



Class overview today - December 3, 2018

- 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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3.12.18



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 $^{40}\text{Ar}/^{39}\text{Ar}$ method)

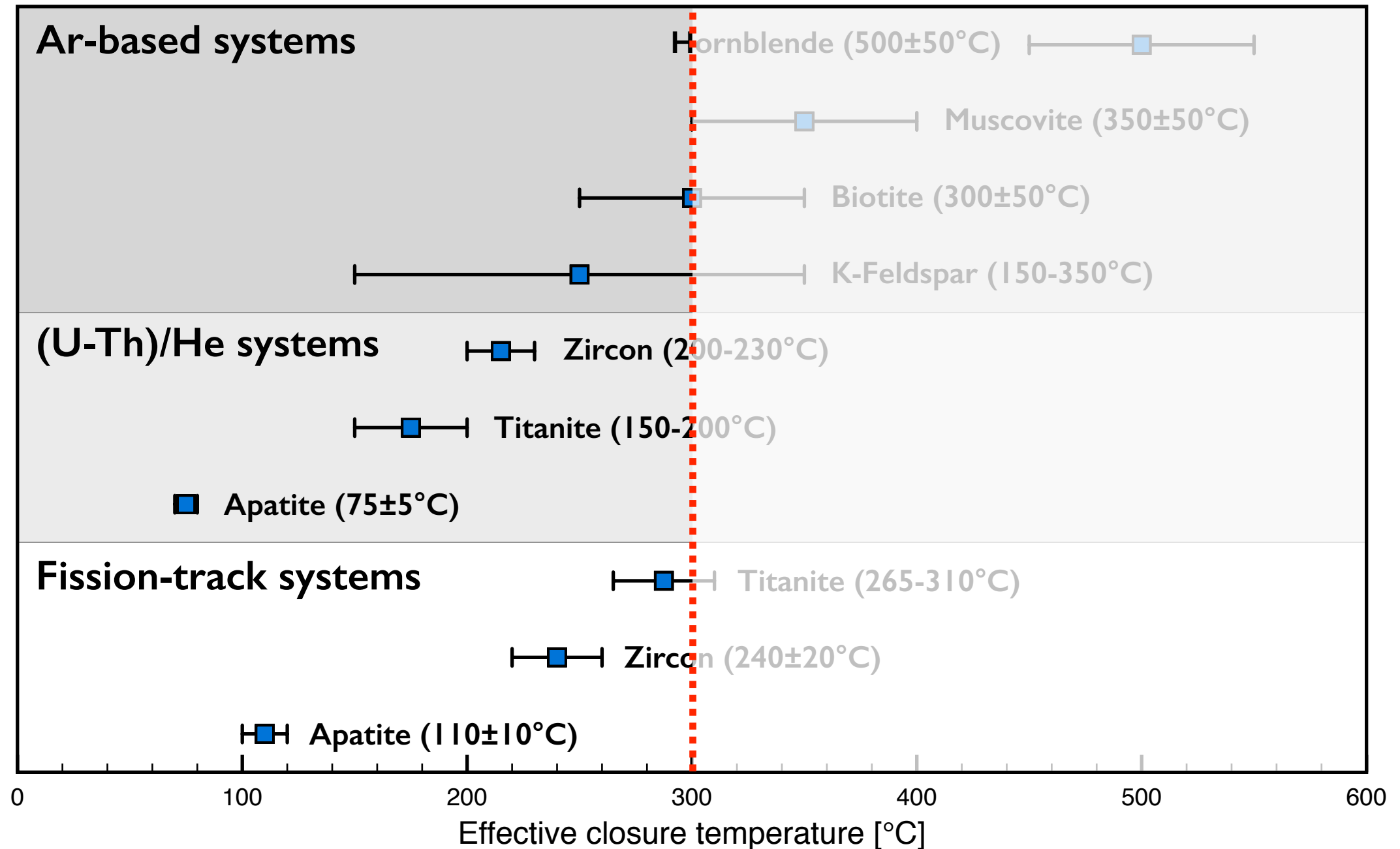


What is low-temperature thermochronology?

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



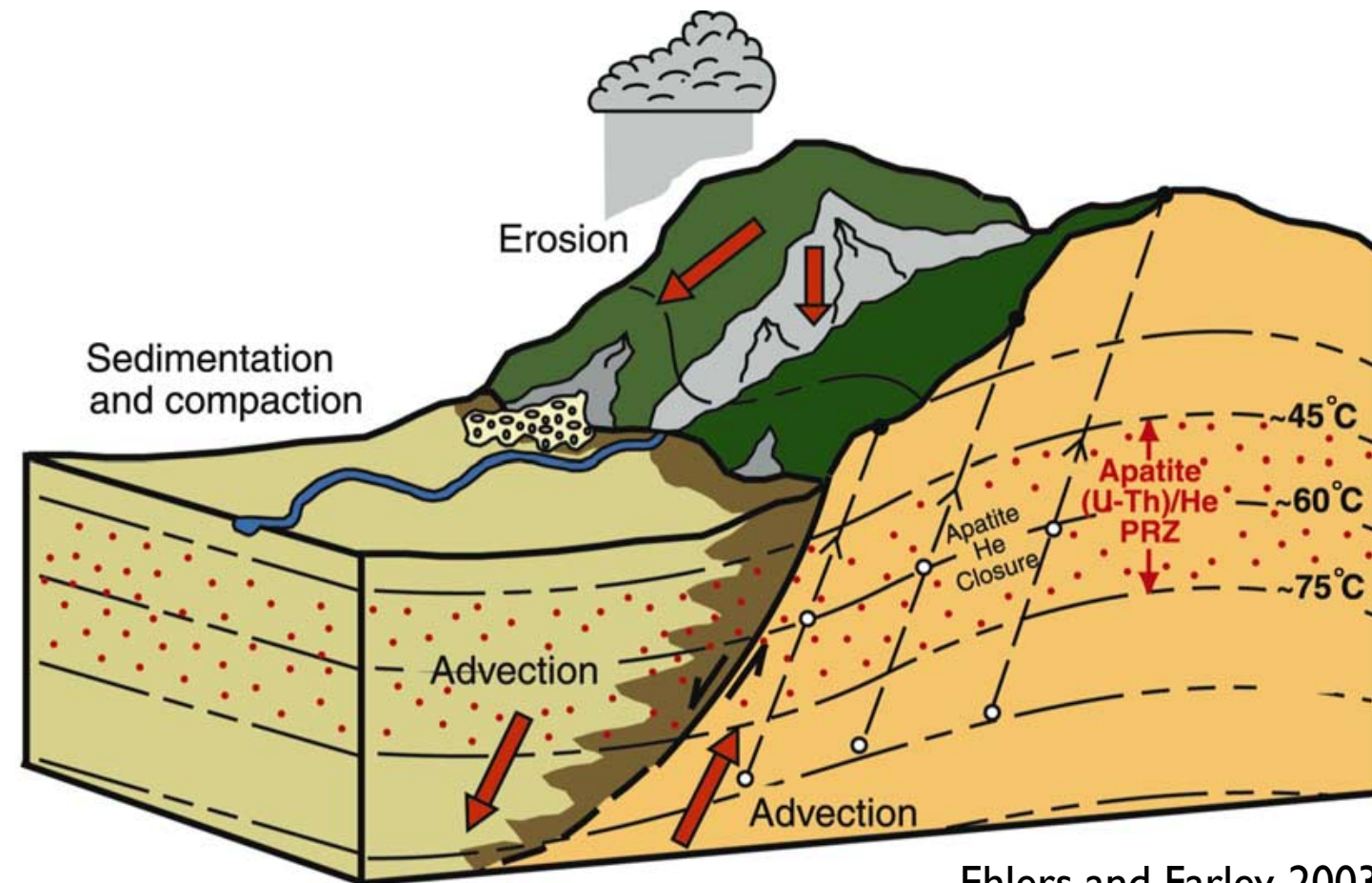
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Why is thermochronology useful?

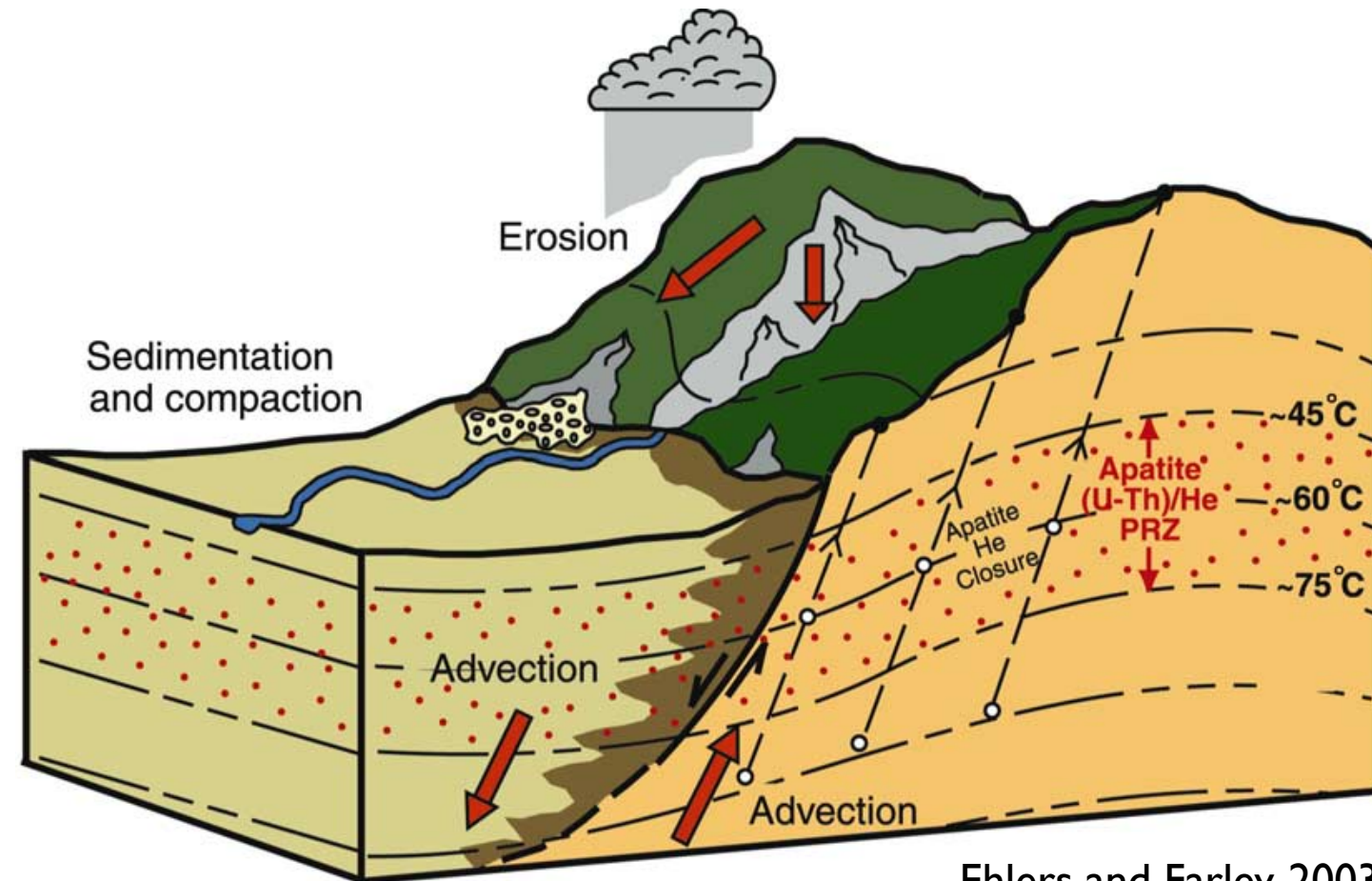


Ehlers and Farley, 2003

- 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



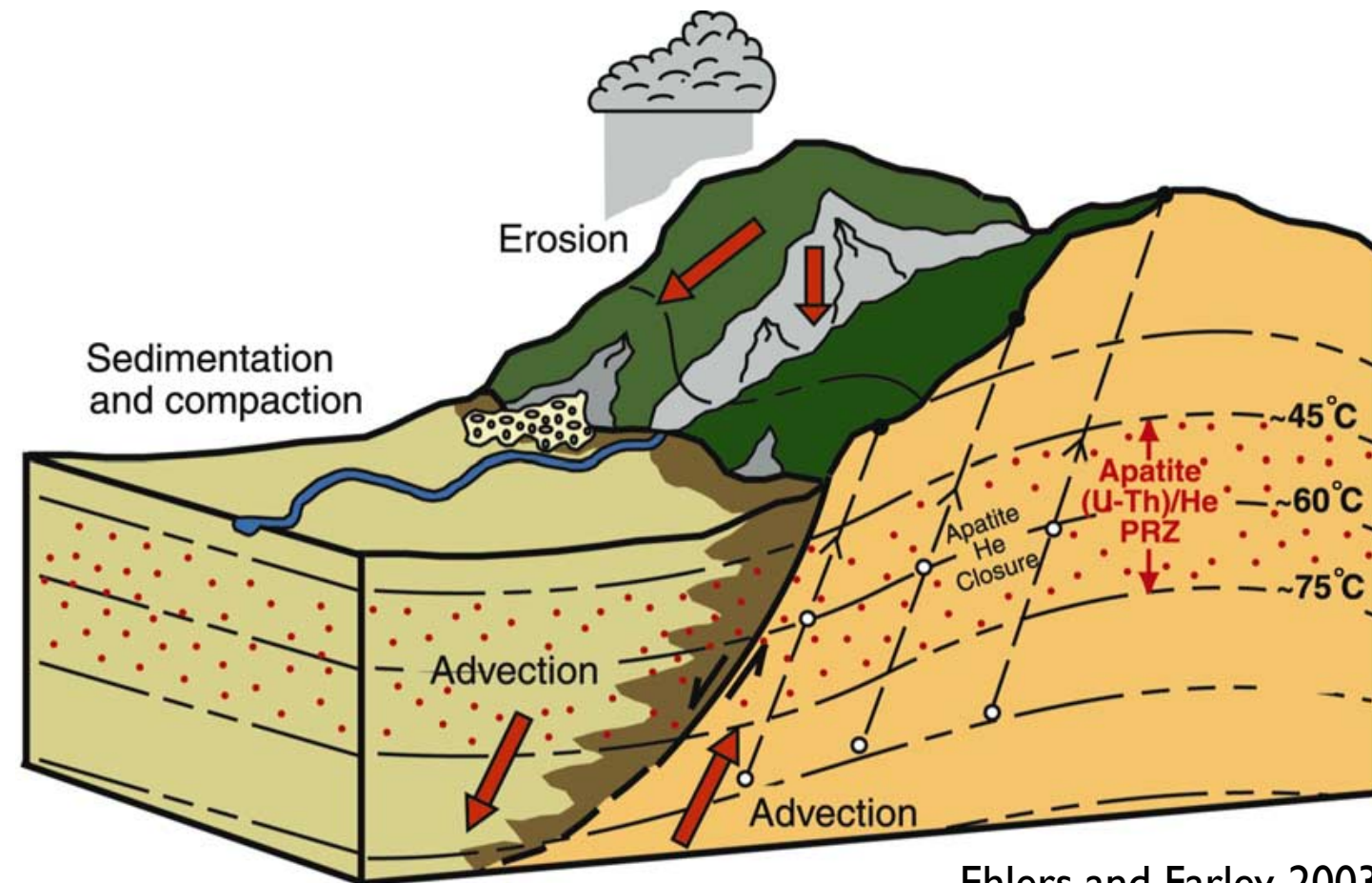
Why is thermochronology useful?



- 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?

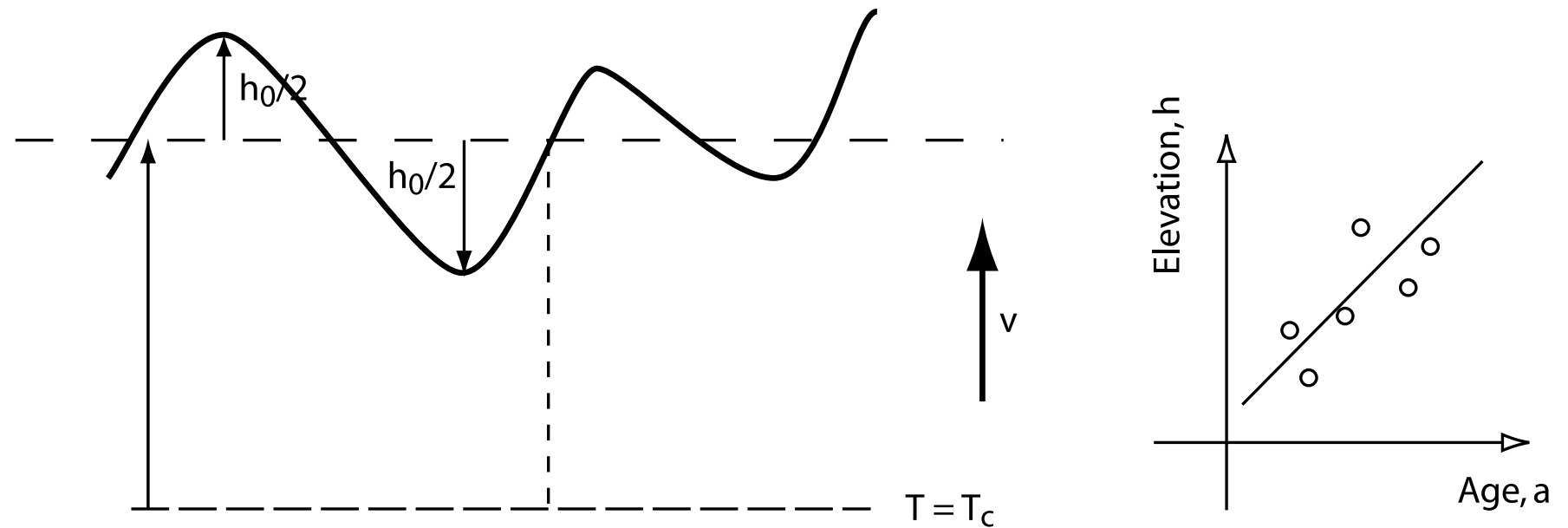


- **Low-temperature thermochronometers** are unique because of their increased sensitivity to topography, erosional and tectonic processes



High temperature = no topography sensitivity

(a) High T_c thermochronometers



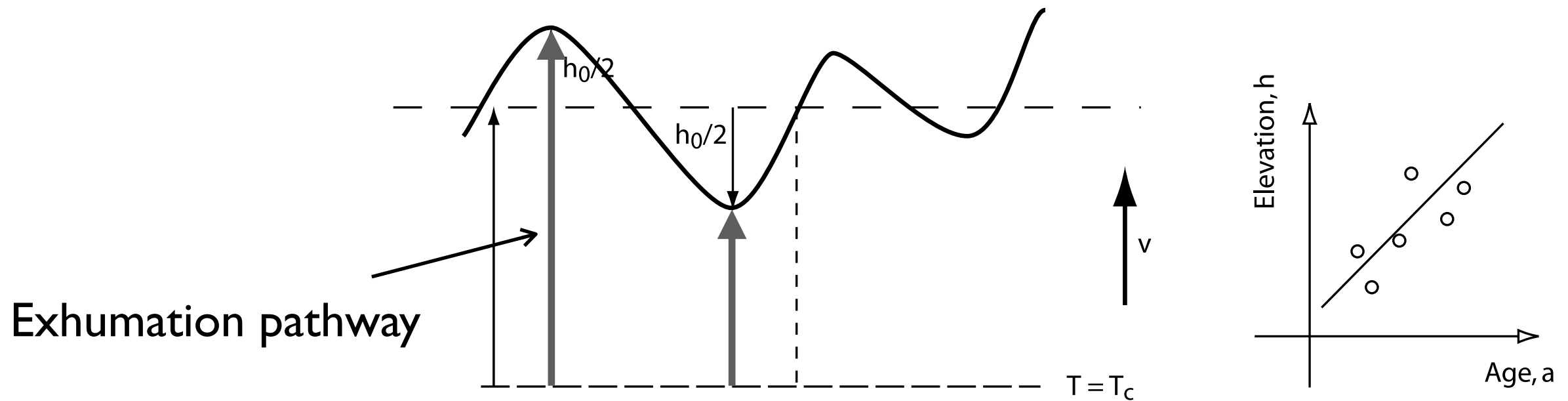
Braun, 2002

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



High temperature = no topography sensitivity

(a) High T_c thermochronometers



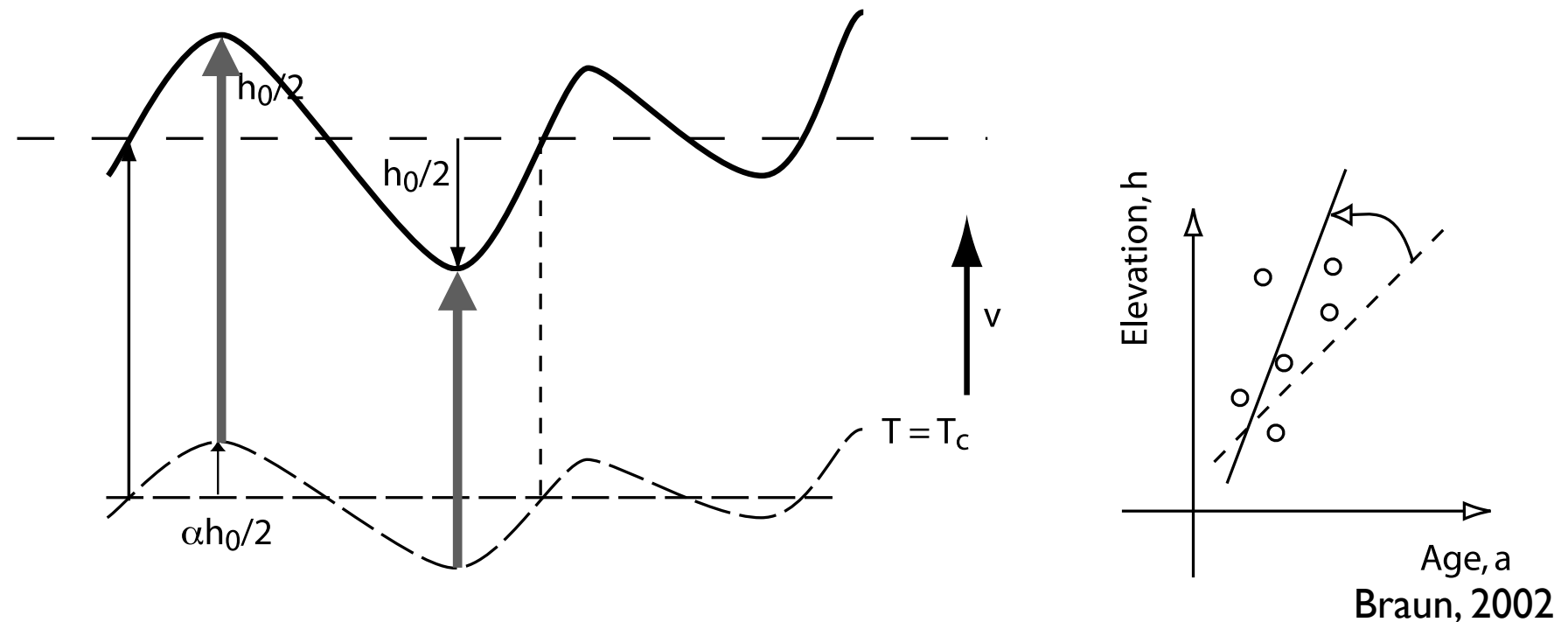
Braun, 2002

- For thermochronometers with a high effective closure temperature, the closure temperature isotherm will not be influenced by surface topography
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Low-temperature = sensitive to topography

(b) Low T_c thermochronometry

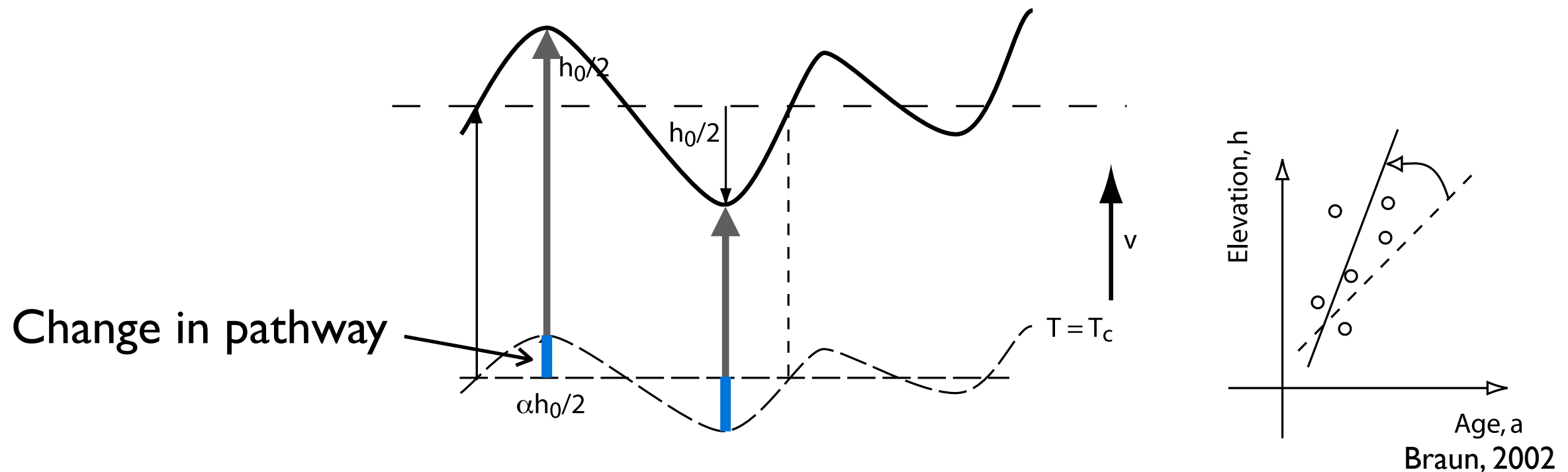


- The effective closure temperature isotherm for low-temperature thermochronometers will generally be “bent” by the surface topography, changing the age-elevation trend
- The lower the value of T_c , the more its geometry will resemble the surface topography



Low-temperature = sensitive to topography

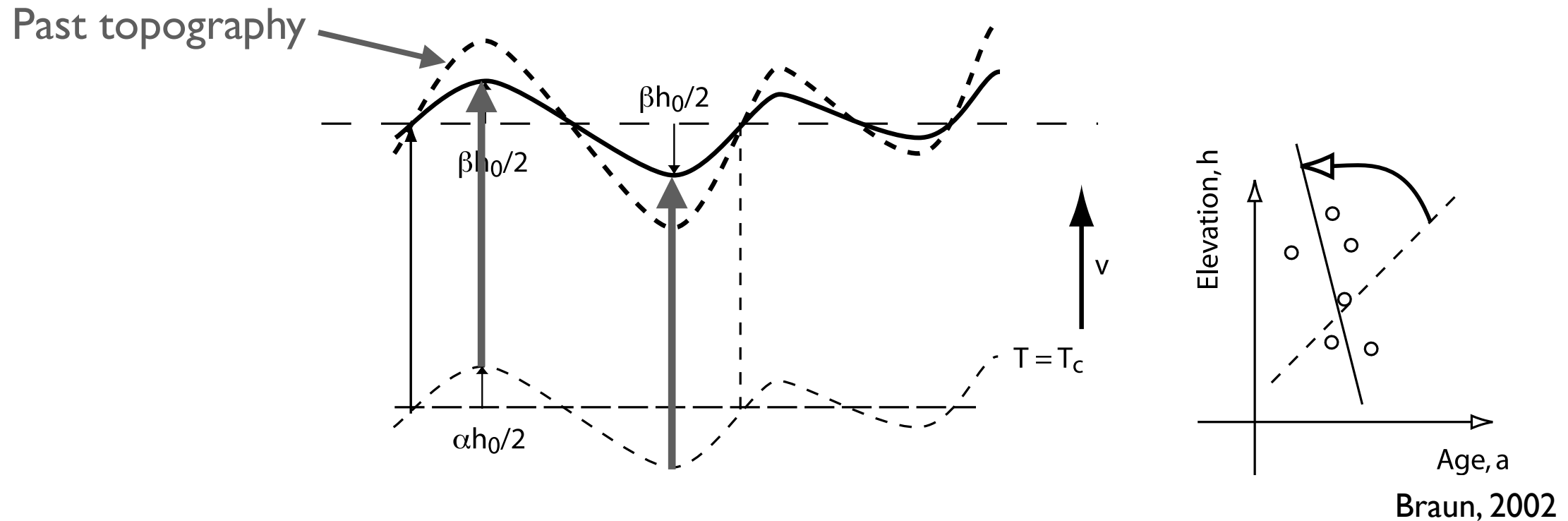
(b) Low T_c thermochronometry



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Sensitivity to changing topography

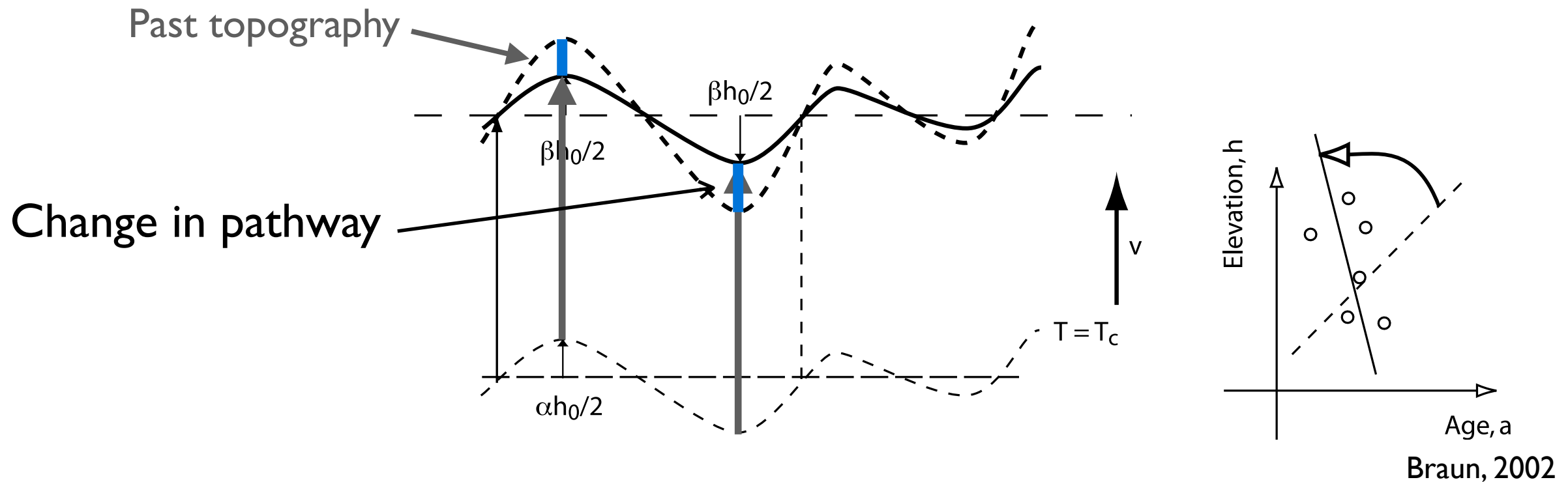
(c) Low T_c thermochronometry + Relief change



- 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

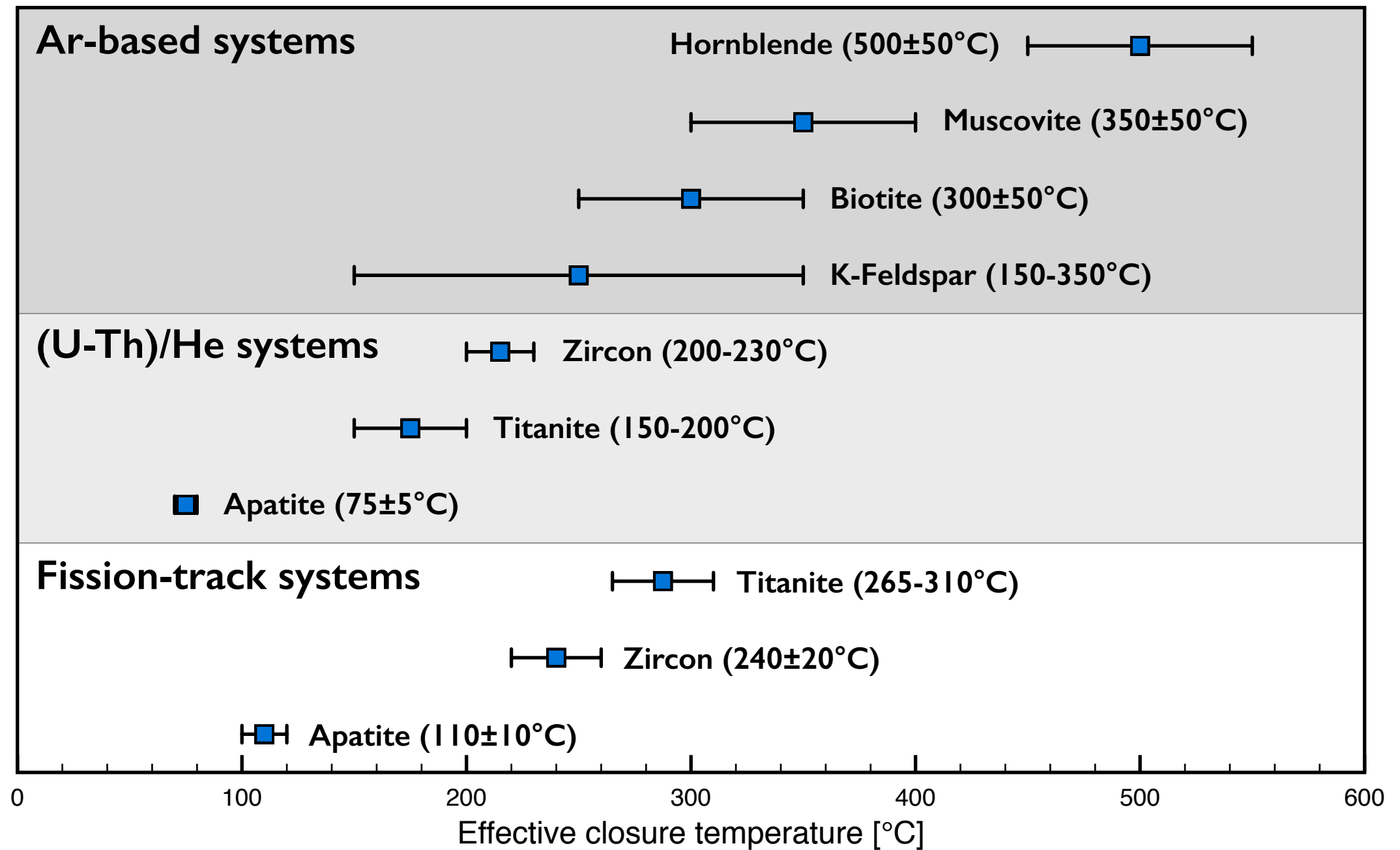
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Common thermochronometers





Helium dating - (U-Th)/He method

Production of alpha particles by decay

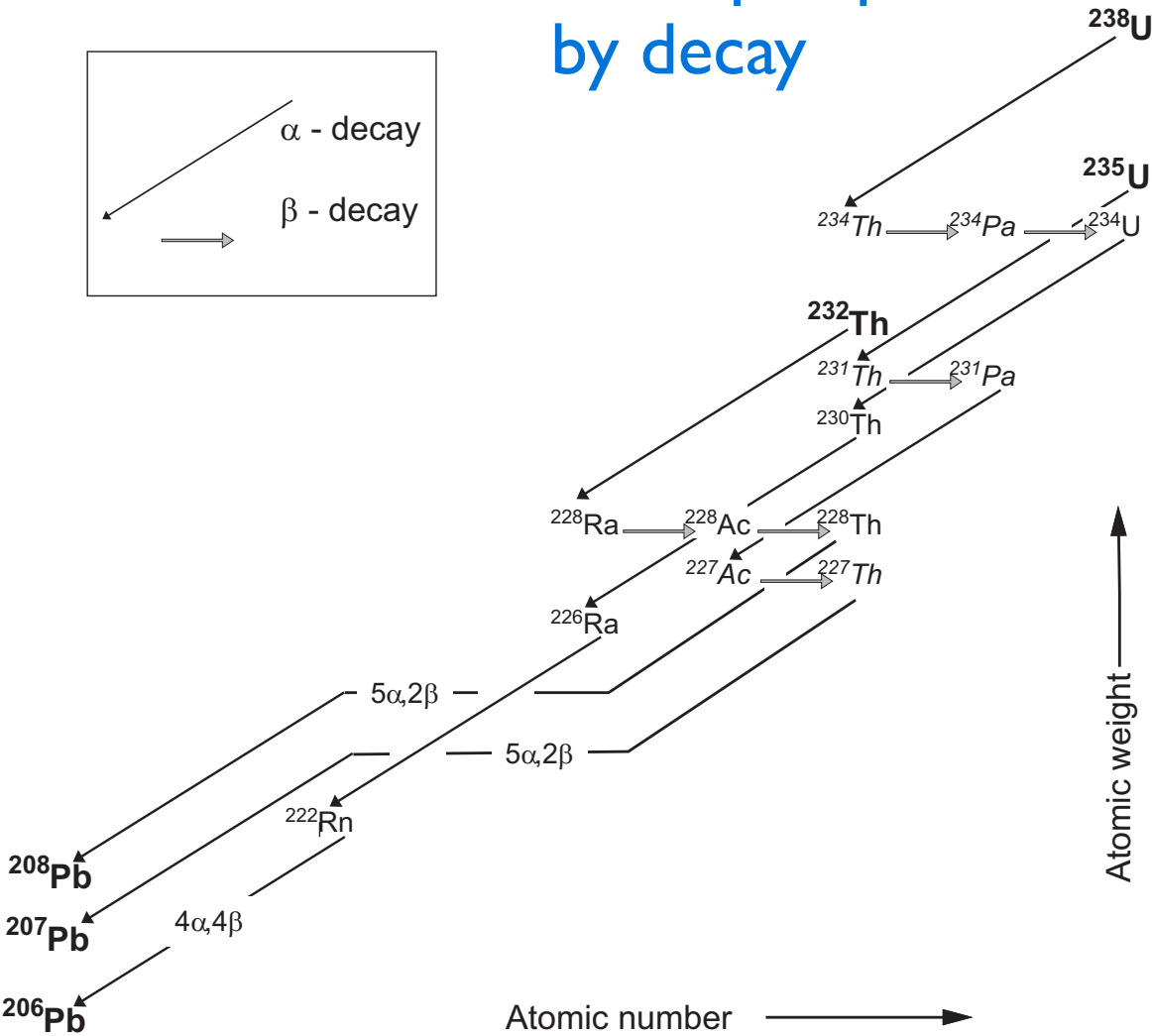
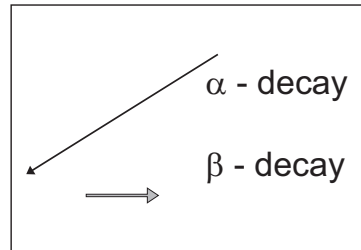


Fig. 3.3, Braun et al., 2006

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

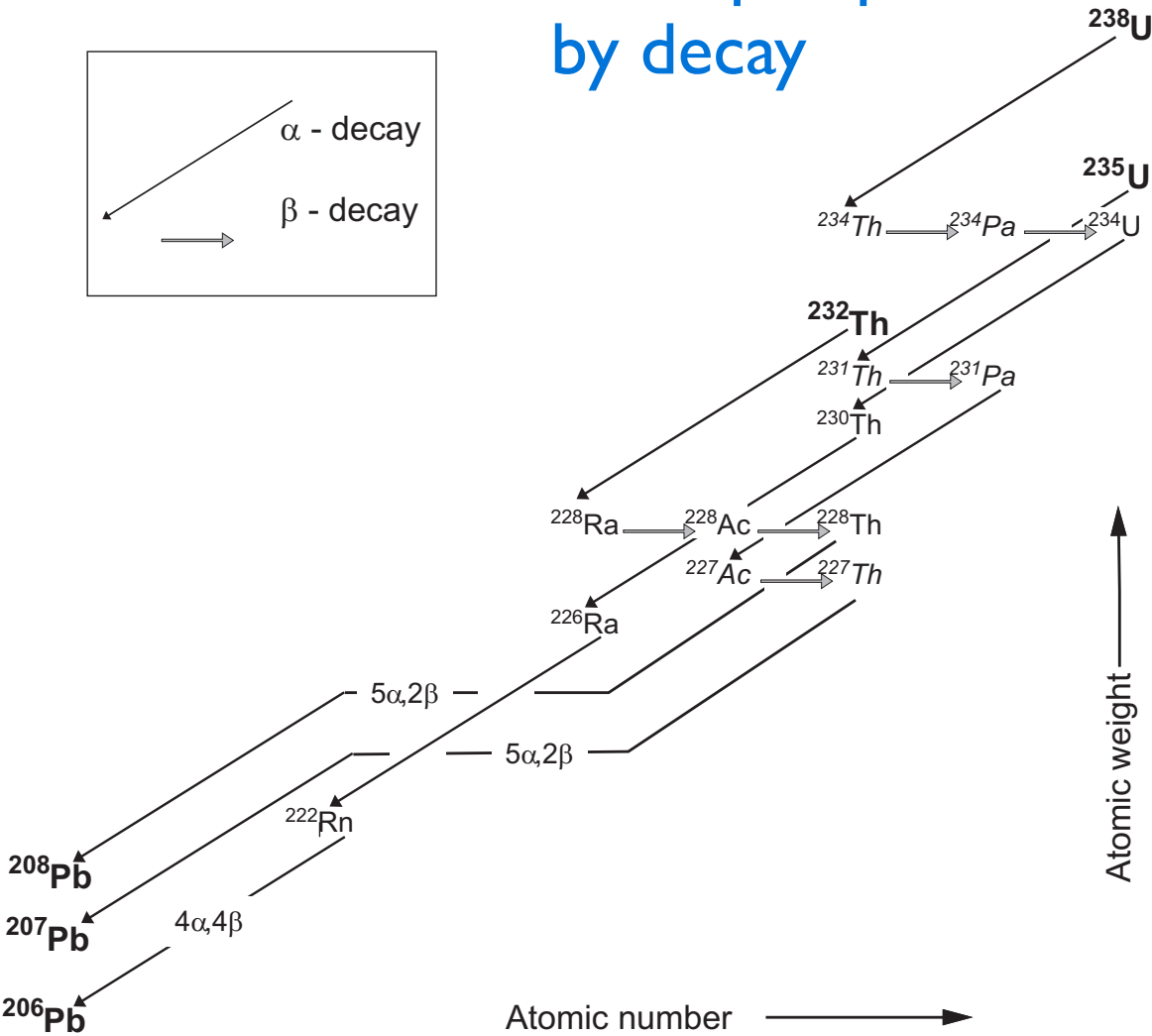
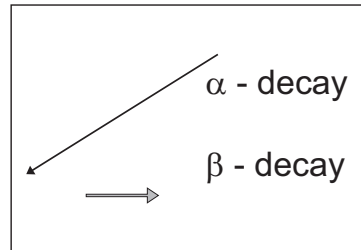


Fig. 3.3, Braun et al., 2006

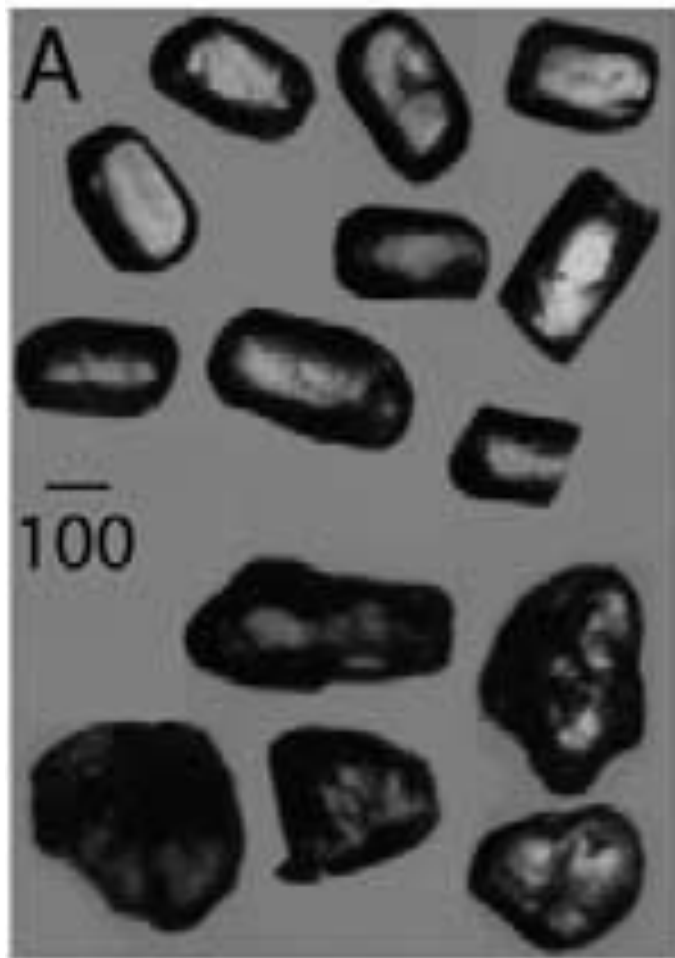
- Ignoring the contribution of ^{147}Sm , we can say that the production of ^4He is

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

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



Helium dating - (U-Th)/He method



Nice, datable apatites

Not-so-nice apatites

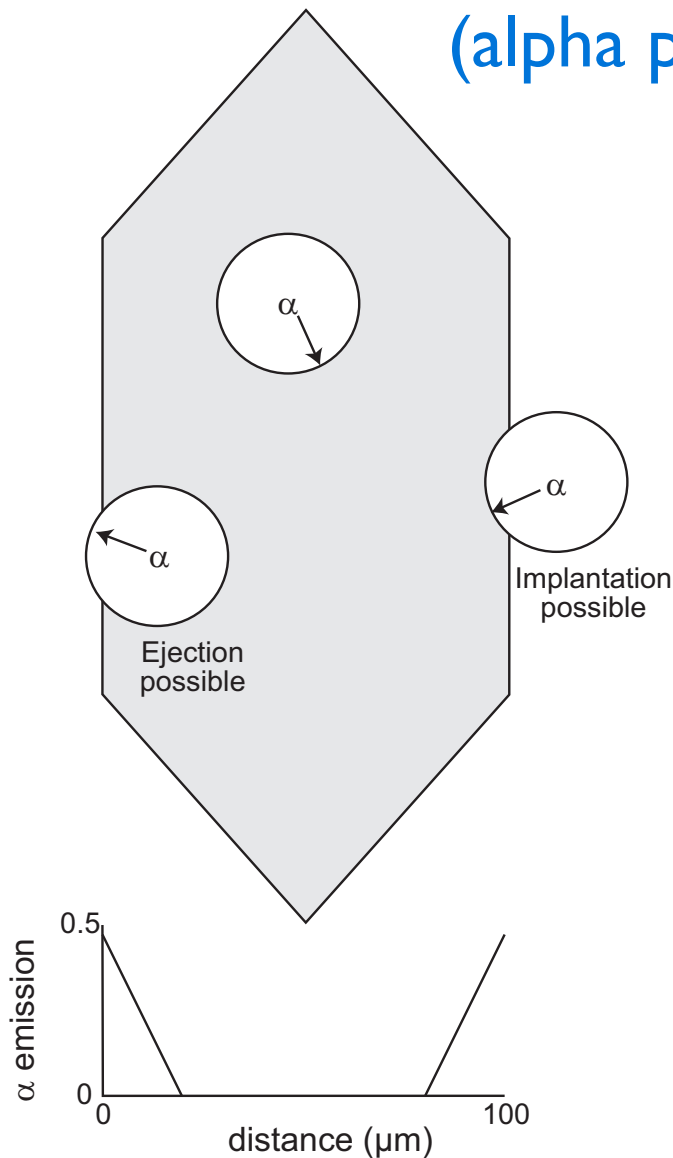
- Ages are calculated by measuring the ^4He concentration by heating and degassing the mineral sample, then separately measuring the U and Th concentrations, for example by using an inductively coupled plasma mass spectrometer (ICP-MS)

Ehlers and Farley, 2003



Helium dating - (U-Th)/He method

Potential ejection of ^4He (alpha particles)



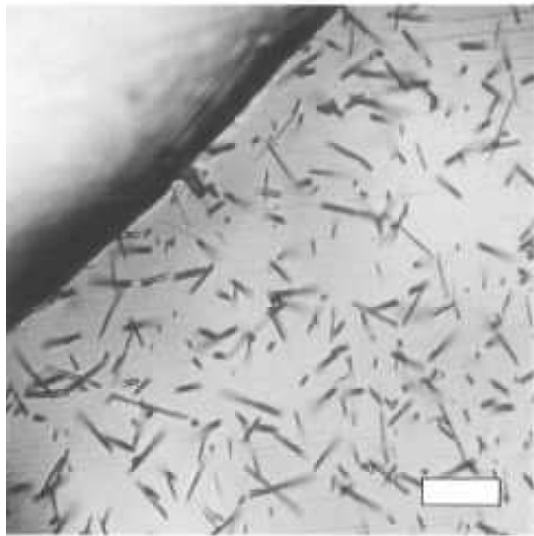
- Selected mineral grains for dating should be high-quality, euhedral minerals free of mineral inclusions with a prismatic crystal form
- Why does the crystal form matter? Alpha particles travel $\sim 20 \mu\text{m}$ when created and may be ejected from or injected to the sample crystal
- We can correct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

Fig. 3.4, Braun et al., 2006

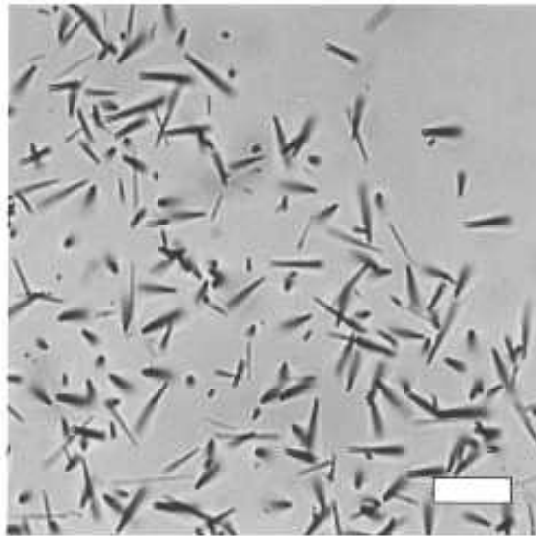
Fission-track dating - FT method

Etched fission tracks in apatite

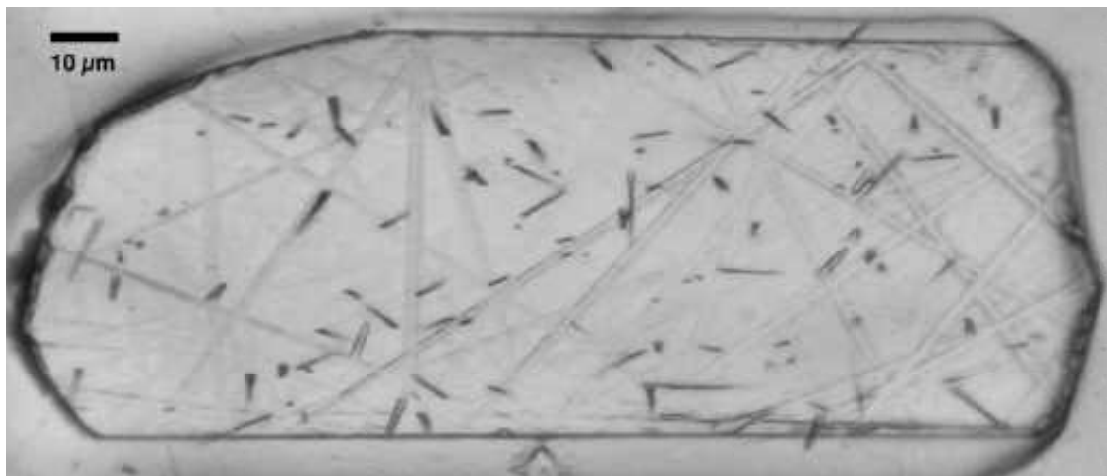
(A)



(B)

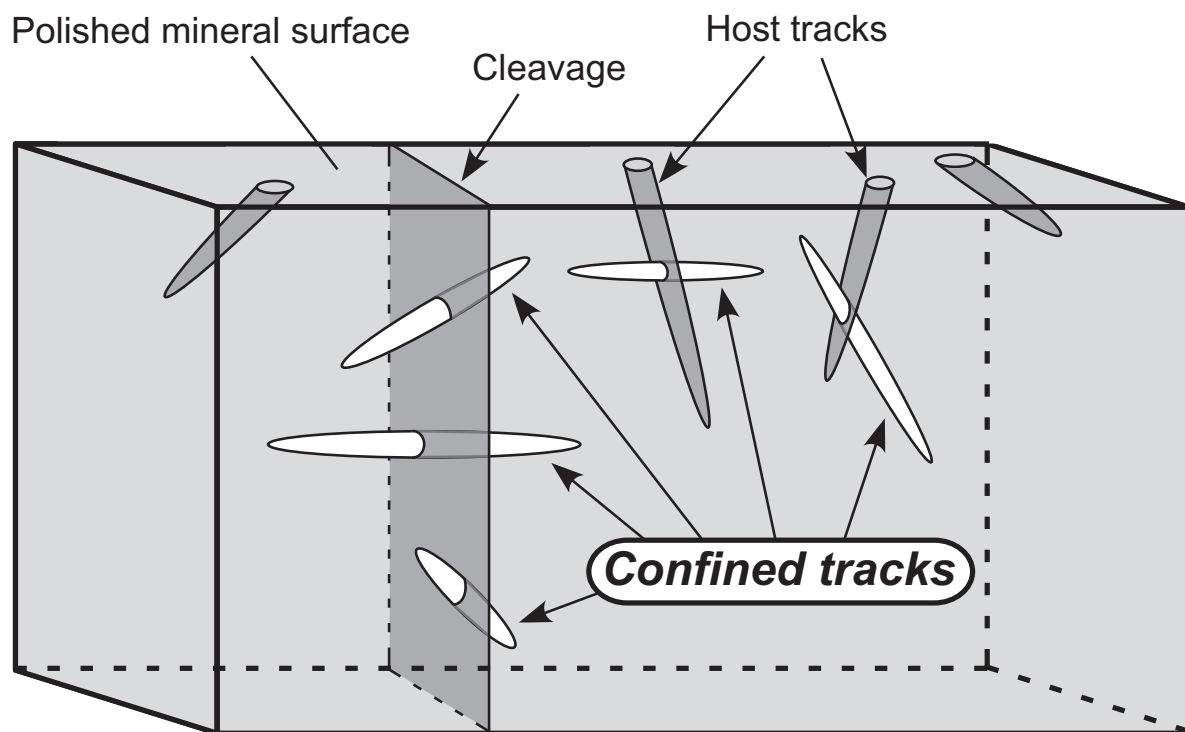


(C)



- **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 $\sim 16 \mu\text{m}$ long and $\sim 1 \mu\text{m}$ 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


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

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



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



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

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

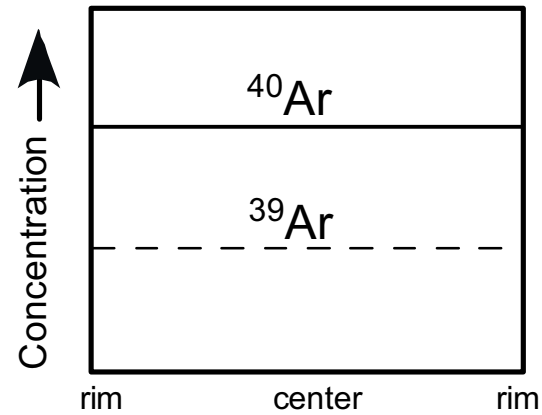
$$J = \frac{e^{\lambda t} - 1}{^{40}\text{Ar}/^{39}\text{Ar}}$$

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

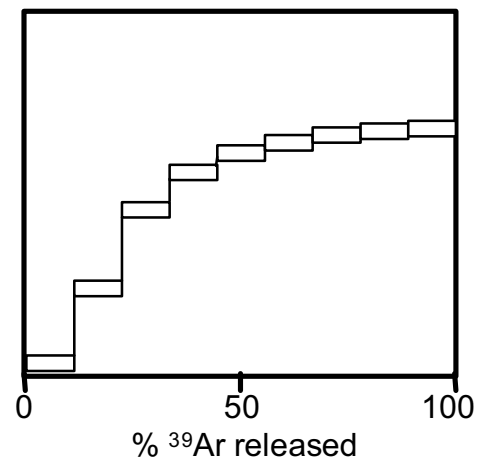
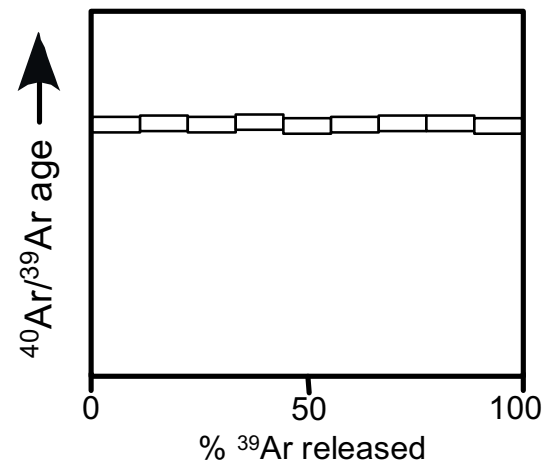
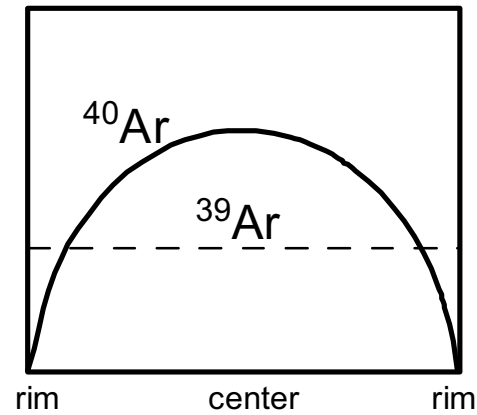


Argon dating - Step heating

Rapid cooling



Slow cooling



- **Step heating** of $^{40}\text{Ar}/^{39}\text{Ar}$ 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

Harrison and Zeitler, 2005

Argon dating - Step heating

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

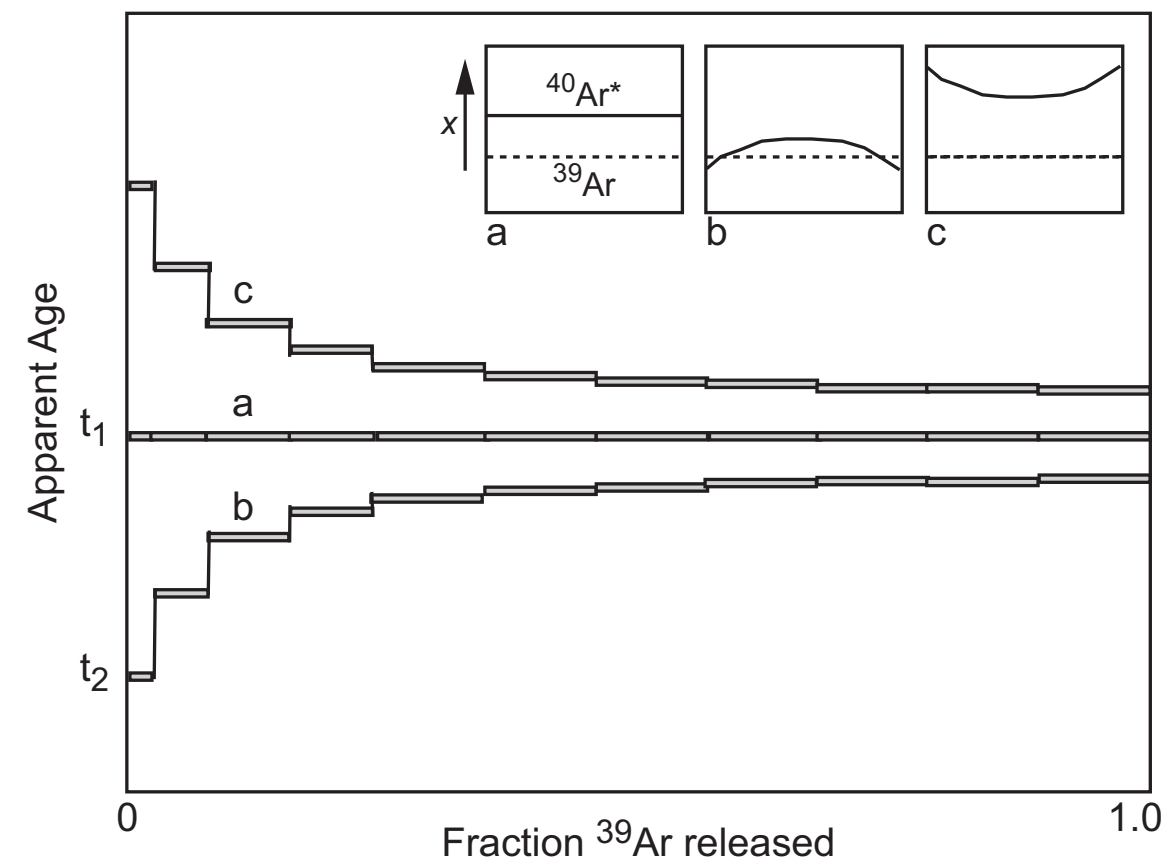
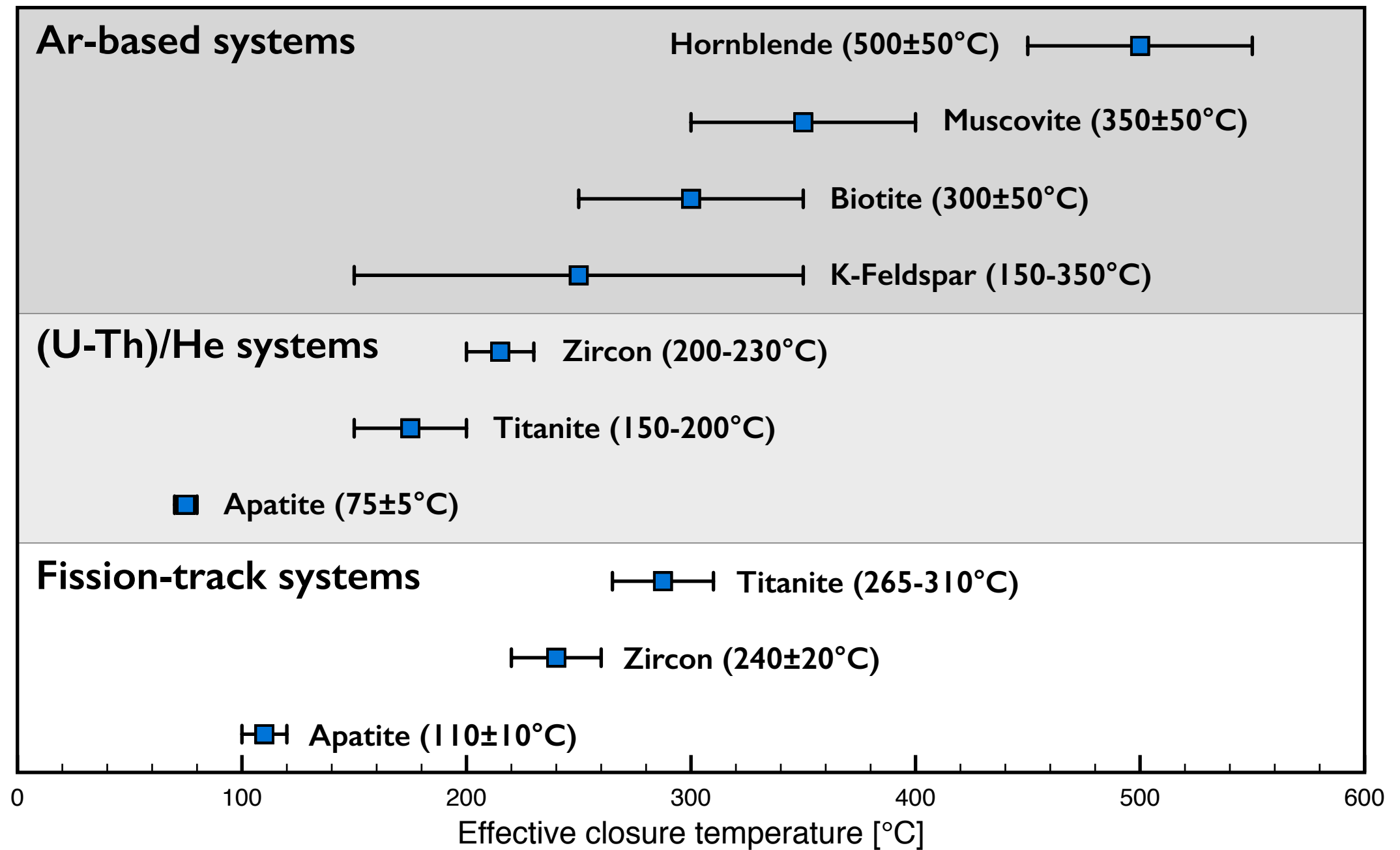


Fig. 3.1, Braun et al., 2006

- 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 $^{40}\text{Ar}/^{39}\text{Ar}$ 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 $^{40}\text{Ar}/^{39}\text{Ar}$ 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.