part of the crust and can be used to calculate long-term average rates of tectonics and erosion

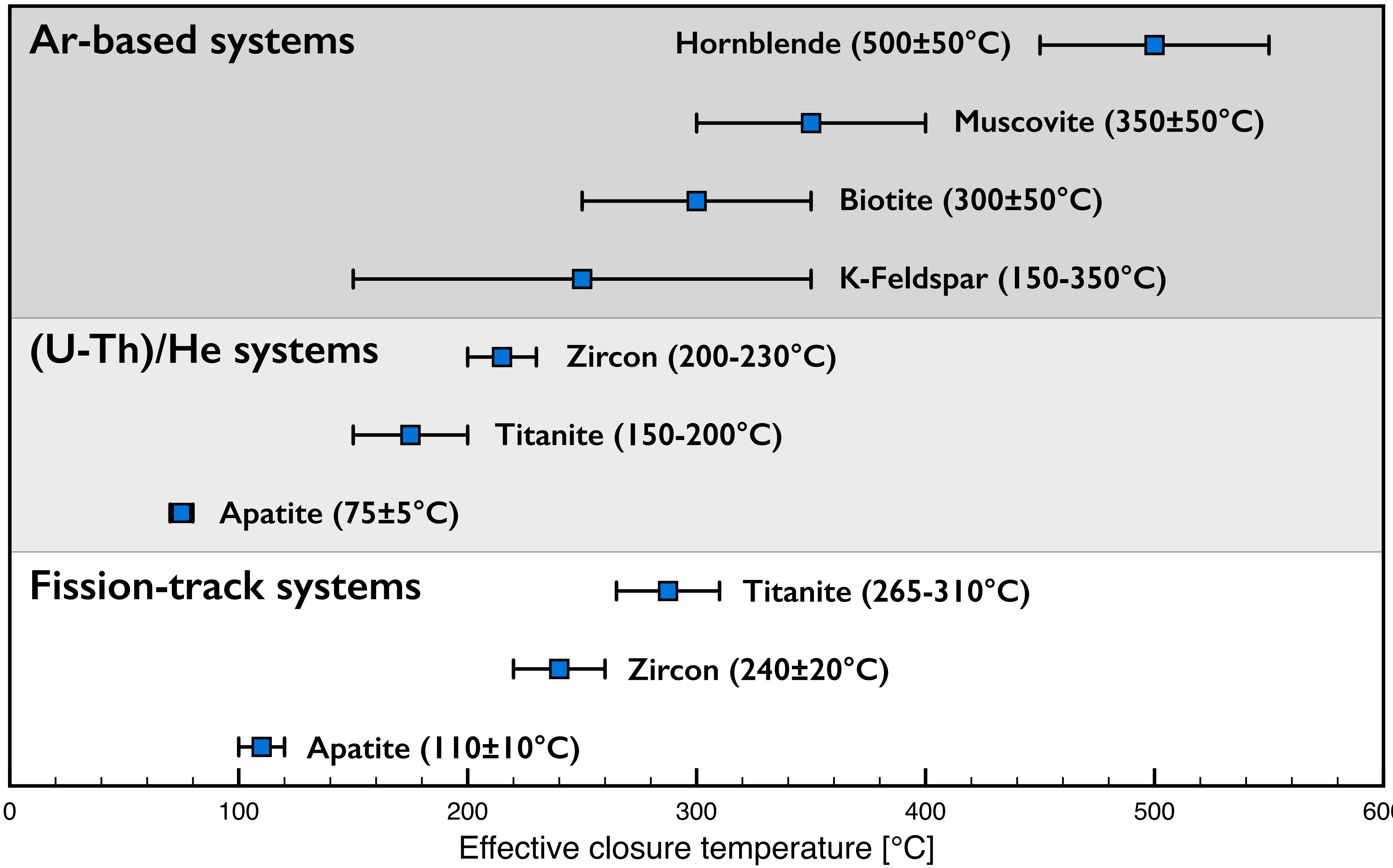
Why is ***low-T*** thermochronology useful?



Ehlers and Farley, 2003

- **Low-temperature thermochronometers** are unique because of their increased sensitivity to topography, erosional and tectonic processes

Common thermochronometers



Helium dating - (U-Th)/He method

Production of alpha particles by decay

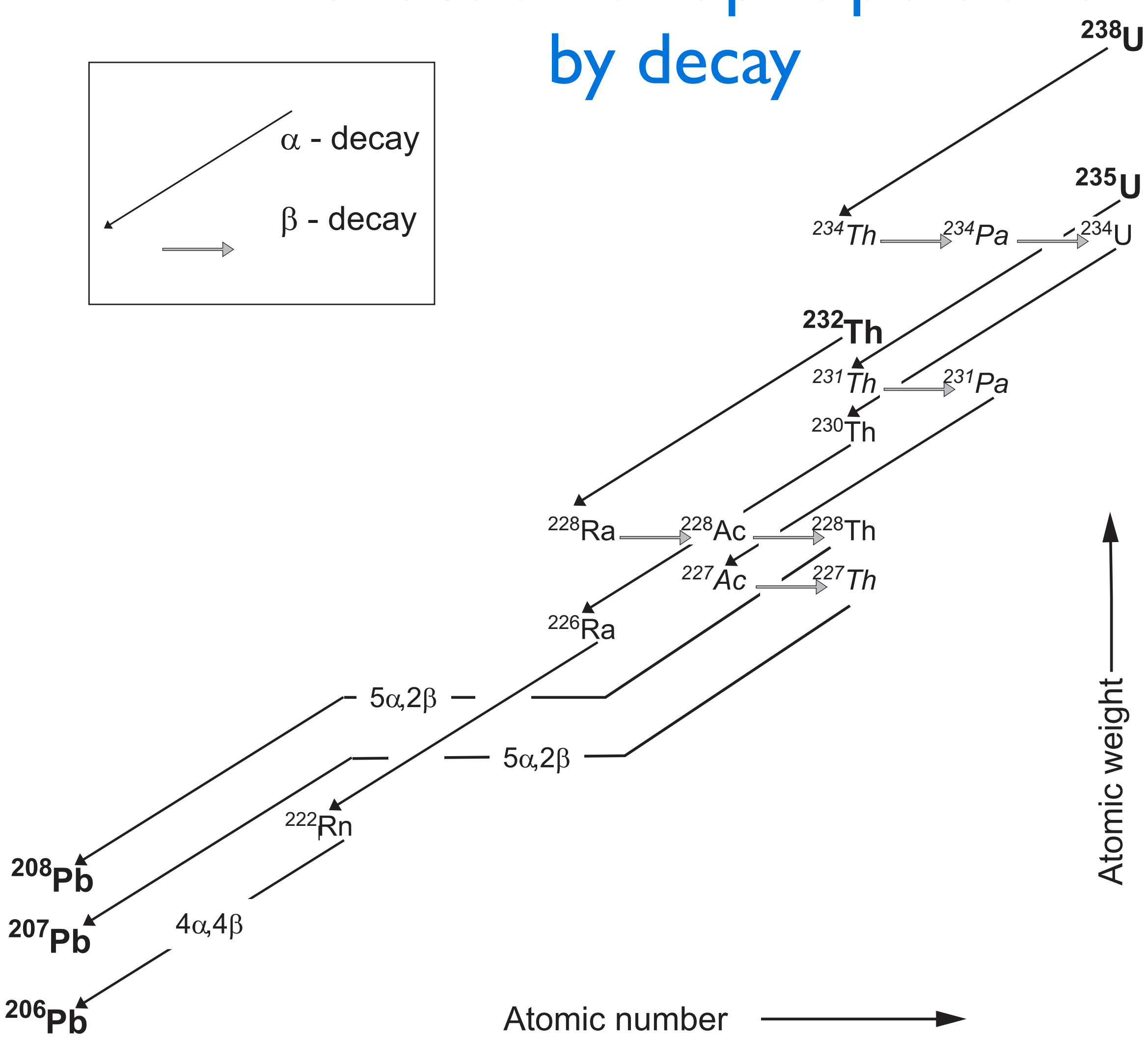


Fig. 3.3, Braun et al., 2006

- **(U-Th)/He thermochronology** is based on the <u>production and accumulation of ^{4}He from parent isotopes ^{238}U, ^{235}U, ^{232}Th and ^{147}Sm</u>
- ^{4}He (α particles) produced during decay chains
  - ^{238}U - 8 α decays
  - ^{235}U - 7 α decays
  - ^{232}Th - 6 α decays
  - ^{147}Sm - 1 α decay

Helium dating - (U-Th)/He method

Production of alpha particles by decay

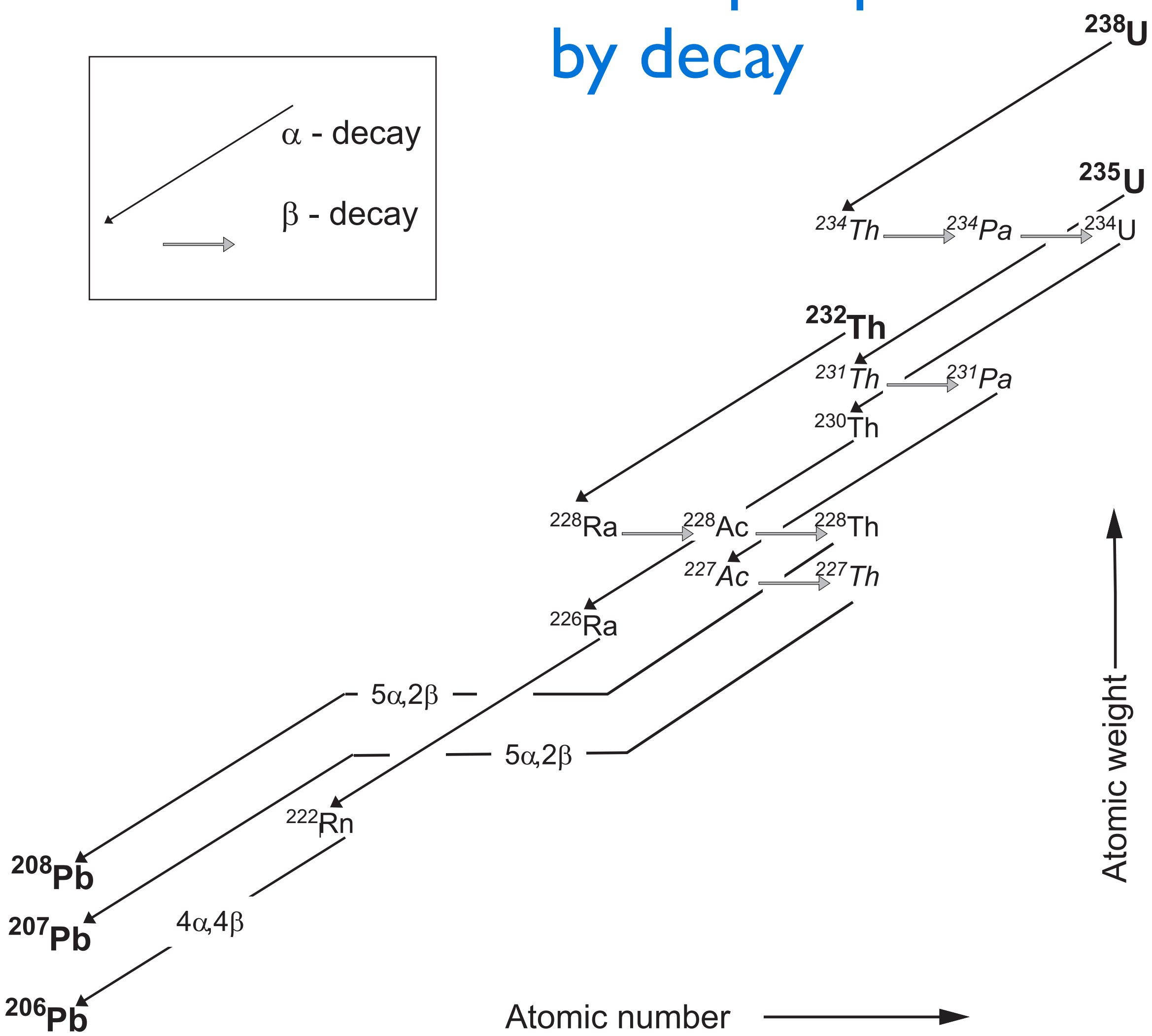


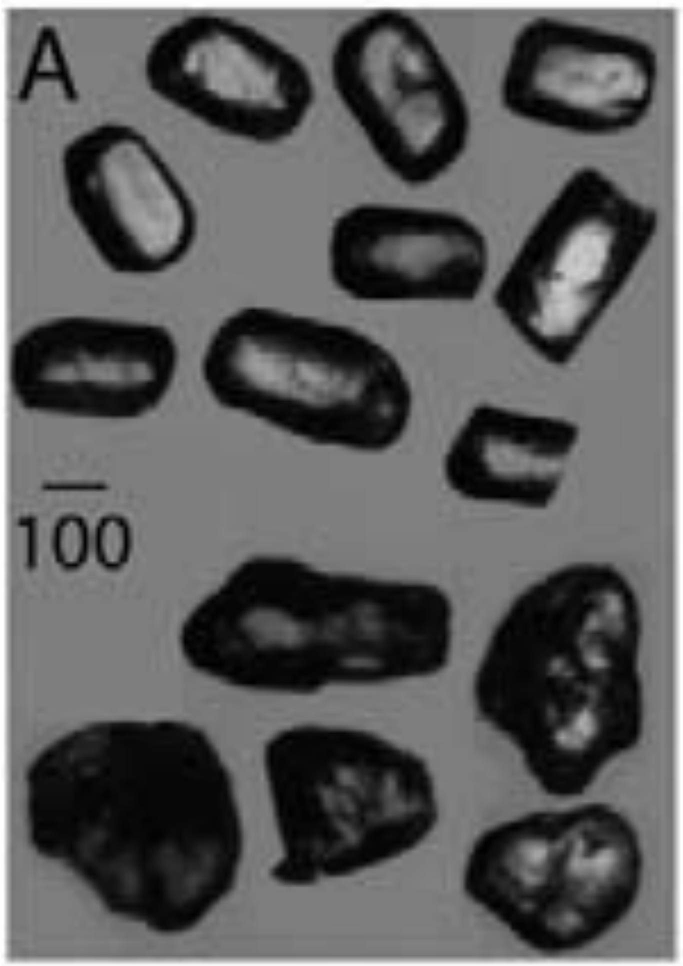
Fig. 3.3, Braun et al., 2006

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

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

where ^{4}He, ^{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

Helium dating - (U-Th)/He method



Ehlers and Farley, 2003

Nice, datable apatites

Not-so-nice apatites

- Ages are calculated by measuring the ^{4}He concentration by heating and degassing the mineral sample, then separately measuring the U and Th concentrations, for example by using an inductively coupled plasma mass spectrometer (ICP-MS)

Helium dating - (U-Th)/He method

Potential ejection of ^4He (alpha particles)

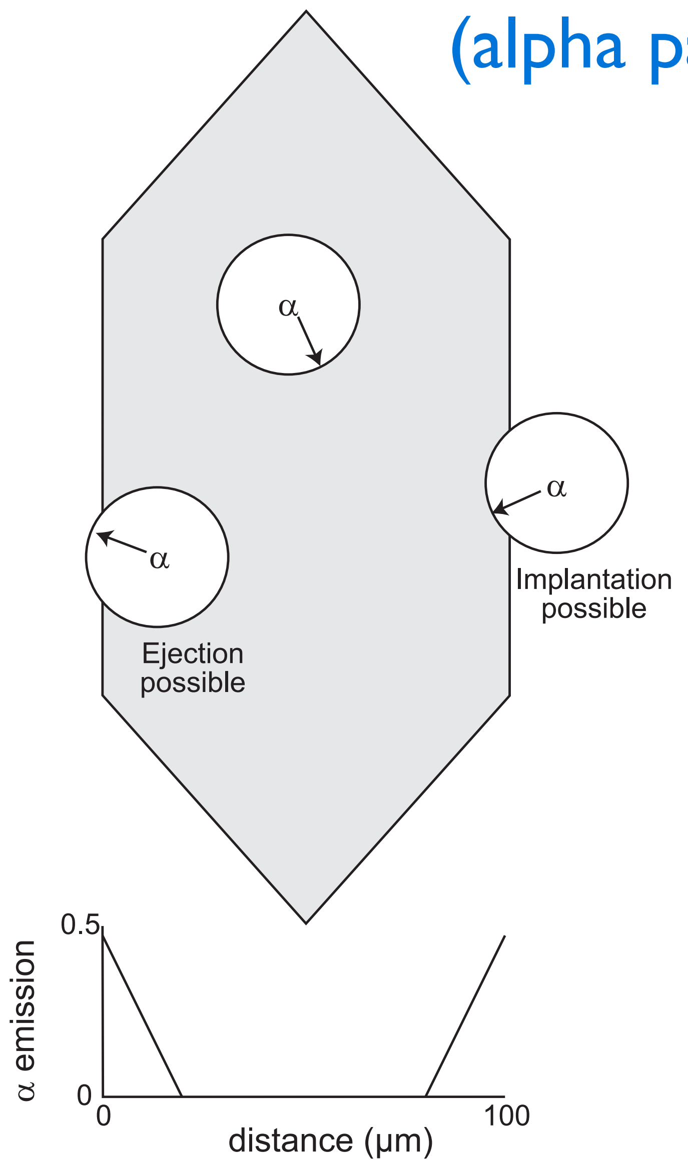
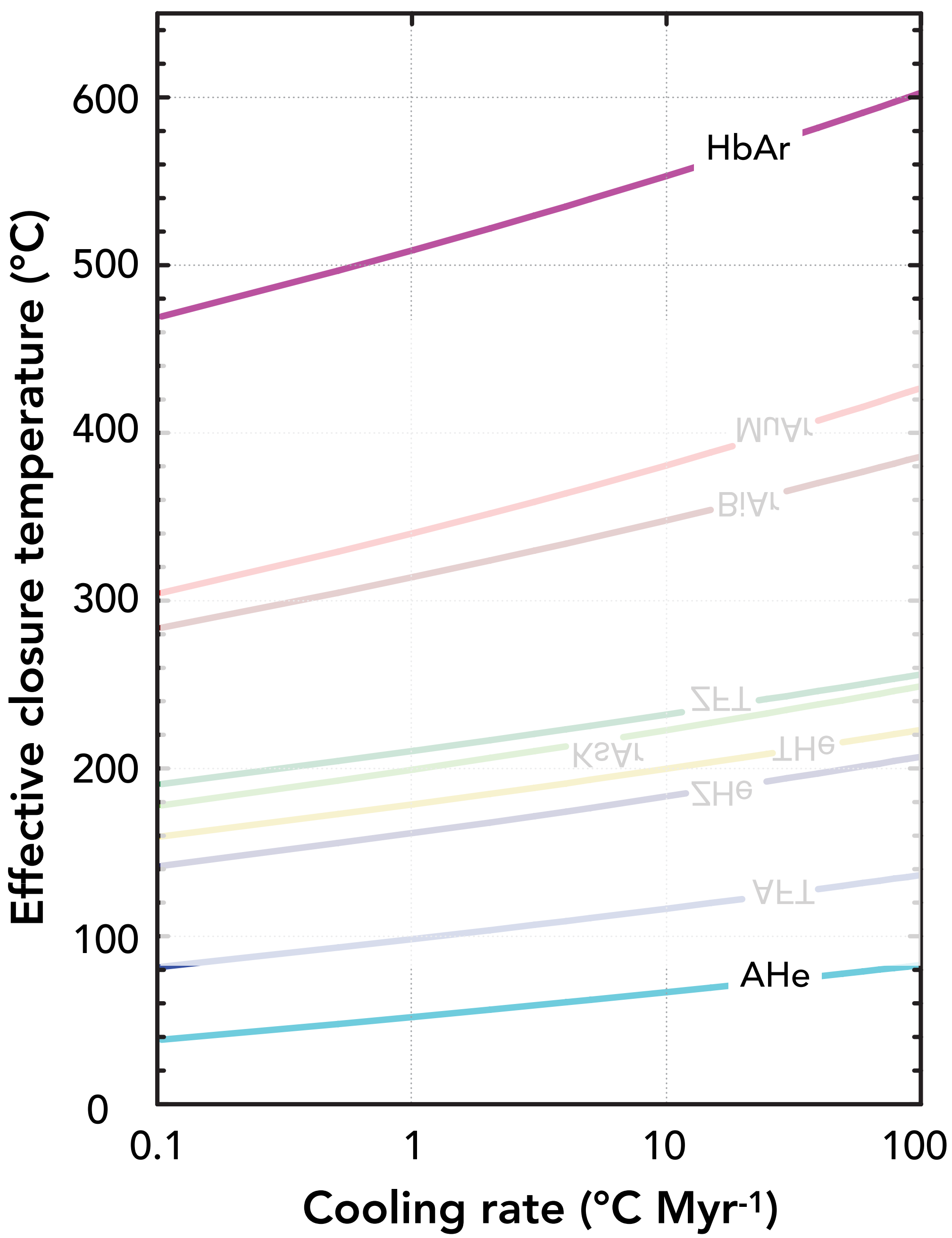


Fig. 3.4, Braun et al., 2006

- Selected mineral grains for dating should be high-quality, euhedral minerals free of mineral inclusions with a prismatic crystal form
    - Why does the crystal form matter? Alpha particles travel ~20 μm when created and may be ejected from or injected to the sample crystal
    - We can correct for this!

Influence of cooling rate on effective T_c

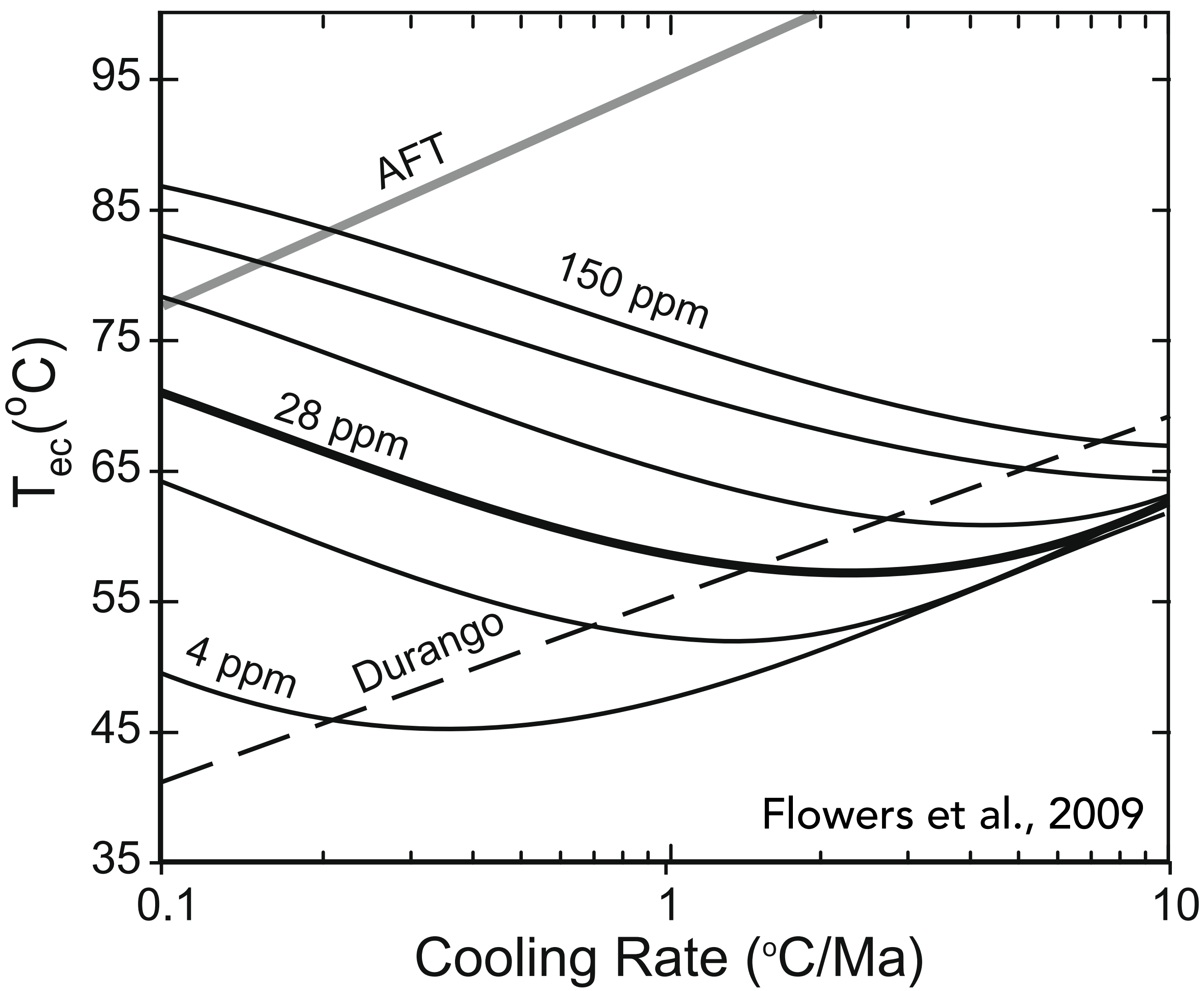
Reiners and Brandon, 2006

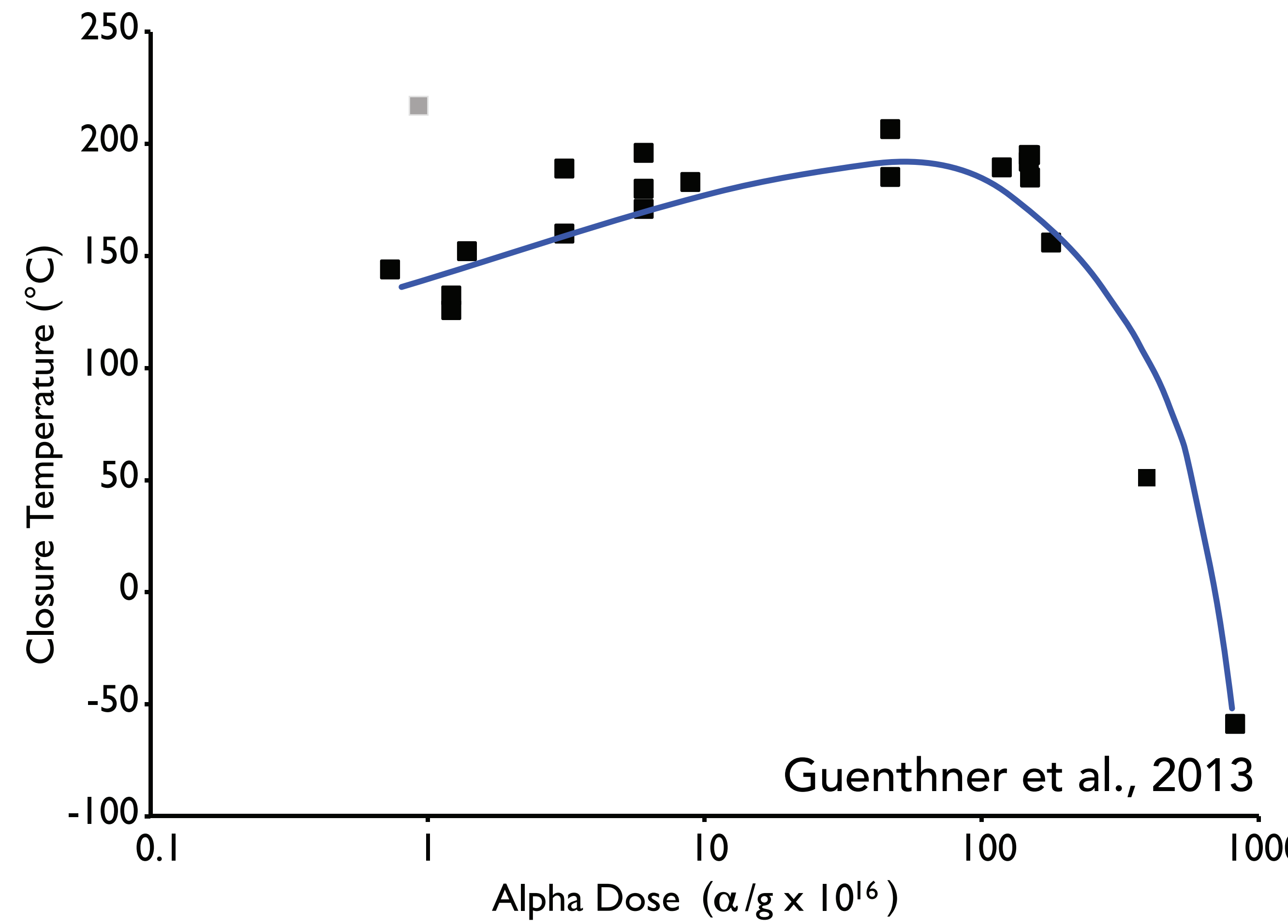


- In general, <u>the effective closure temperature for a given thermochronometer system will increase with increasing cooling rate</u>
    - For the retention of ^{4}He in apatite, the effective closure temperature is ~40°C at a cooling rate of 0.1 °C/Ma and ~80°C at a rate of 100°C/Ma
- The absolute difference in effective closure temperature is also larger for higher temperature thermochronometers
    - ~40°C for ^{4}He in apatite
    - ~130°C for ^{40}Ar in hornblende

Radiation damage in (U-Th)/He chronometers

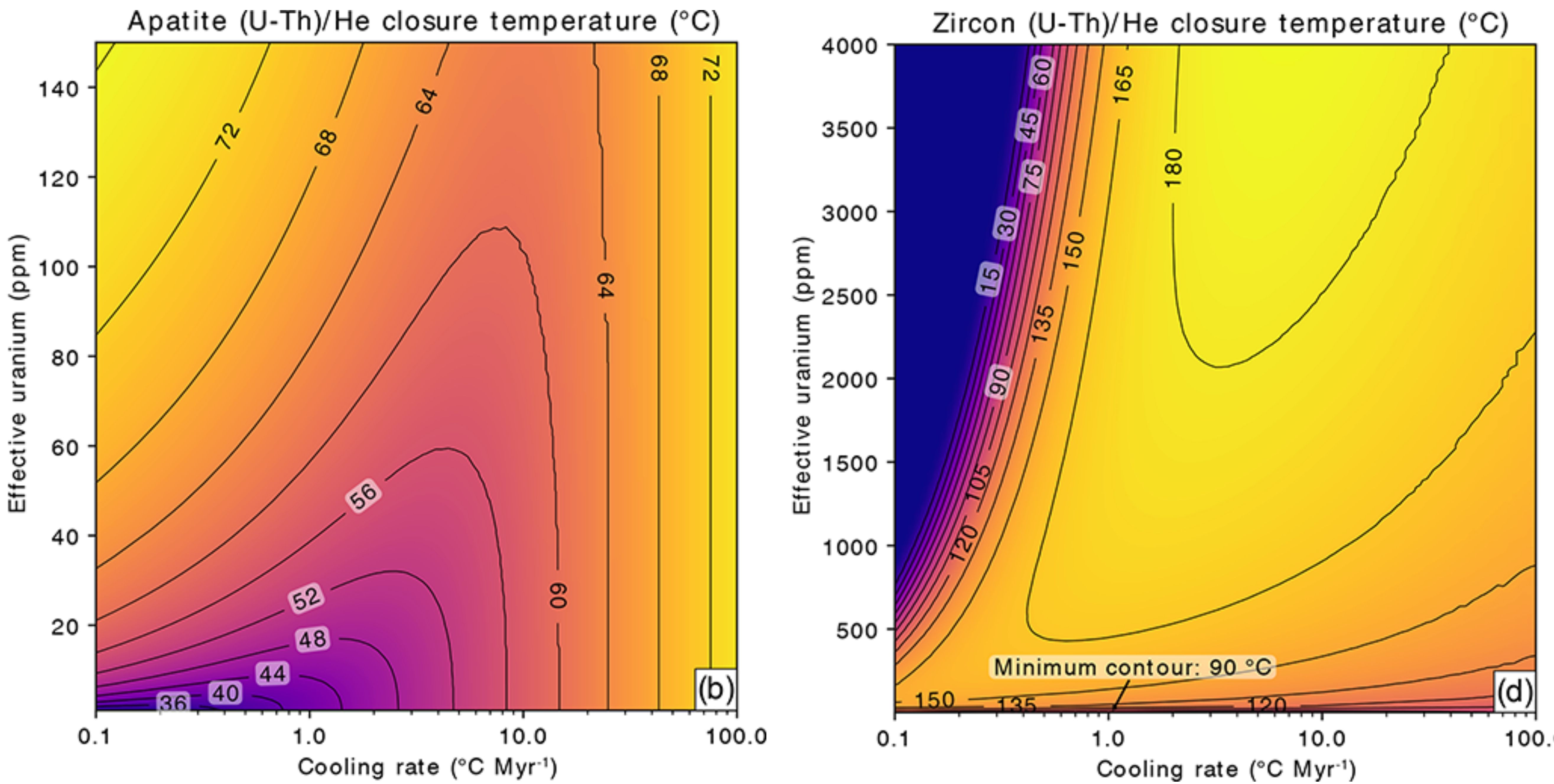
Note: These are not the same type of plot!





Crystal lattice damage from alpha decay can affect diffusion of He in apatite and zircon

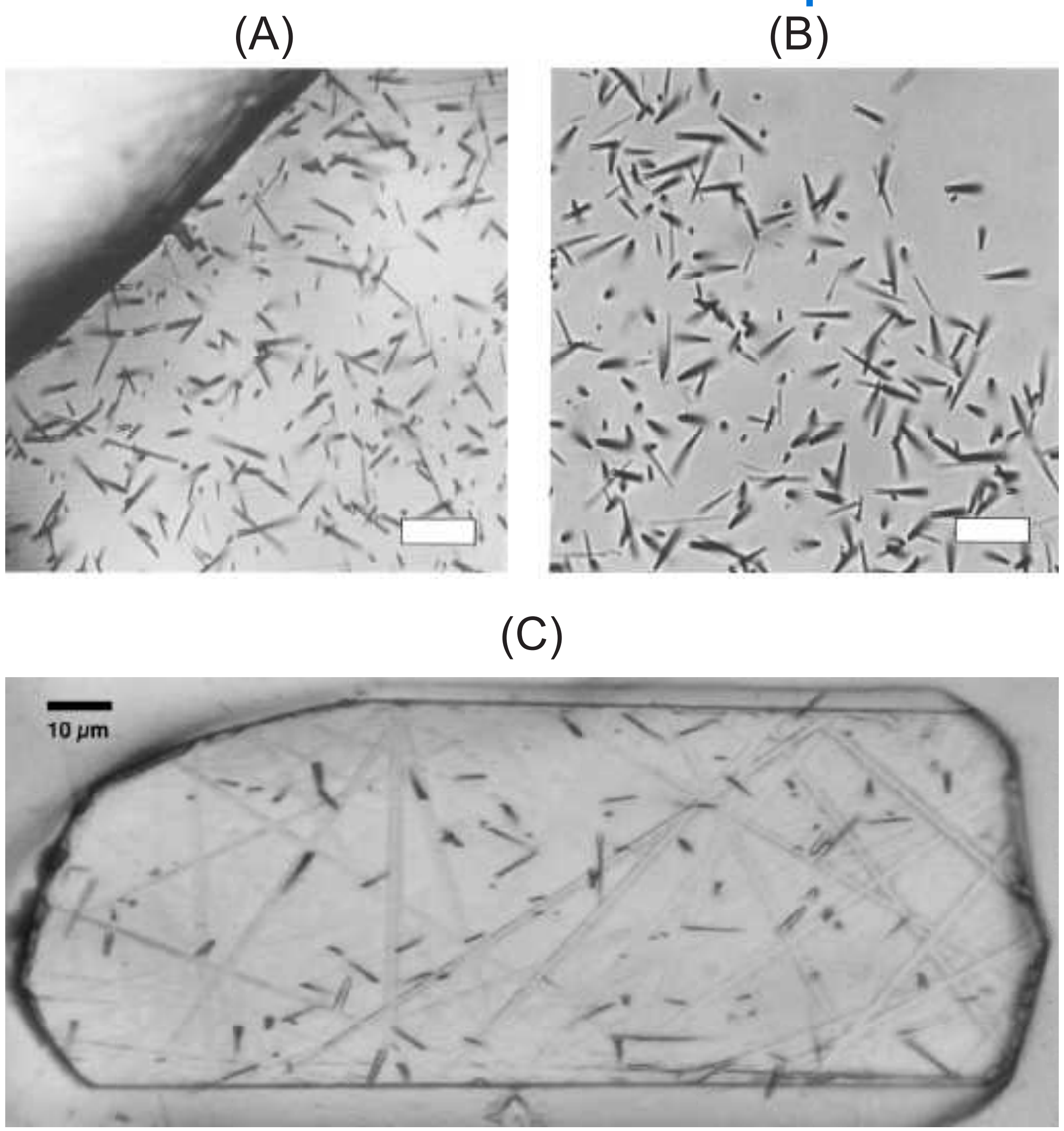
Radiation damage in (U-Th)/He chronometers



Whipp et al., 2022

Fission-track dating - FT method

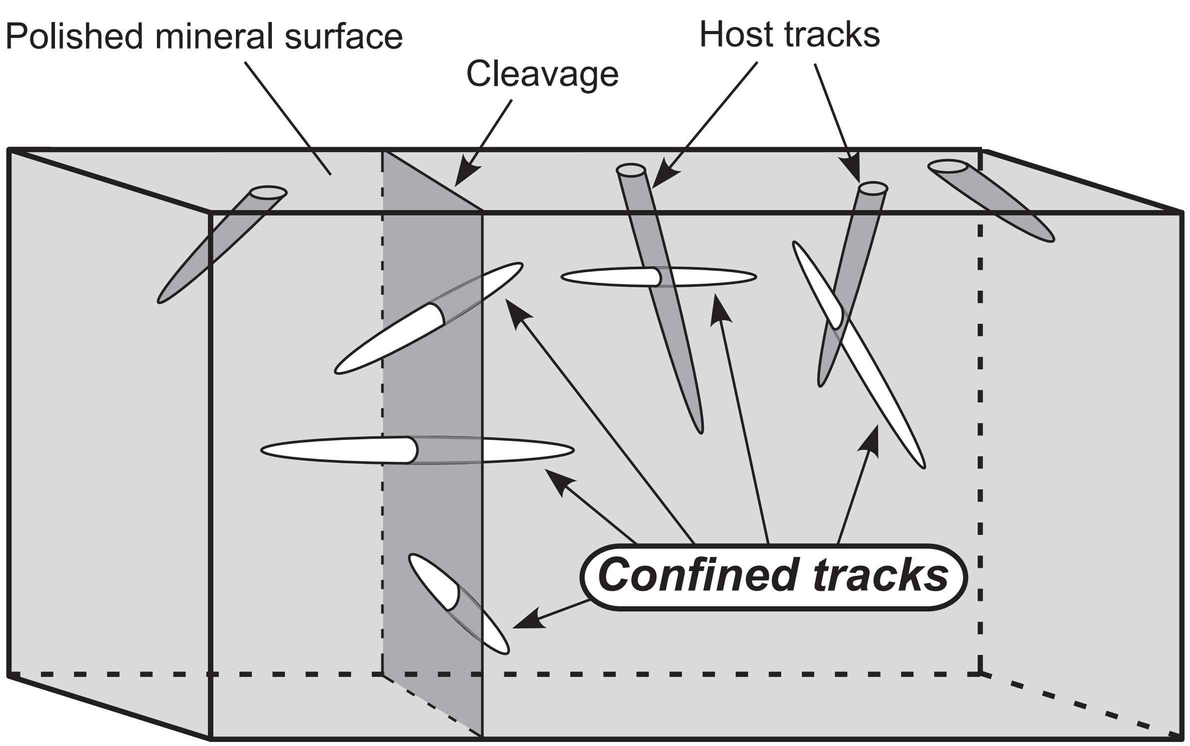
Etched fission tracks in apatite



Tagami and O'Sullivan, 2005

- **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
    - In apatite, fresh fission tracks are ~16 μm long and ~11 μm long in zircon
- Similar to diffusive loss of ^4He, these damage trails will be repaired, or anneal, at temperatures above T_c

Fission-track dating - FT method



Tagami and O'Sullivan, 2005

- To be visible under a microscope, tracks must be chemically etched and enlarged
- At this point, tracks can be manually (or automatically) counted to determine the track density
- The FT age can be calculated as

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

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

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

- **Argon dating** is based on the decay of ^{40}K to radiogenic ^{40}Ar
    - Potassium is one of the most abundant elements in the crust, making argon dating one of the more common thermochronology methods
- $^{40}Ar/^{39}Ar$ dating is used on white micas, biotite, K-feldspar and amphiboles

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

- $^{40}Ar/^{39}Ar$ ages are found by irradiating a sample (and standard) with fast neutrons, producing ^{39}Ar from ^{39}K in the sample
- The $^{40}Ar/^{39}Ar$ ratio is then measured as samples are either degassed entirely or step heated (next slide)
- The $^{40}Ar/^{39}Ar$ age can be calculated as

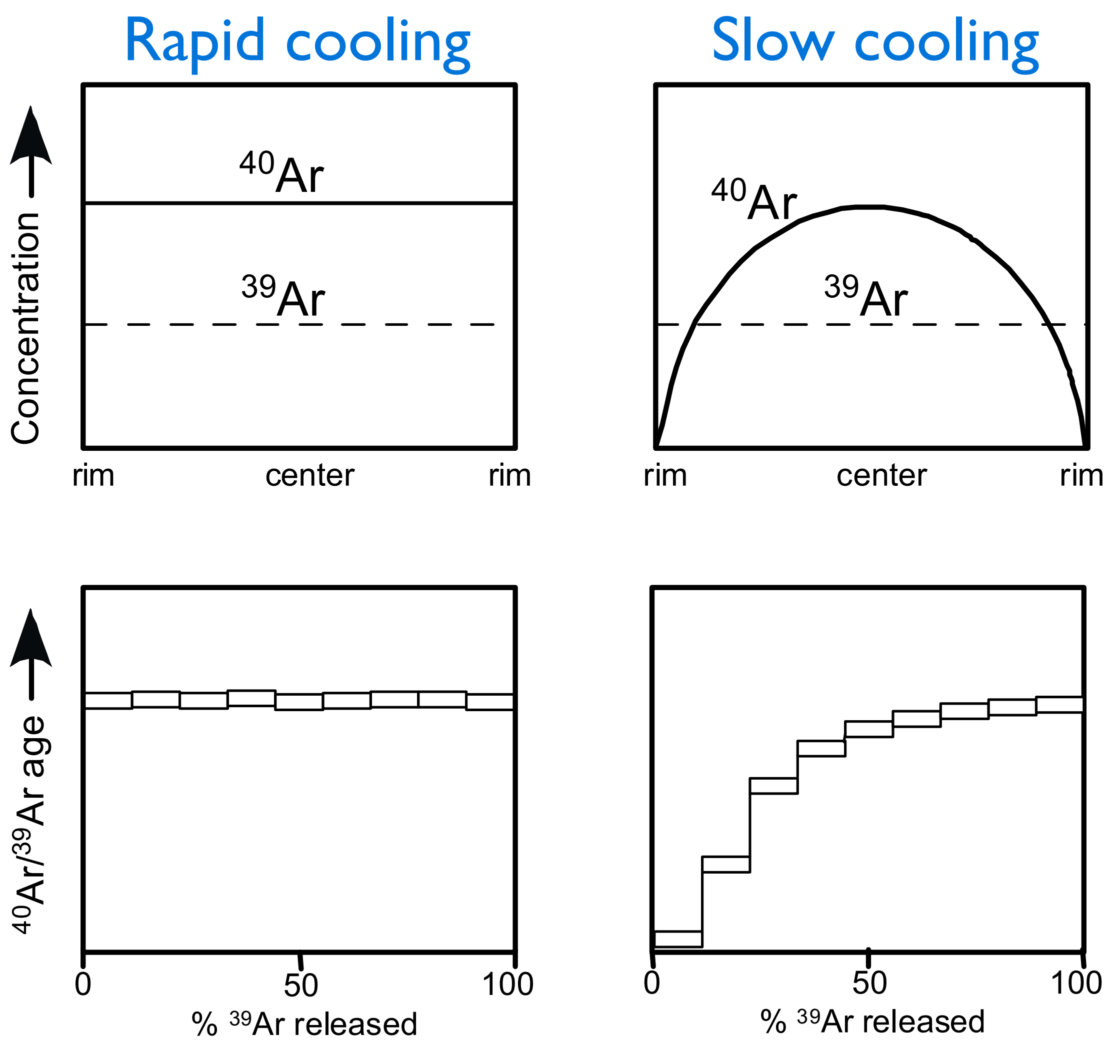
$$t = \frac{1}{\lambda} \ln \left(1 + J \frac{^{40}\mathrm{Ar}}{^{39}\mathrm{Ar}} \right)$$

where λ is the decay constant of ^{40}K, $^{40}Ar/^{39}Ar$ is the measured sample $^{40}Ar/^{39}Ar$ ratio and J is the irradiation factor

$$J = \frac{\mathrm{e}^{\lambda t} - 1}{^{40}\mathrm{Ar}/^{39}\mathrm{Ar}}$$

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

Argon dating - Step heating



Harrison and Zeitler, 2005

- **Step heating** of $^{40}Ar/^{39}Ar$ samples involves stepwise heating of samples to gradually release Ar as the sample temperature increases
- With this, it is possible to see the ^{40}Ar distribution in the sample, which is a function of the sample cooling history

Argon dating - Step heating

$^{40}Ar/^{39}Ar$ age spectra

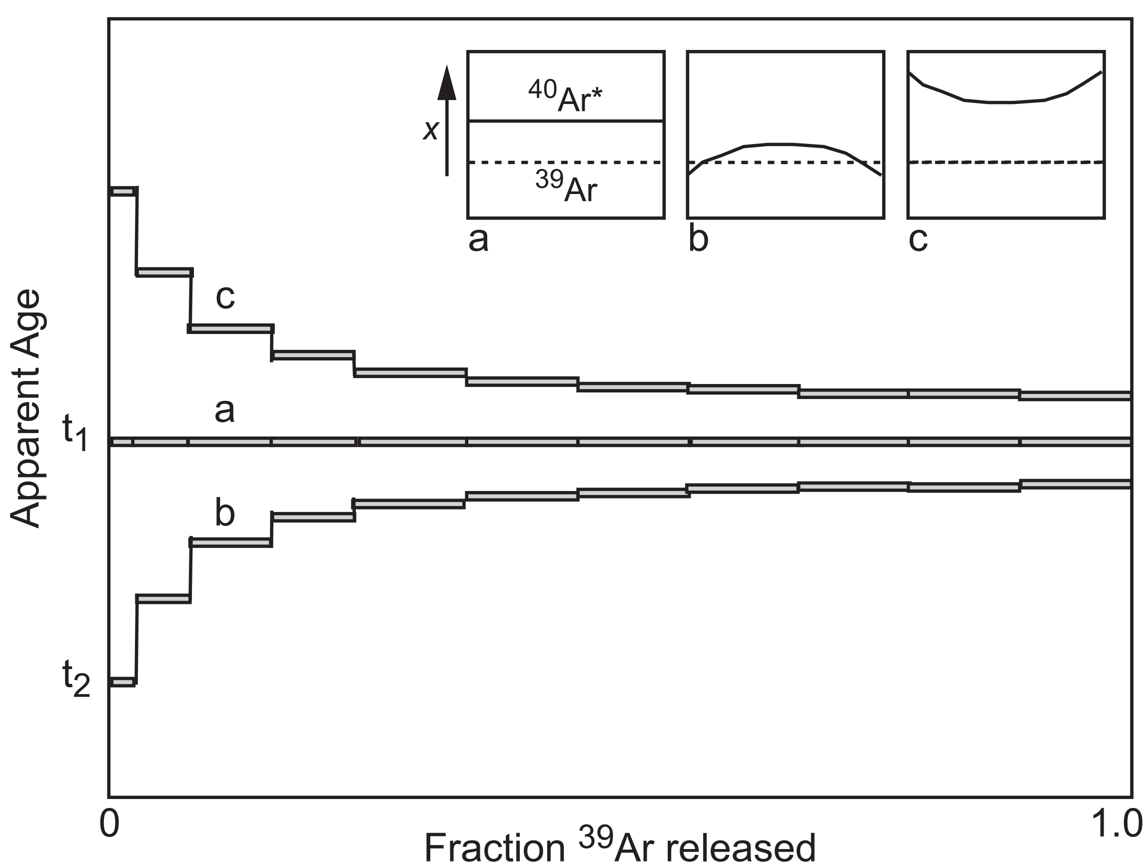


Fig. 3.1, Braun et al., 2006

- As we have seen on the previous slide,

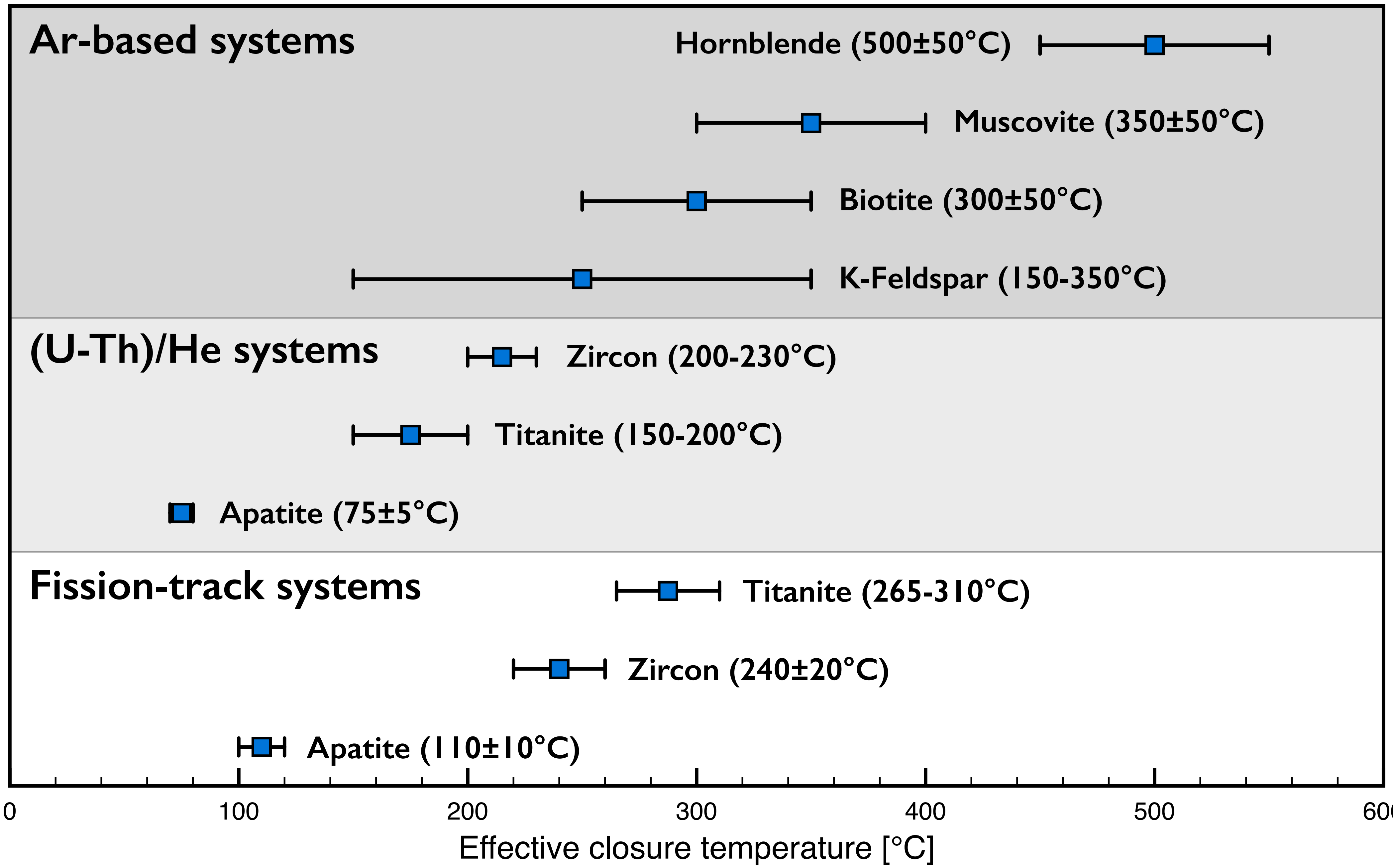
  (a) flat age spectra indicate rapid cooling of a rock sample (at time t_1, here)

  (b) 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) an unexpected behavior with higher Ar concentrations initially (i.e., near the rim of the grain)!

  - This "excess" Ar may have been taken up from surrounding minerals

Common thermochronometers



Recap

- Why is low-temperature thermochronology a particularly interesting tool for those interested in geomorphology or active tectonics?

- How is are (U-Th)/He or $^{40}Ar/^{39}Ar$ methods different from fission-track dating?

Recap

- Why is low-temperature thermochronology a particularly interesting tool for those interested in geomorphology or active tectonics?

- **How is are (U-Th)/He or $^{40}Ar/^{39}Ar$ methods different from fission-track dating?**

Final project primer

- The final two exercises will be based on **thermochronology**
  - The exercises will be divided into two parts, with the second exercise building on what you will have done the previous week
  - As usual, you will modify a Jupyter notebook to produce some plots and provide short answers to related questions
  - The questions you will answer for the write-ups for these two exercises will be relatively simple (especially in Exercise 7) because…

Lab and final project primer

- …you will expand on the work you do in the final two exercises in a formal written report
- The report will be in a Jupyter notebook or a document that is no longer than 6-8 typed pages (single spaced) including figures
- The idea is to describe some background on the data you will work with, the concept for its interpretation and your results/ conclusions
- The structure for the report is described in detail on the course webpage, where you can also find a link to a Jupyter notebook template for the final paper

References

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