Class overview today - December 2, 2019

- Part I - Basic concepts of thermochronology
  - Basic concepts of thermochronology
  - Estimating closure temperatures
- **Part II - Low-temperature thermochronology** (online only)
  - Definition of low-temperature thermochronology
  - Three common low-temperature thermochronometers
- **Part III - Quantifying erosion with thermochronology** (online only)
  - Basic concepts of heat transfer as a result of erosion
  - Estimation of exhumation rates from thermochronometers

Introduction to Quantitative Geology

Lesson 6.2

Low-temperature thermochronology

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2.12.19

Goals of this lecture

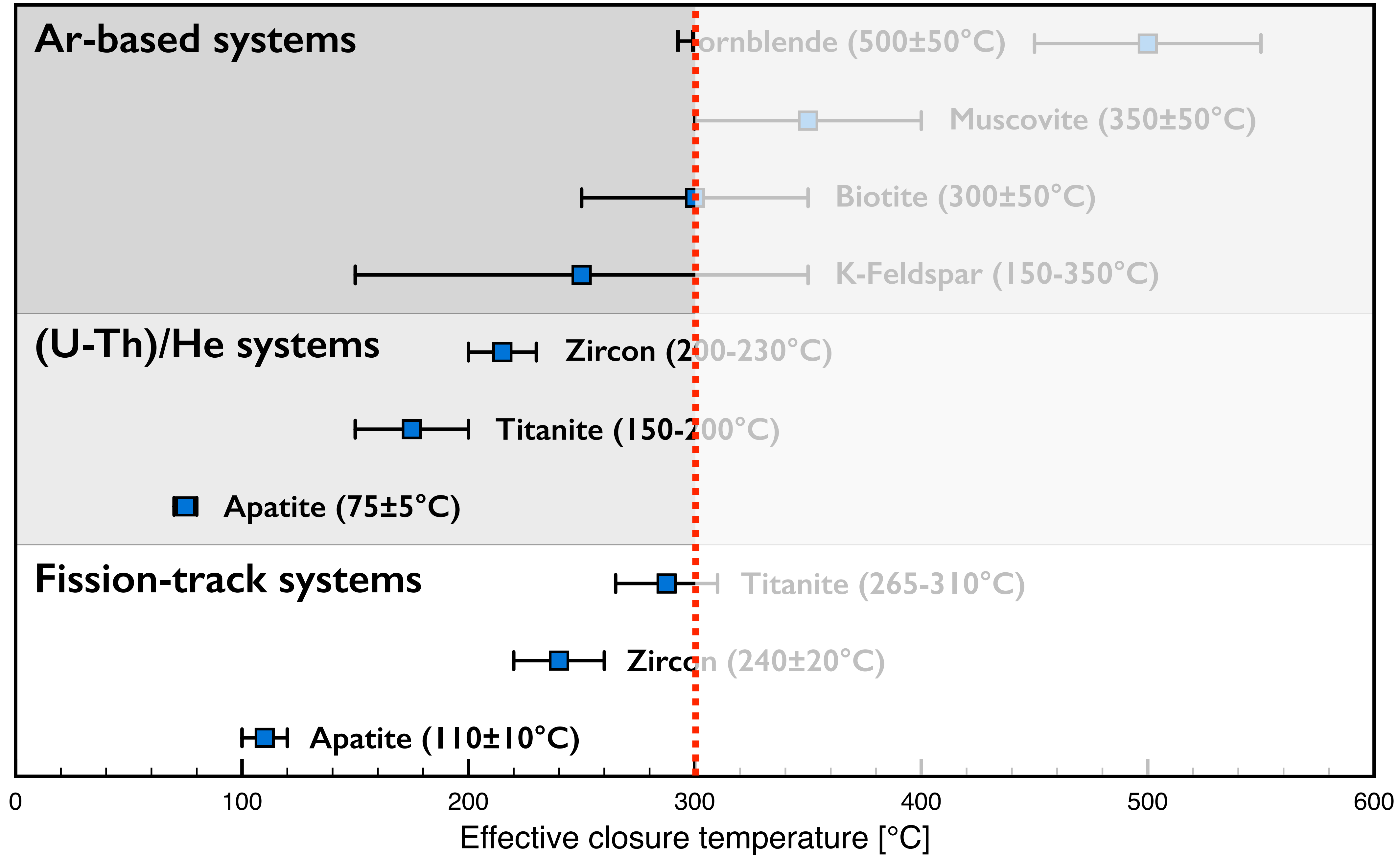
- Define **low-temperature thermochronology**

- 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?

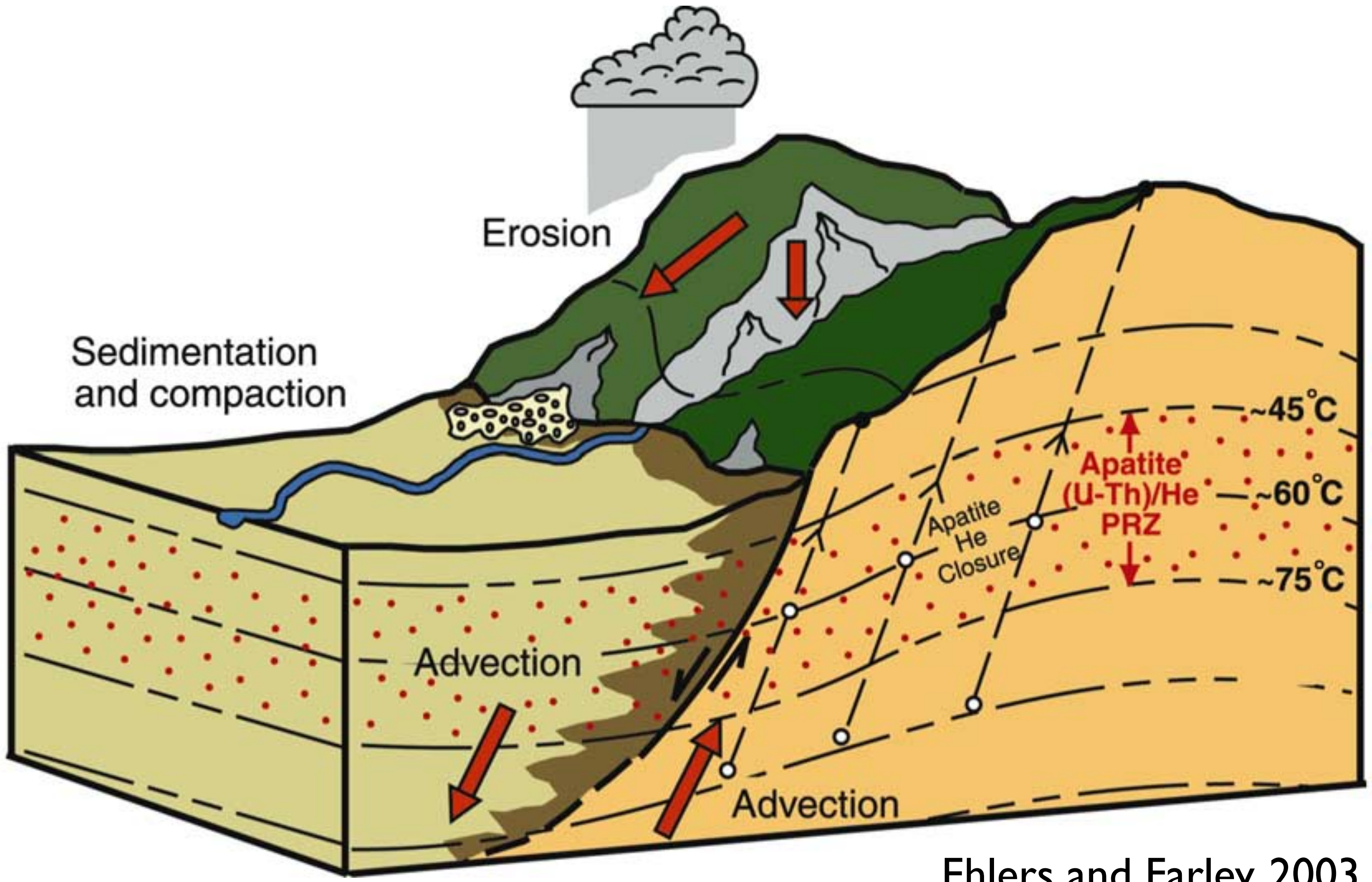
- **Low-T thermochronology** uses thermochronometers with effective closure temperatures **below ~300°C**

What is low-temperature thermochronology?



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

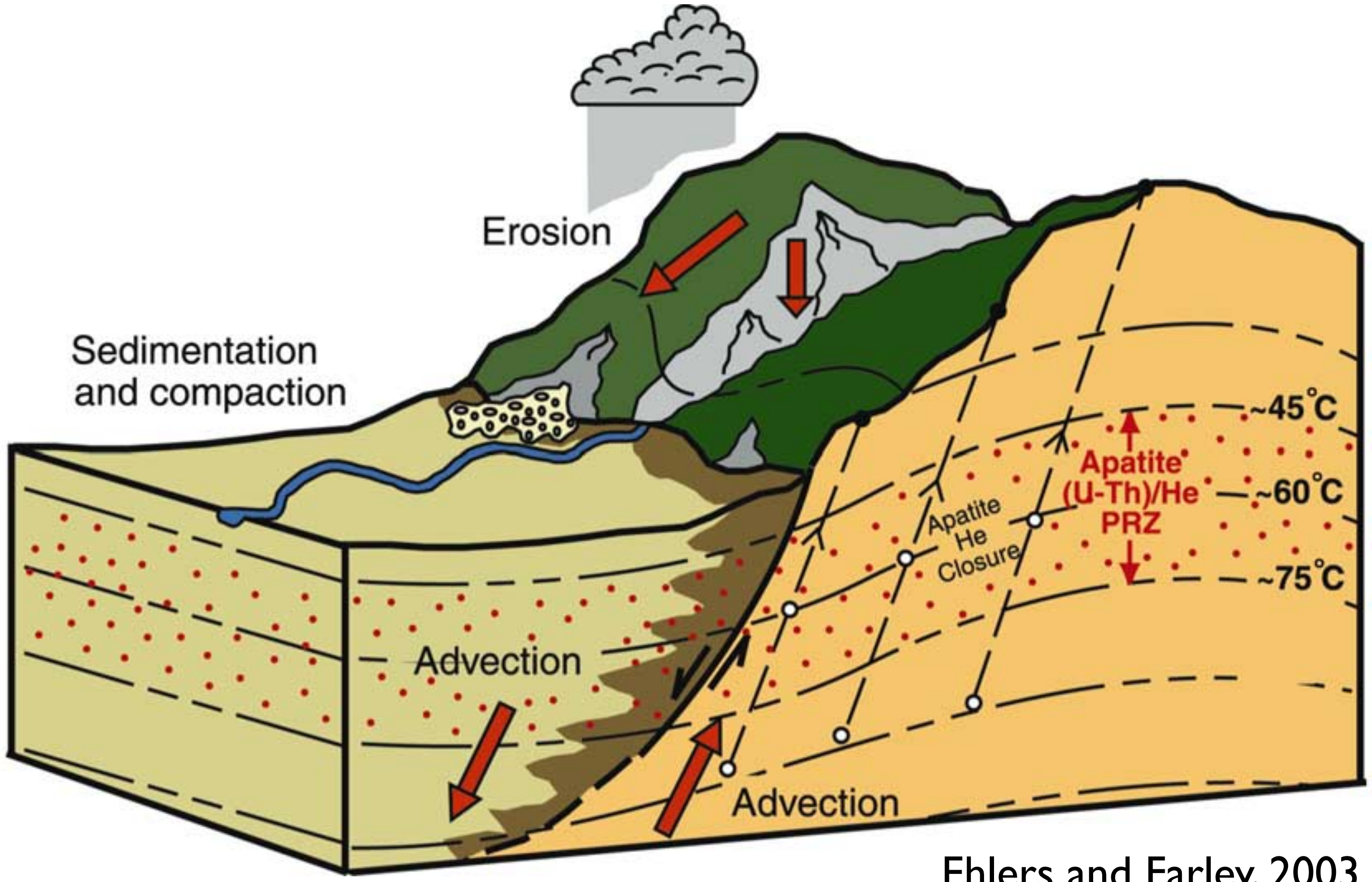
Why is thermochronology useful?



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

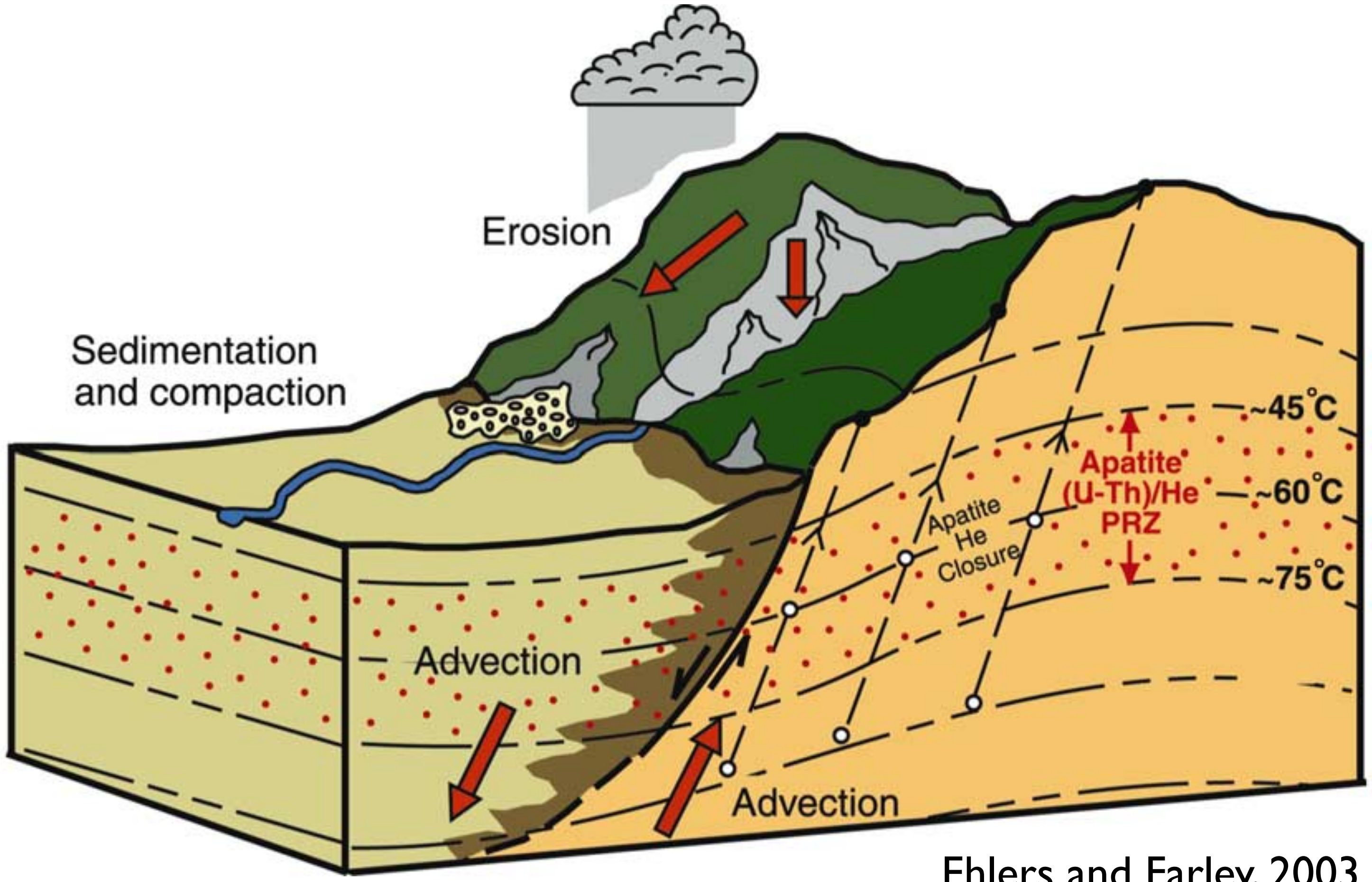
Why is thermochronology useful?



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

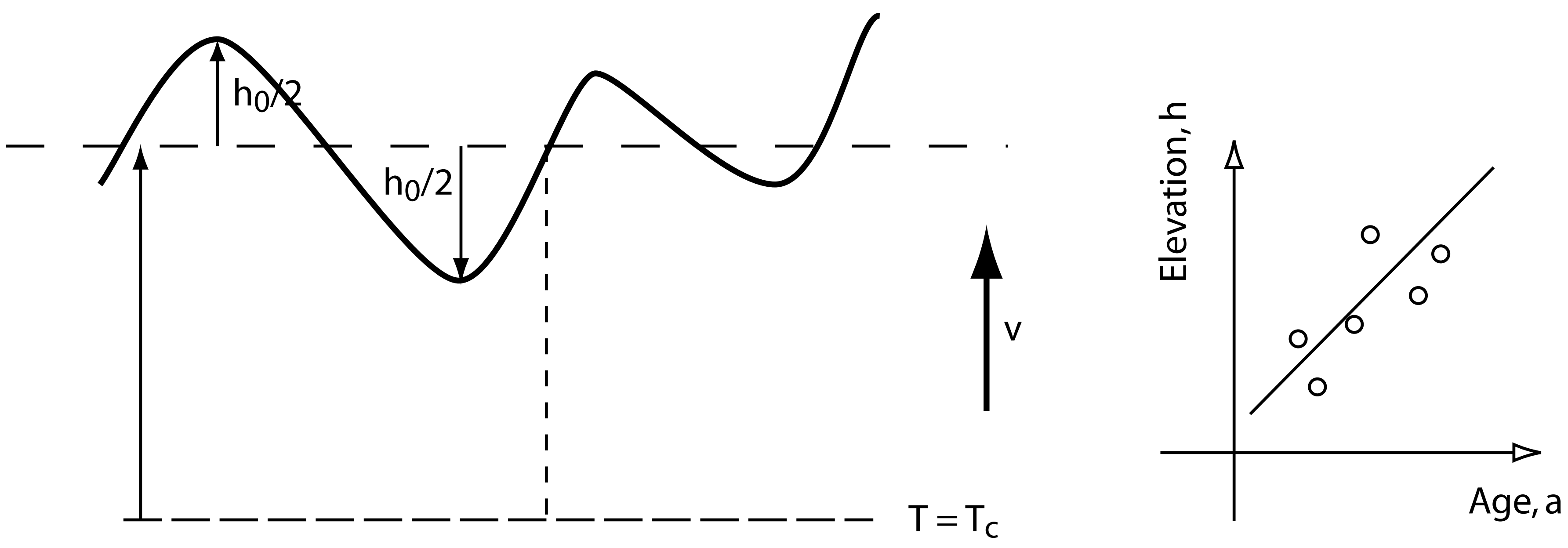
Why is ***low-T*** thermochronology useful?



Ehlers and Farley, 2003

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

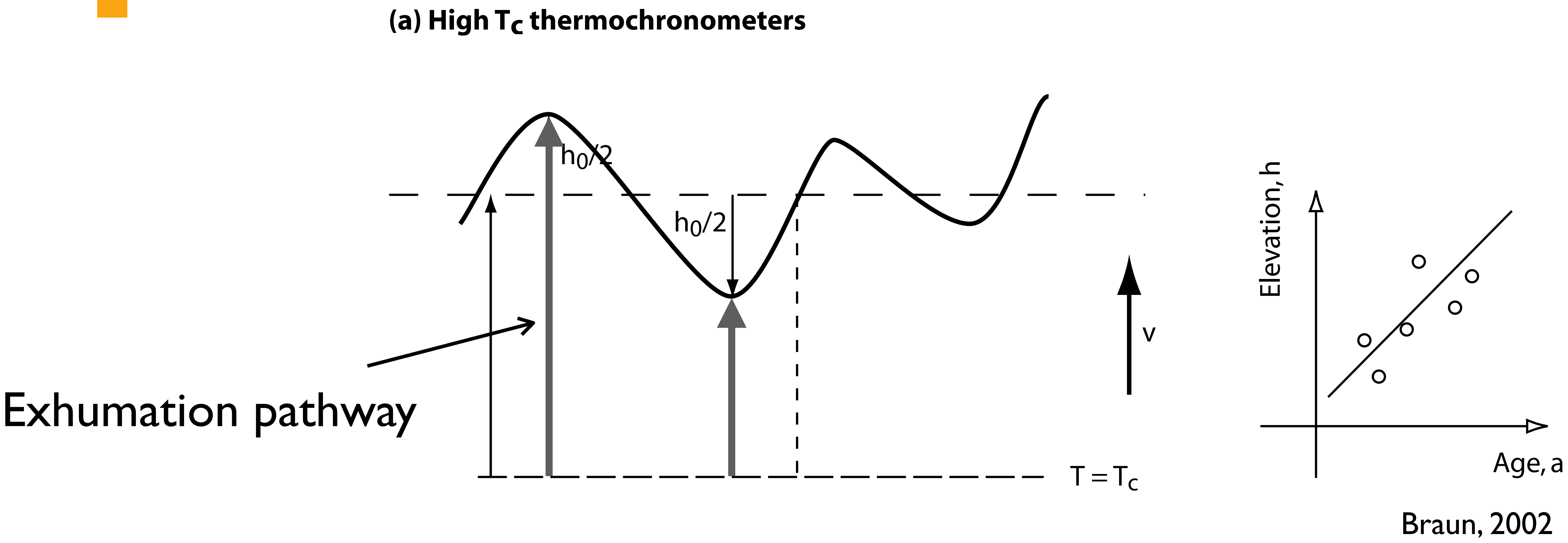
High temperature = no topography sensitivity


(a) High T_c thermochronometers

Braun, 2002

- For thermochronometers with a high effective closure temperature, <u>the closure temperature isotherm will not be influenced by surface topography</u>
  - Note that age will increase with elevation as a result of the topography

High temperature = no topography sensitivity



Braun, 2002

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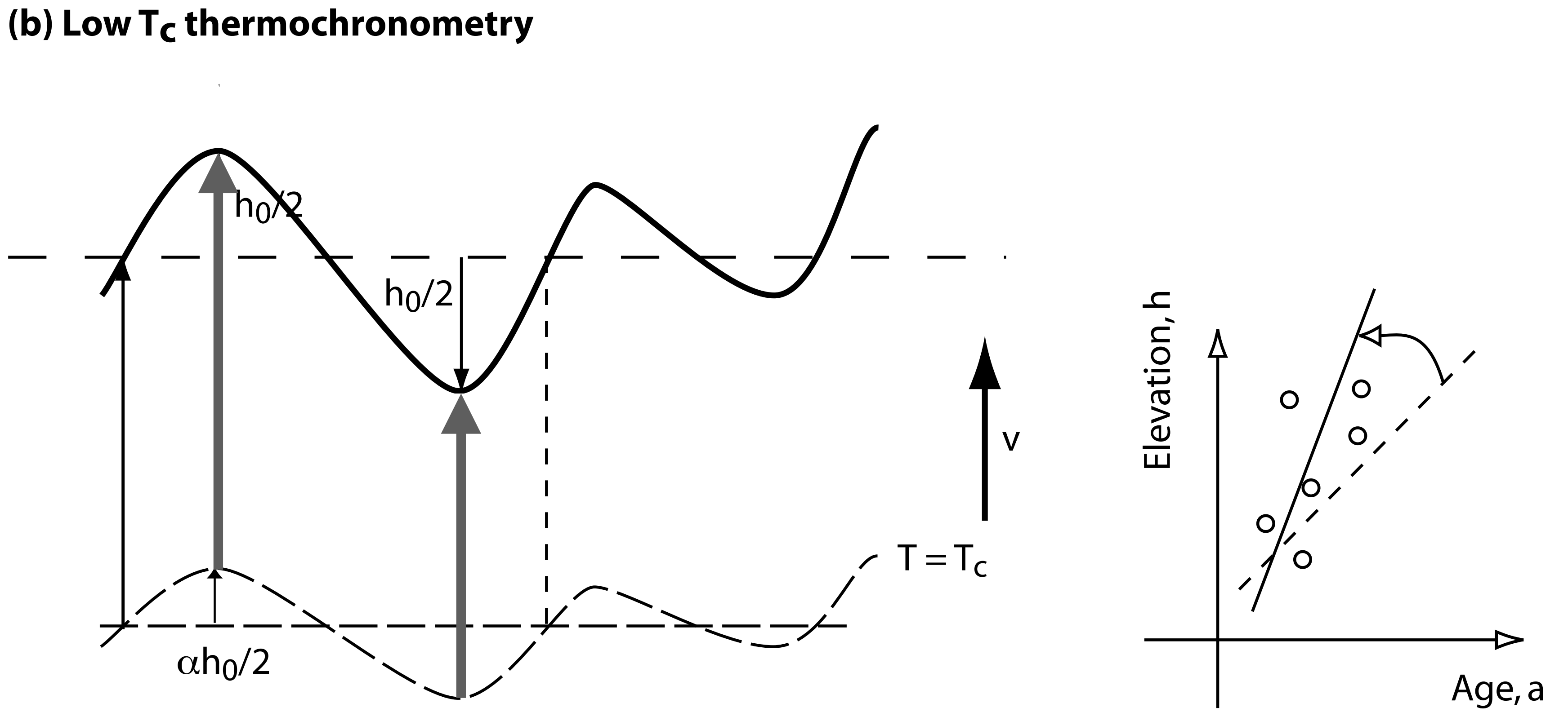
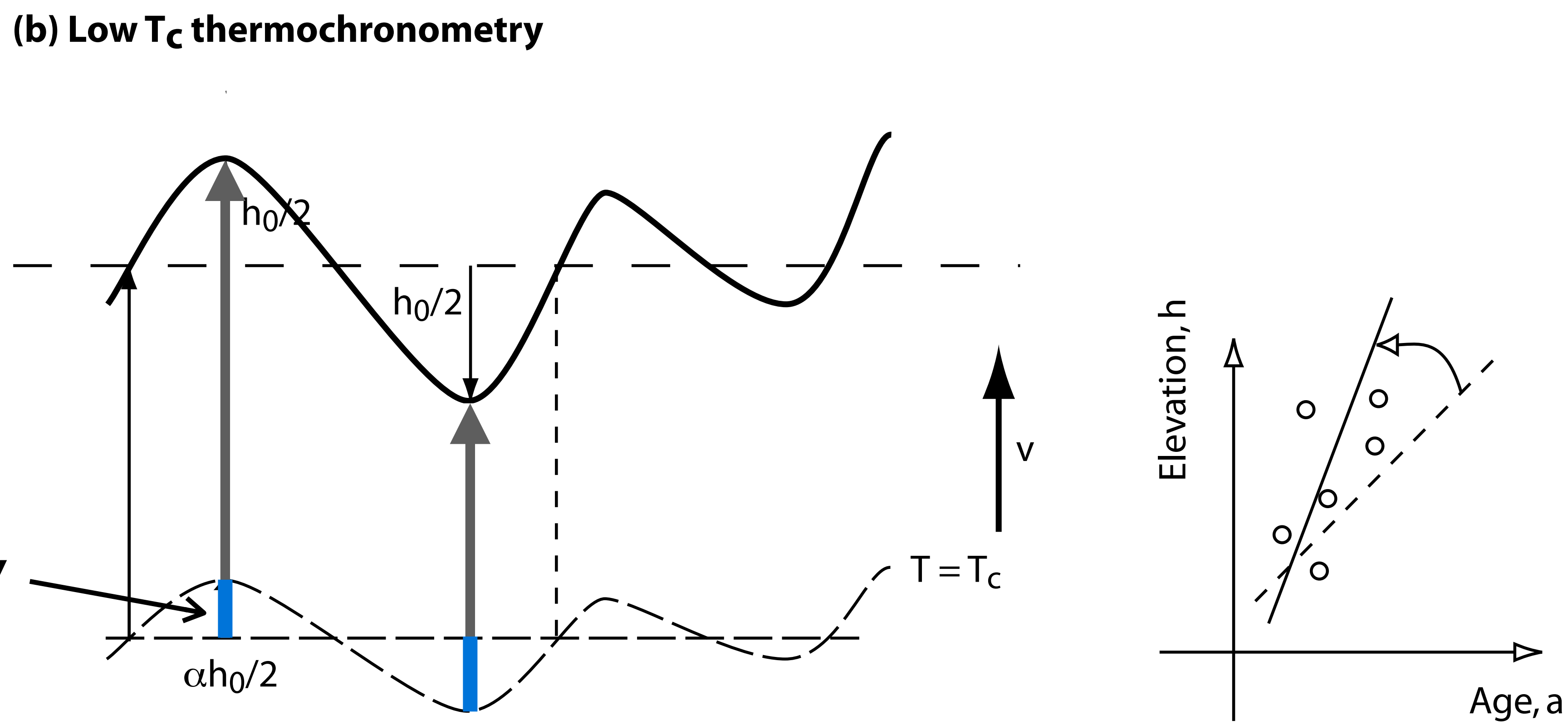
Low-temperature = sensitive to topography



Braun, 2002

- The effective closure temperature isotherm for low-temperature thermochronometers <u>will generally be “bent” by the surface topography</u>, changing the age-elevation trend
  - The lower the value of T_c, the more its geometry will resemble the surface topography

Low-temperature = sensitive to topography



Change in pathway

Braun, 2002

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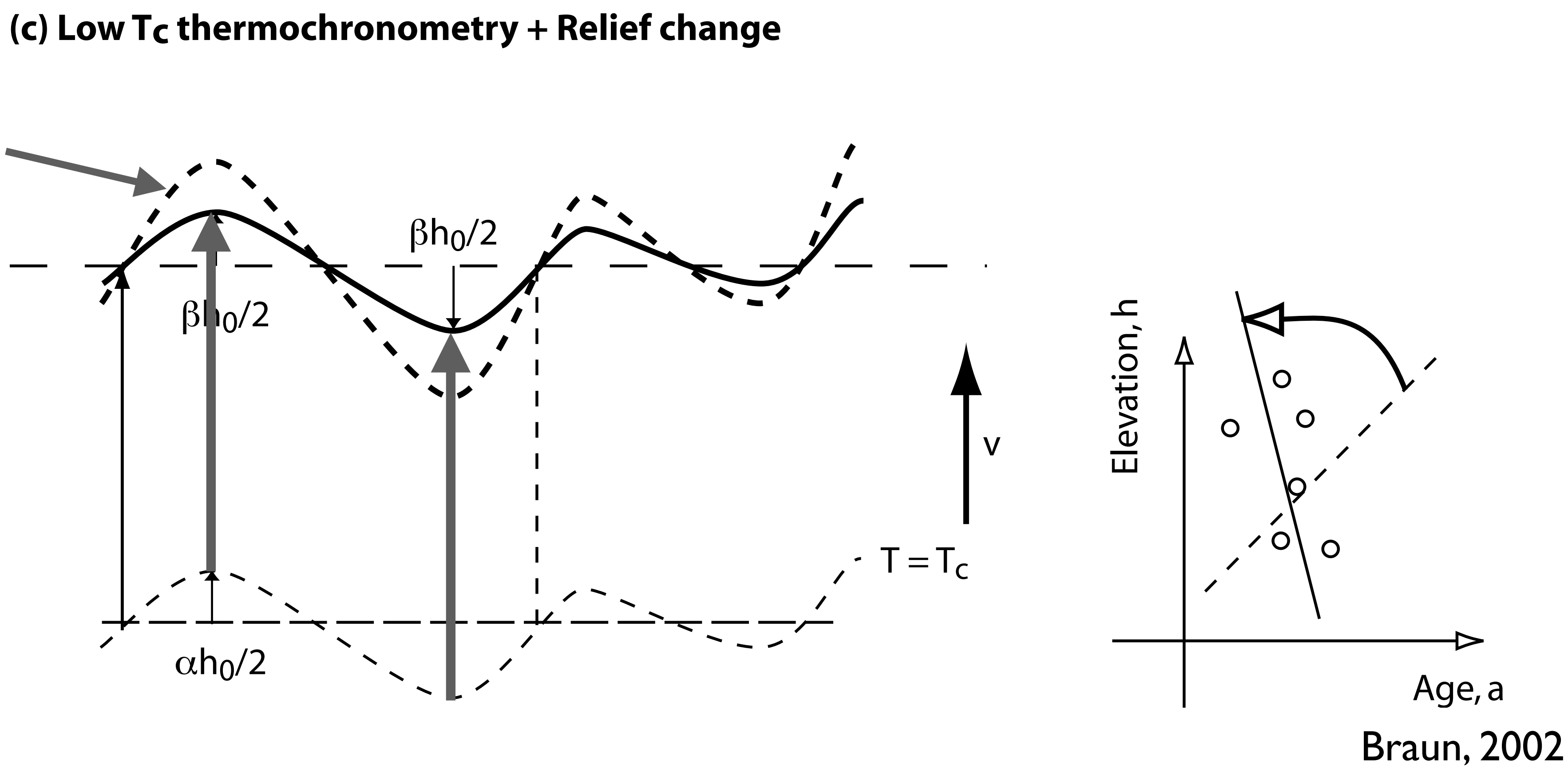
Sensitivity to changing topography



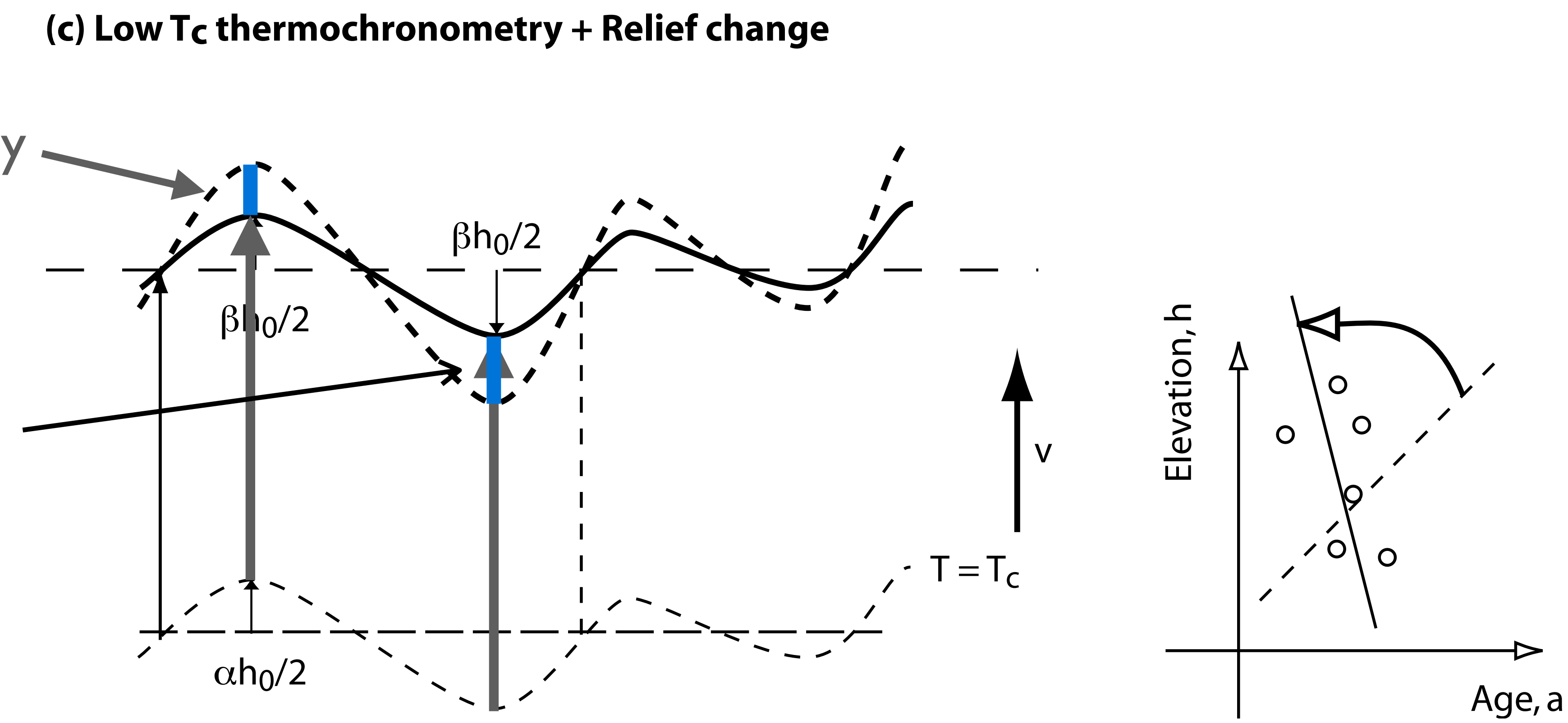
Braun, 2002

- Because T_c is sensitive to topography for low-temperature thermochronometers, it is possible to record changes in topography in the past (!)
  - Here, topographic relief decreases and the age-elevation trend gets inverted (older at low elevation)

Sensitivity to changing topography

Past topography

Change in pathway

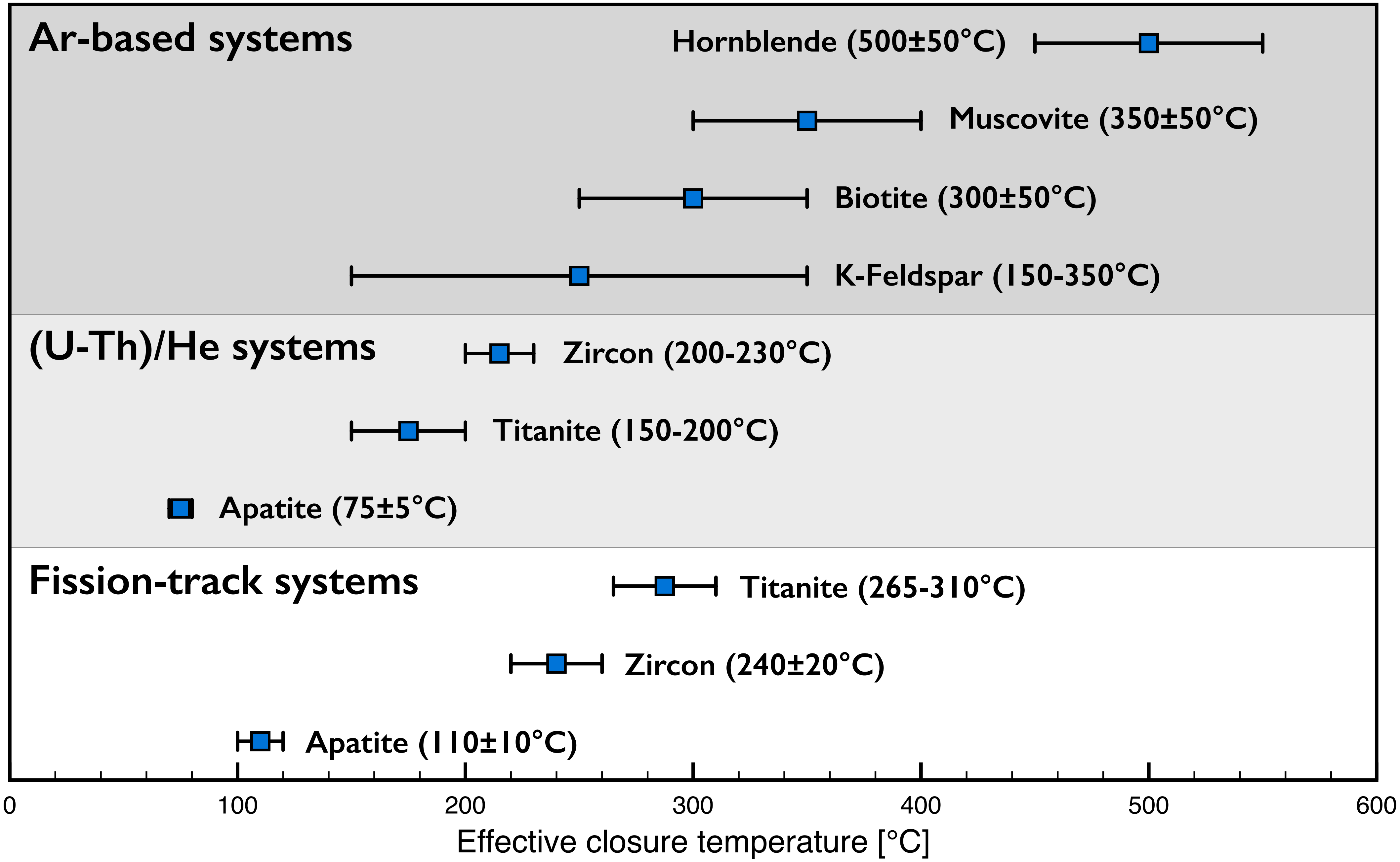


(c) Low T_C thermochronometry + Relief change

Braun, 2002

- Because T_c is sensitive to topography for low-temperature thermochronometers, it is possible to record changes in topography in the past (!)
  - Here, topographic relief decreases and the age-elevation trend gets inverted (older at low elevation)

Common thermochronometers



Helium dating - (U-Th)/He method

Production of alpha particles by decay

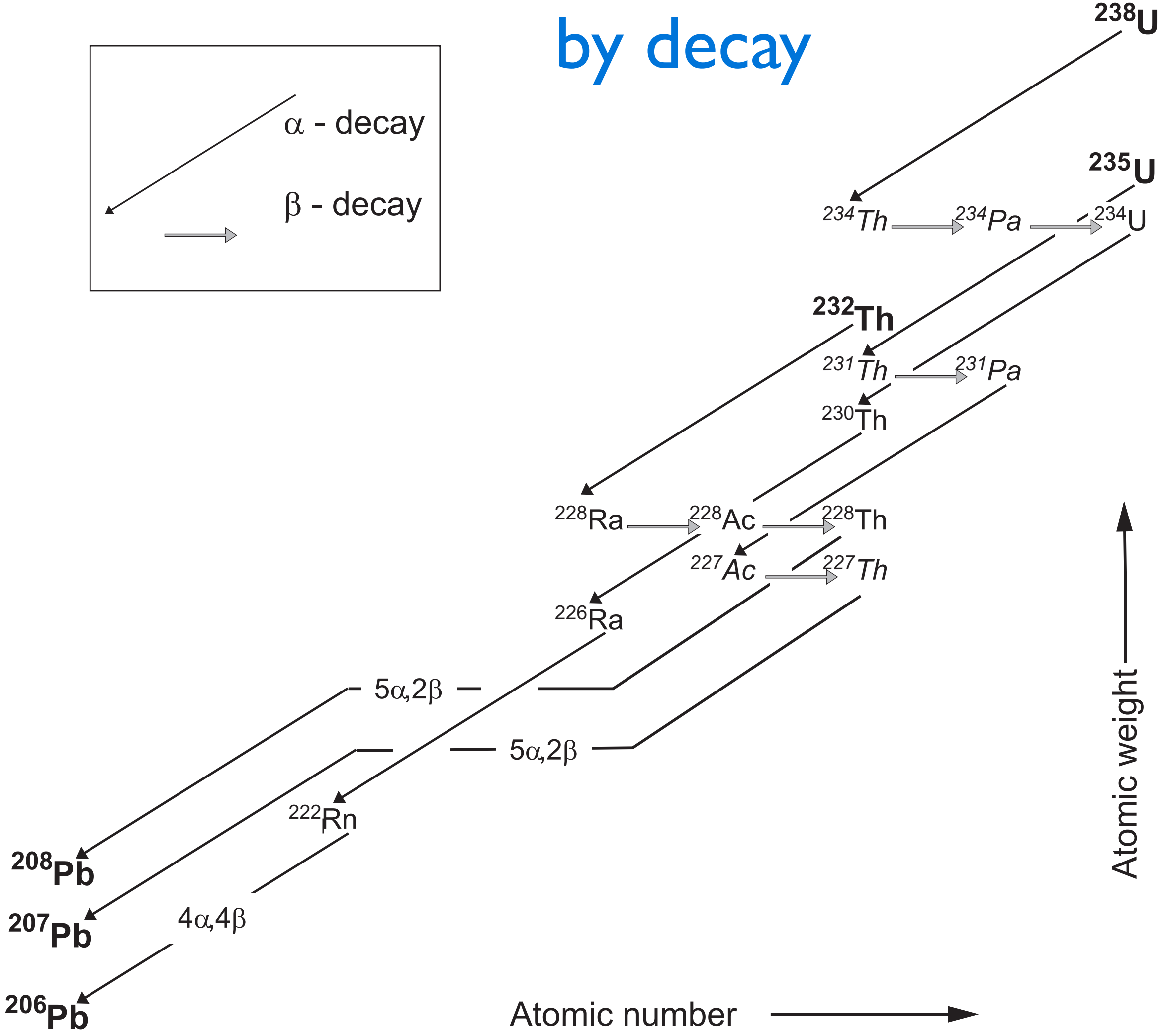


Fig. 3.3, Braun et al., 2006

- **(U-Th)/He thermochronology** is based on the production and accumulation of ^{4}He from parent isotopes ^{238}U, ^{235}U, ^{232}Th and ^{147}Sm
- ^{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

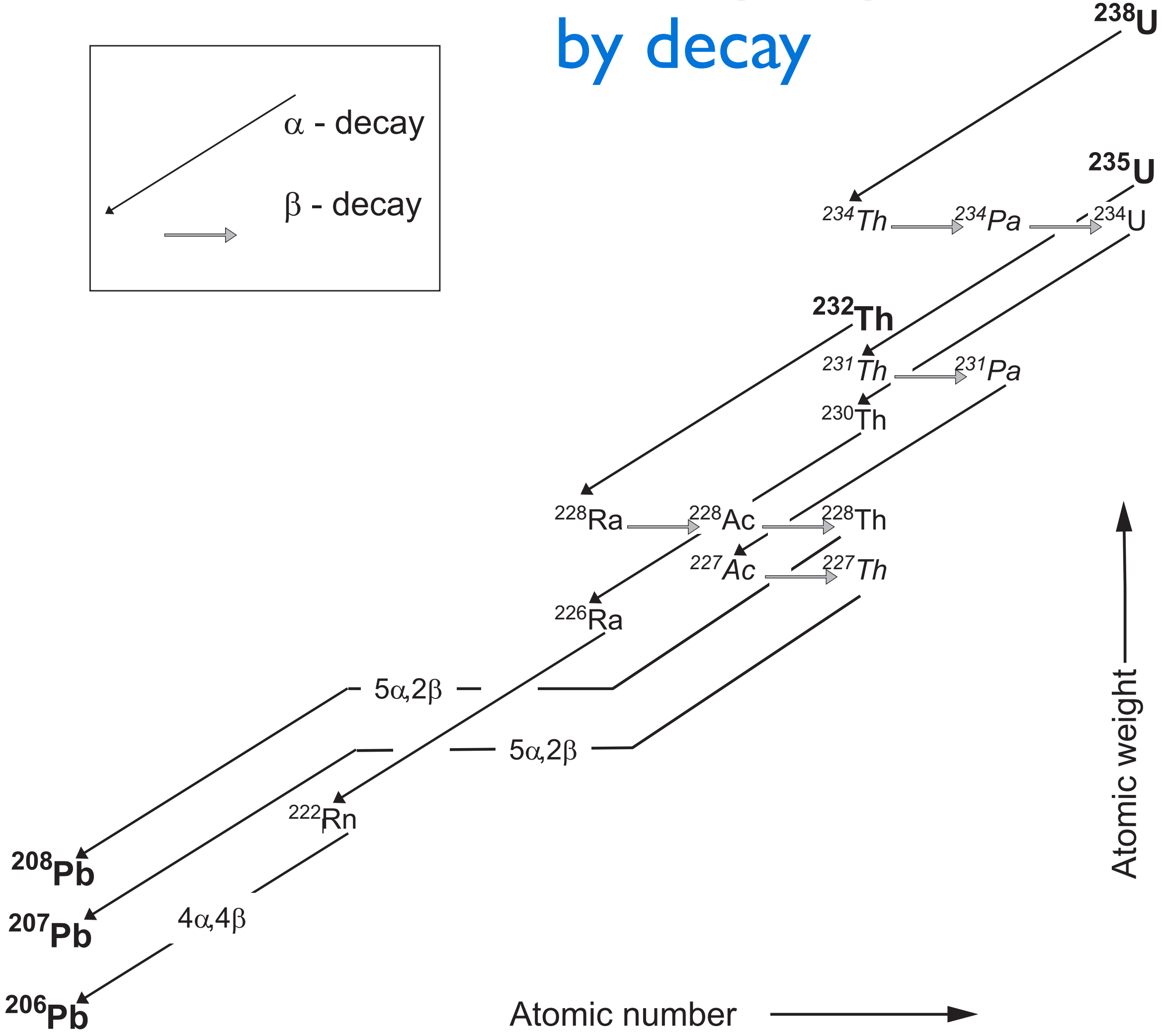


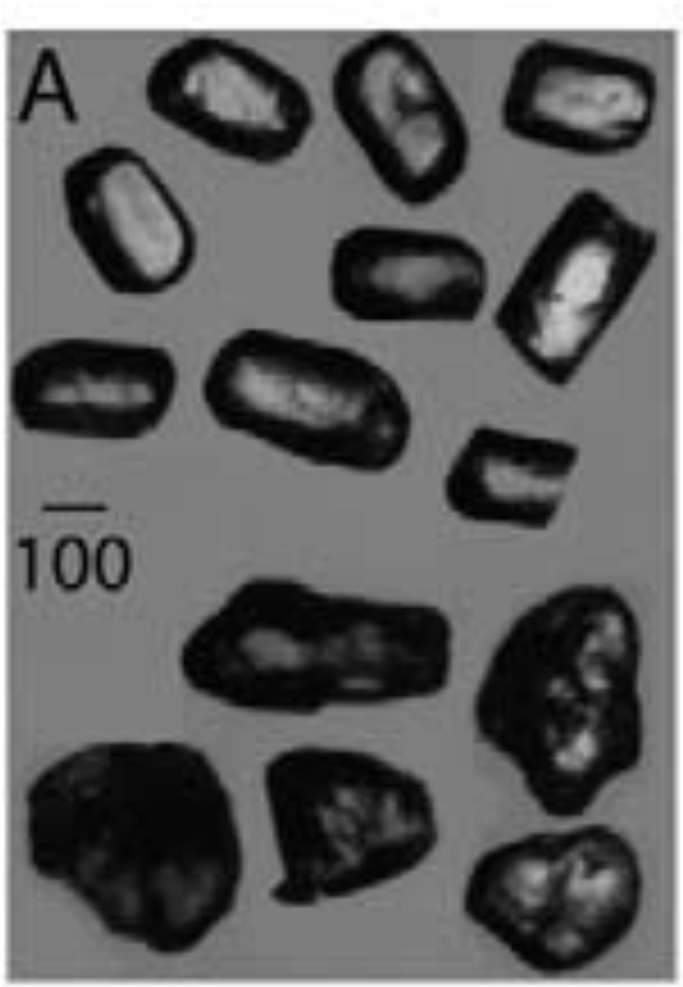
Fig. 3.3, Braun et al., 2006

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

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

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 ^{4}He (alpha particles)

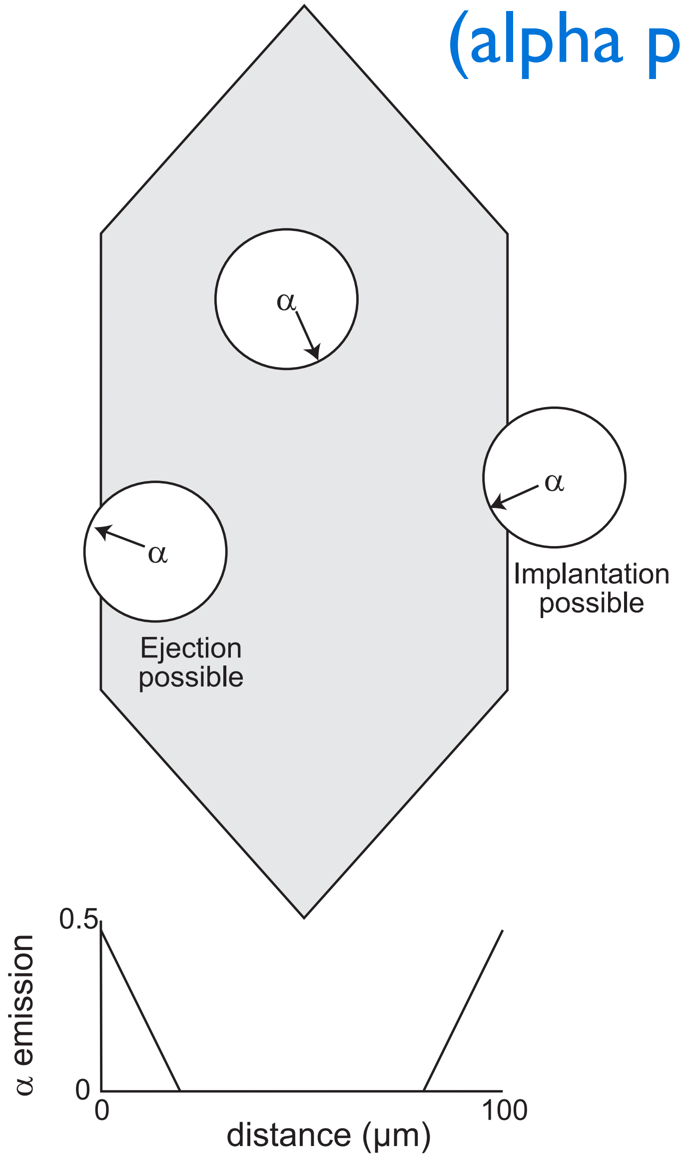
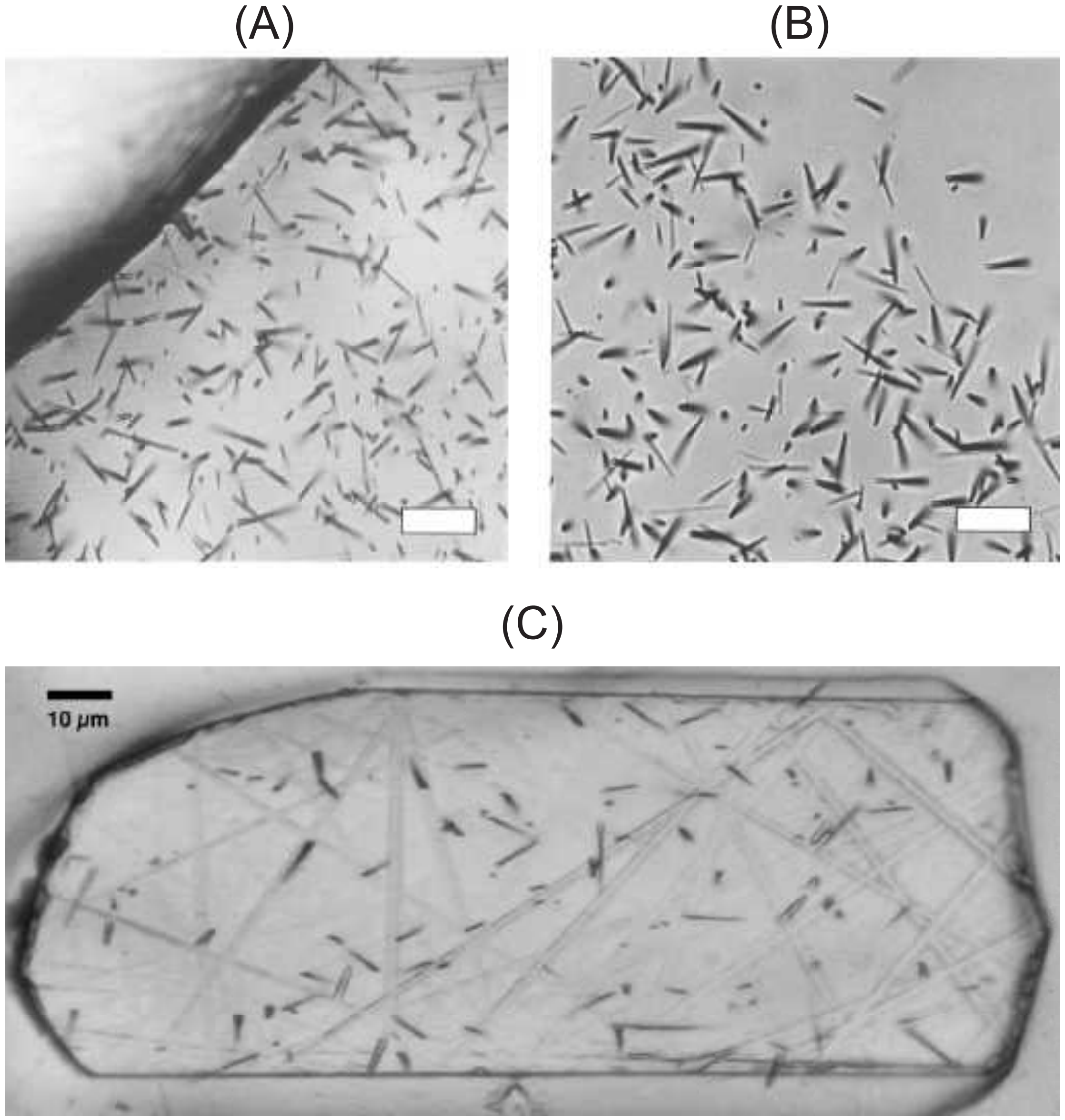


Fig. 3.4, Braun et al., 2006

- 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!

Fission-track dating - FT method

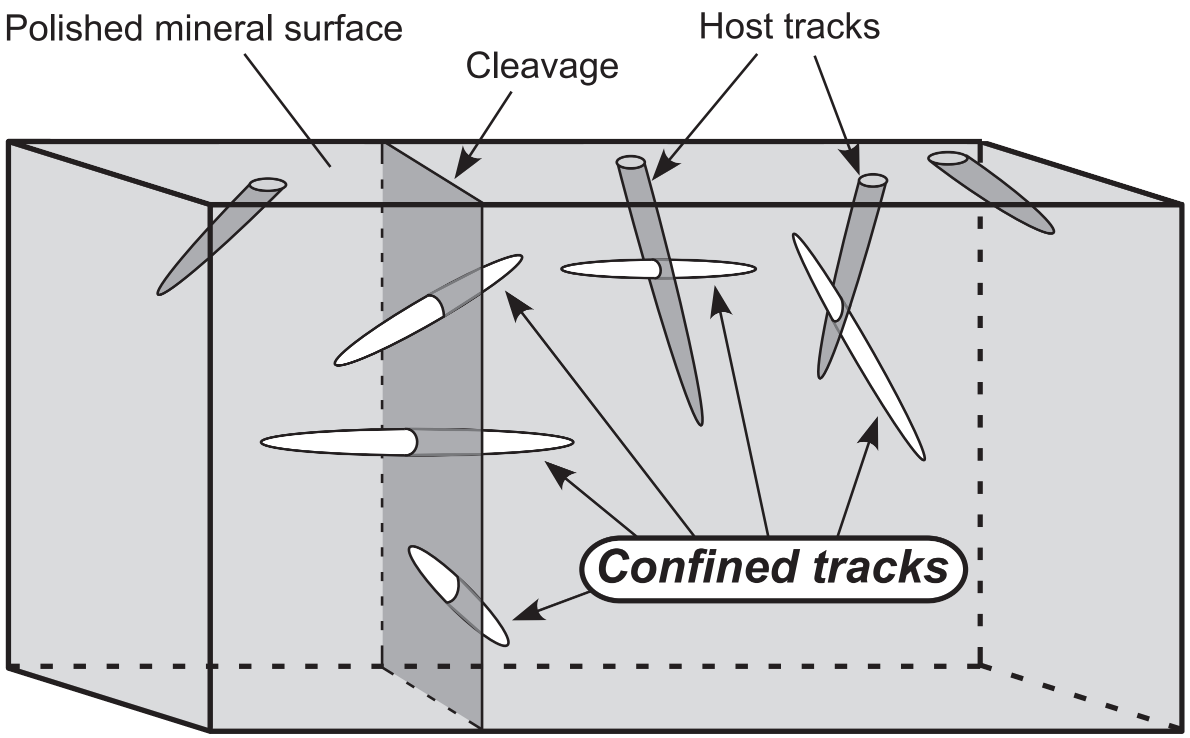
Etched fission tracks in apatite



Tagami and O'Sullivan, 2005

- **Fission-track dating** is based on measuring the <u>accumulation of damage trails in a host crystal</u> 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 ^{4}He, these <u>damage trails will be repaired, or anneal</u>, 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

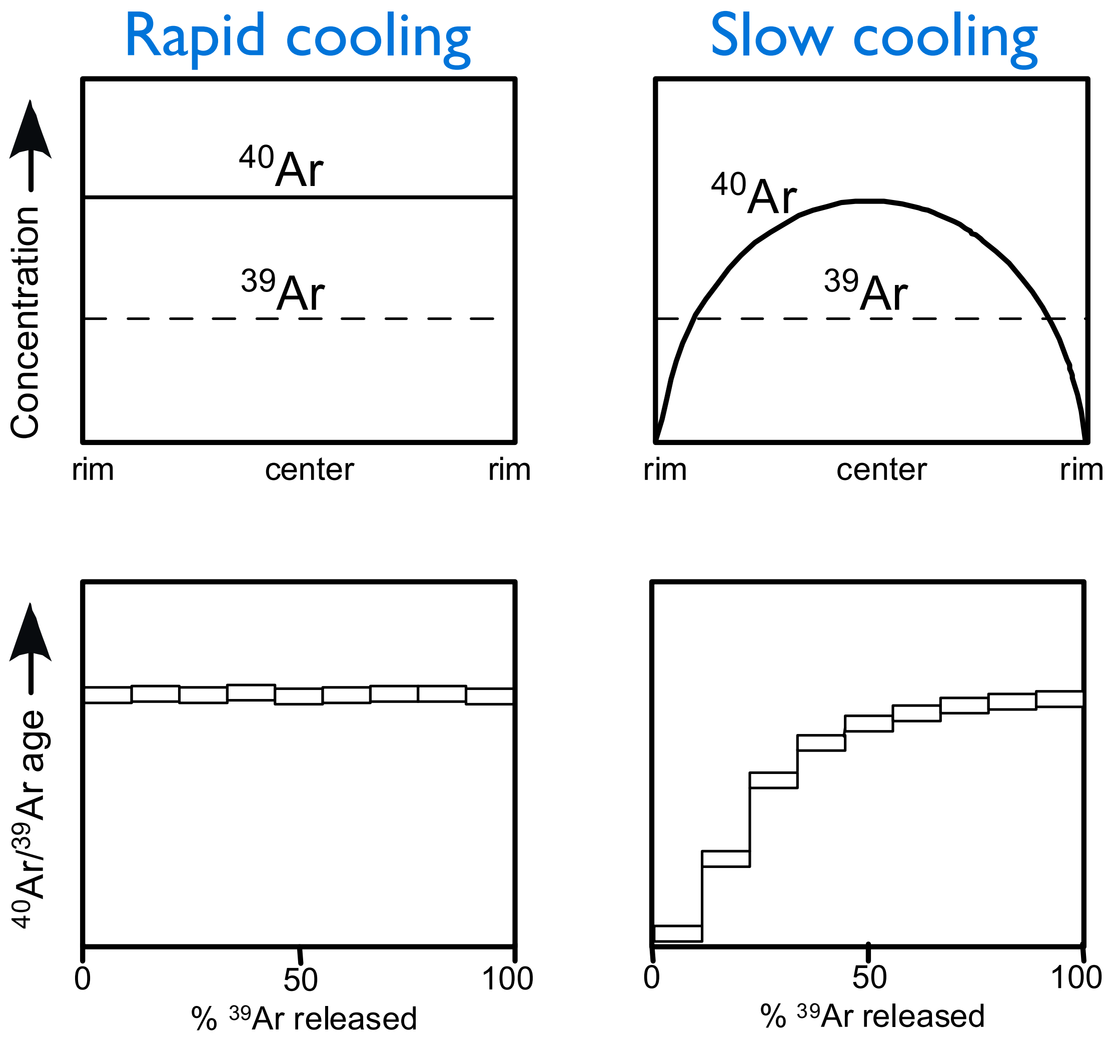
$$t = \frac{1}{\lambda} \ln \left(1 + J \frac{^{40}\mathrm{Ar}}{^{39}\mathrm{Ar}} \right)$$

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

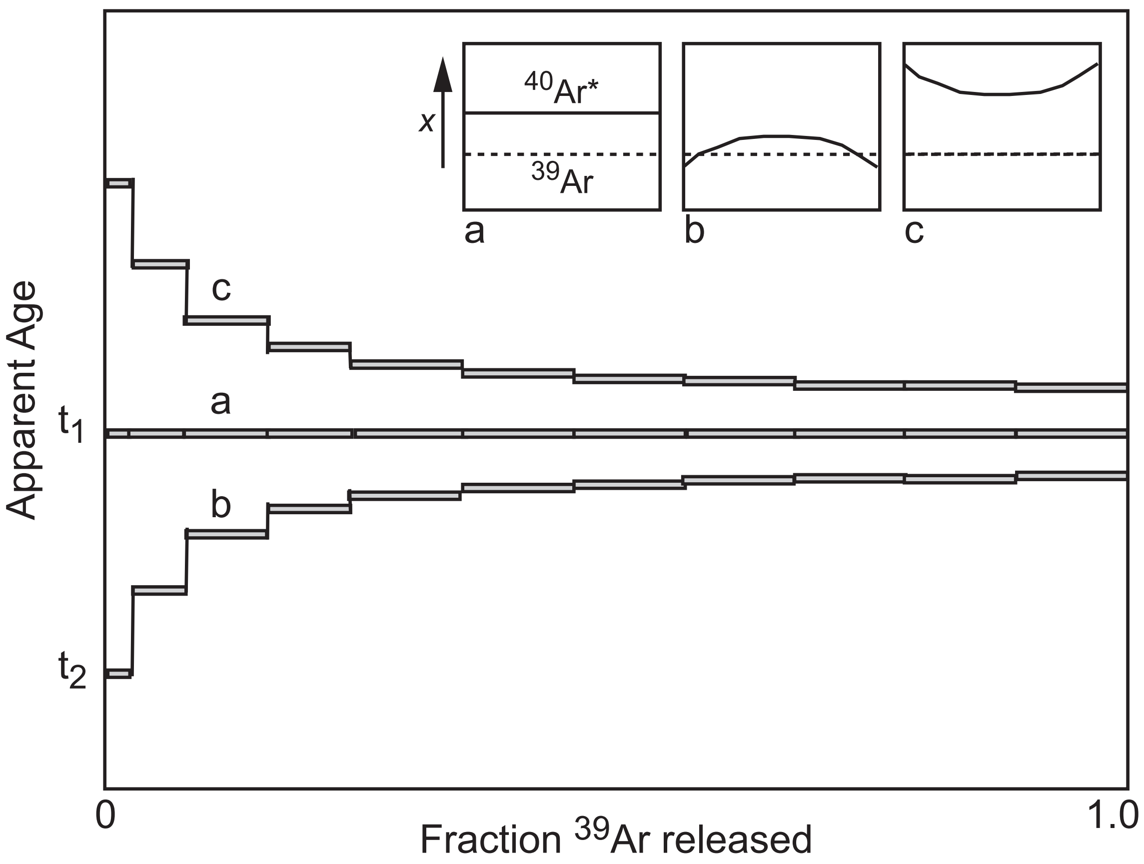


Fig. 3.1, Braun et al., 2006

- As we have seen on the previous slide,

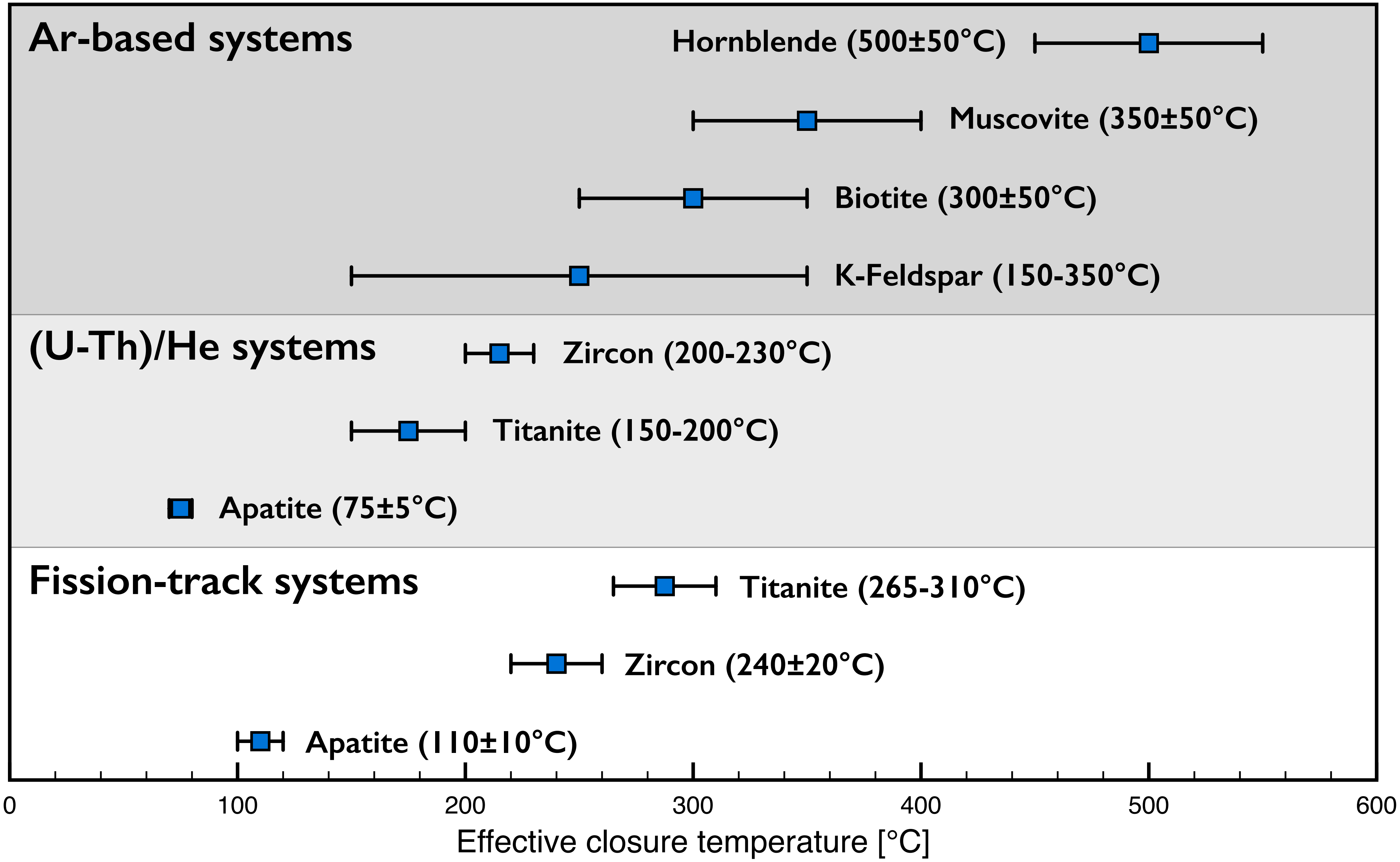
  (a) flat age spectra indicate rapid cooling of a rock sample (at time t_1, here)

  (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 write/modify a Jupyter notebook code to produce some plots and provide short answers to some related questions
  - The questions you will answer for the write-ups for these two exercises will be relatively simple, only to let me know that you were able to do the requested tasks, because…

Lab and final project primer

- …you will expand on the work you do in the final two labs in a formal written report
- The report will be no longer than 6-8 typed pages (single spaced) including figures and references
- 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

References

Braun, J. (2002), Quantifying the effect of recent relief changes on age-elevation relationships, *Earth and Planetary Science Letters*, *200*(3-4), 331–343.

Braun, J., der Beek, van, P., & Batt, G. E. (2006). *Quantitative Thermochronology*. Cambridge University Press.

Coutand, I., Whipp, D. M., Grujic, D., Bernet, M., Fellin, M. G., Bookhagen, B., et al. (2014). Geometry and kinematics of the Main Himalayan Thrust and Neogene crustal exhumation in the Bhutanese Himalaya derived from inversion of multithermochronologic data. *Journal of Geophysical Research: Solid Earth*. doi: 10.1002/2013JB010891

Ehlers, T. A., & Farley, K. A. (2003). Apatite (U-Th)/He thermochronometry; methods and applications to problems in tectonic and surface processes. *Earth and Planetary Science Letters*, *206*(1-2), 1–14.

Harrison, T. M., and P. K. Zeitler (2005), Fundamentals of Noble Gas Thermochronometry, in *Low-Temperature Thermochronology: Techniques, Interpretations and Applications*, vol. 58, edited by P. W. Reiners and T. A. Ehlers, pp. 123–149, Mineralogical Society of America.

Tagami, T., & O'Sullivan, P. B. (2005). Fundamentals of Fission-Track Thermochronology. In P. W. Reiners & T. A. Ehlers (Eds.), *Low-Temperature Thermochronology: Techniques, Interpretations and Applications* (Vol. 58, pp. 19–47). Mineralogical Society of America.