Low-temperature thermochronology

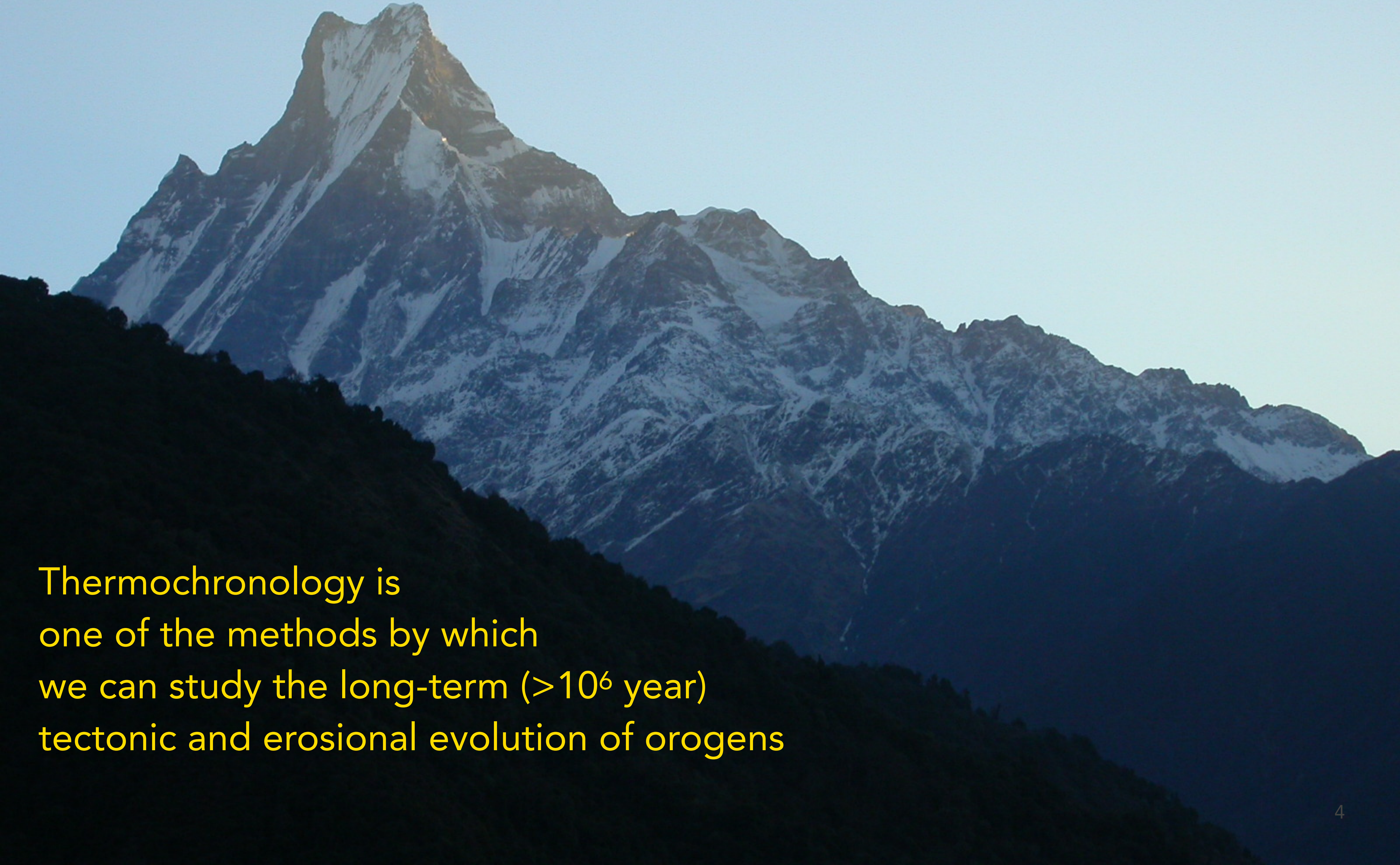
Lesson 1.1 - Basics of thermochronology

David Whipp

Goals for this lecture

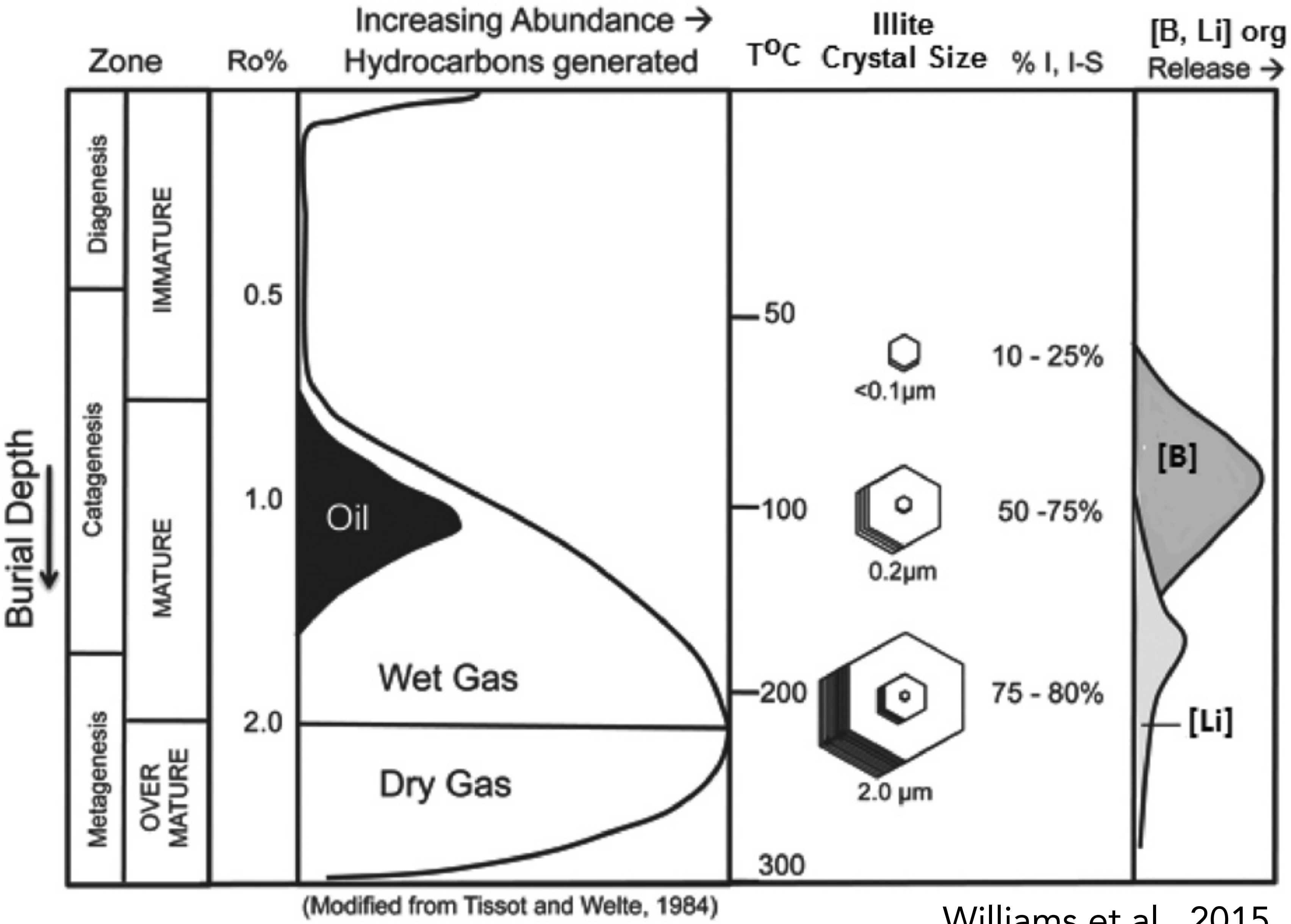
- Introduce the **concept of thermochronology** and how it differs from traditional geochronology
- Discuss the **closure temperature concept** and its relationship to thermochronology
- Highlight the benefits of **low-temperature thermochronology**

Motivation: Modern orogens



Thermochronology is
one of the methods by which
we can study the long-term ($>10^6$ year)
tectonic and erosional evolution of orogens

Motivation: Oil and gas industry

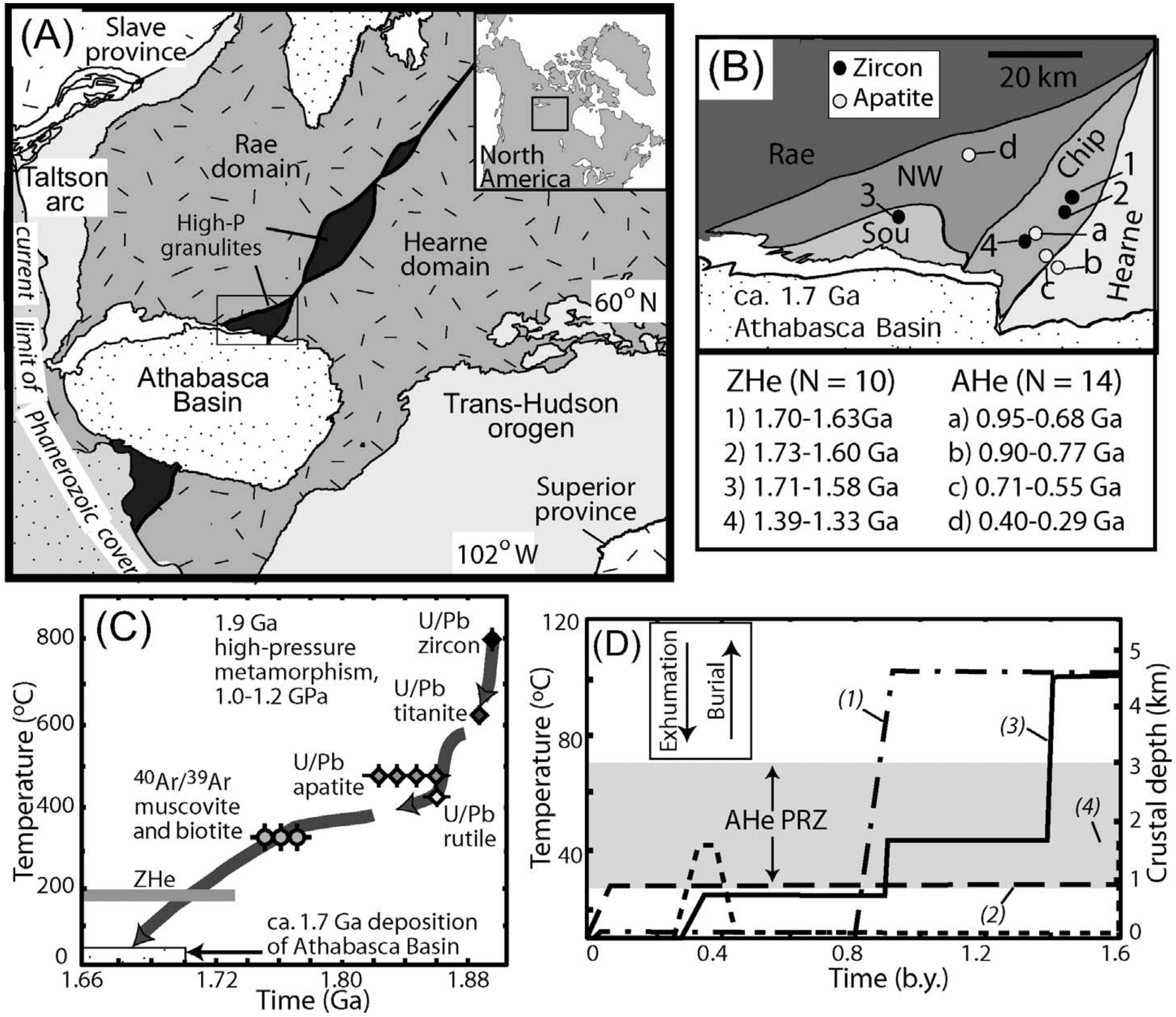


(Modified from Tissot and Welte, 1984)

Williams et al., 2015

- Several low-temperature thermochronometer systems overlap with the temperature range where hydrocarbons mature
- Chronology is a key part of determining whether maturation is coincident with timing of formation for oil and gas traps

Motivation: Ancient settings



Flowers et al., 2006

- Although technical challenges can complicate data analysis, thermochronology can also be used to study ancient settings and rates of (very) long-term exhumation
  - In this study, the average rates of exhumation of the Canadian shield are ≤2.5 μm a^{-1} (!)

Geochronology versus thermochronology

- **Geochronology** is the science of dating geological materials, and in many ways most radioisotopic chronometers are also thermochronometers
- An important distinction lies in what the ages mean and their interpretation
  - **Geochronological ages** are generally interpreted as ages of the materials (crystallization ages)
  - **Thermochronological ages** are often interpreted as the time since the material cooled below a given temperature (cooling ages)

What is a thermochronometer?

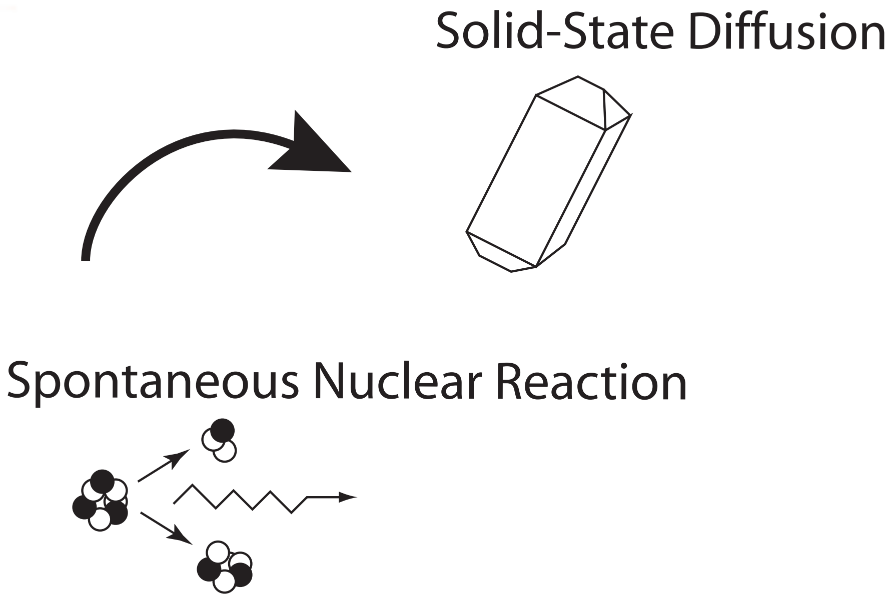
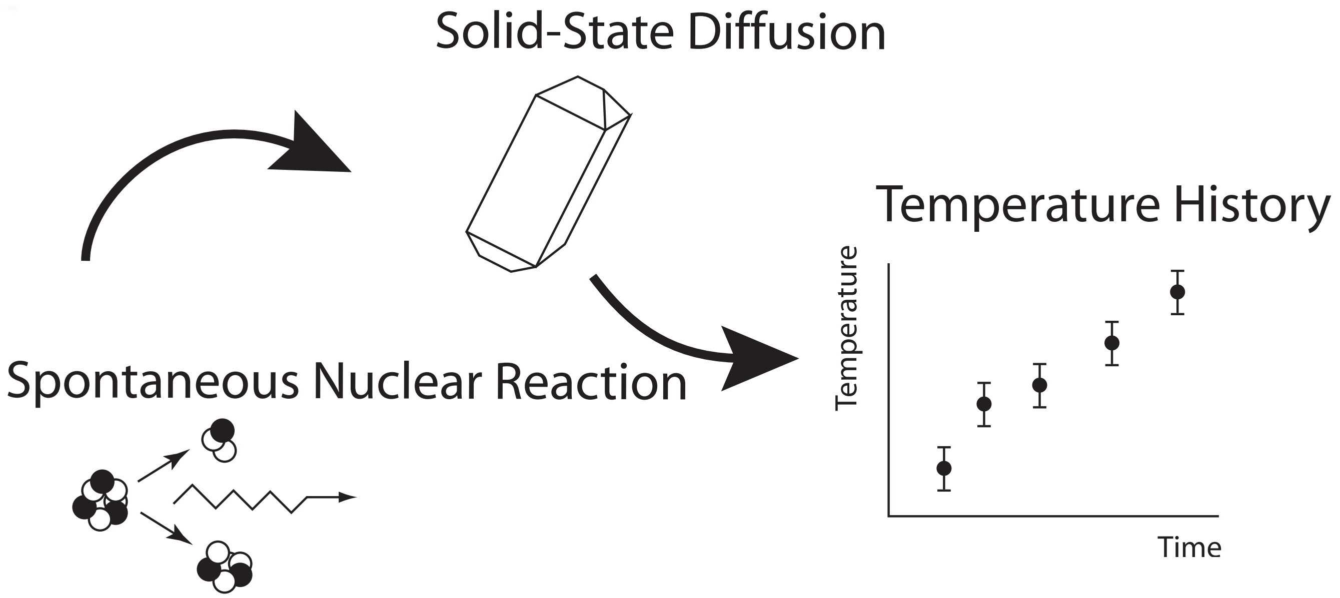


Fig 1.1, Braun et al., 2006

- **Thermochronometer**
  A radioisotopic system consisting of:
  - a radioactive parent
  - a radiogenic daughter isotope or crystallographic feature
  - the mineral in which they are found

What is a thermochronometer?



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- **Thermochronometry**
  The analysis, practice, or application of a thermochronometer to understand thermal histories of rocks or minerals

What is a thermochronometer?

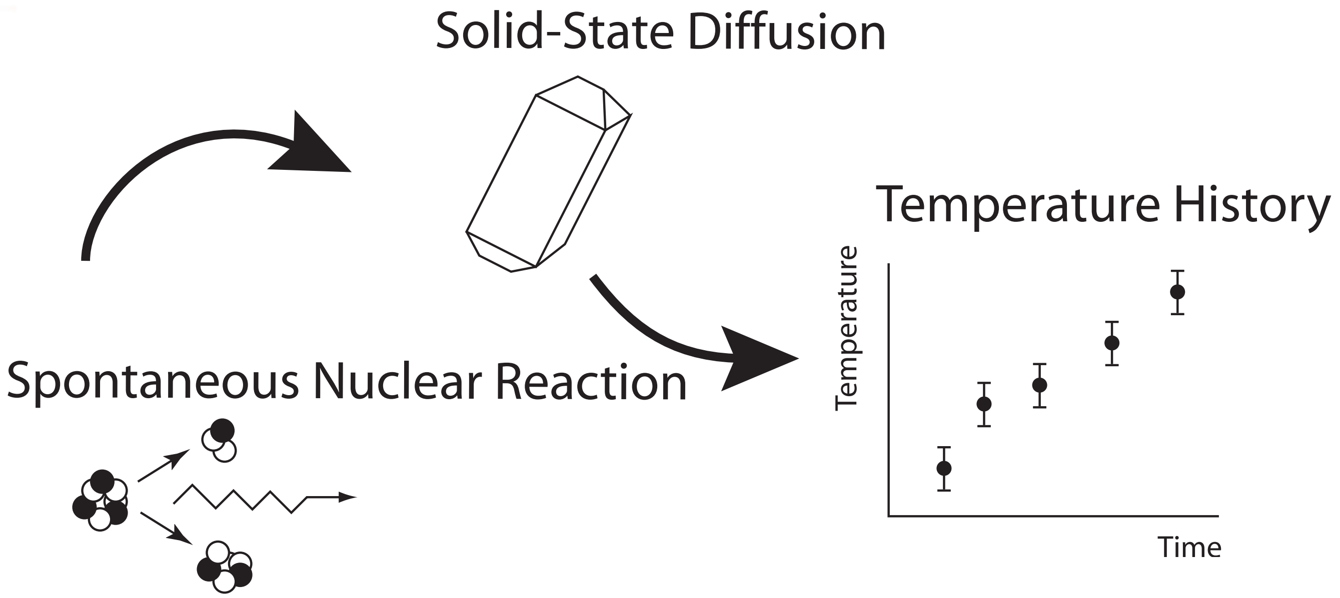
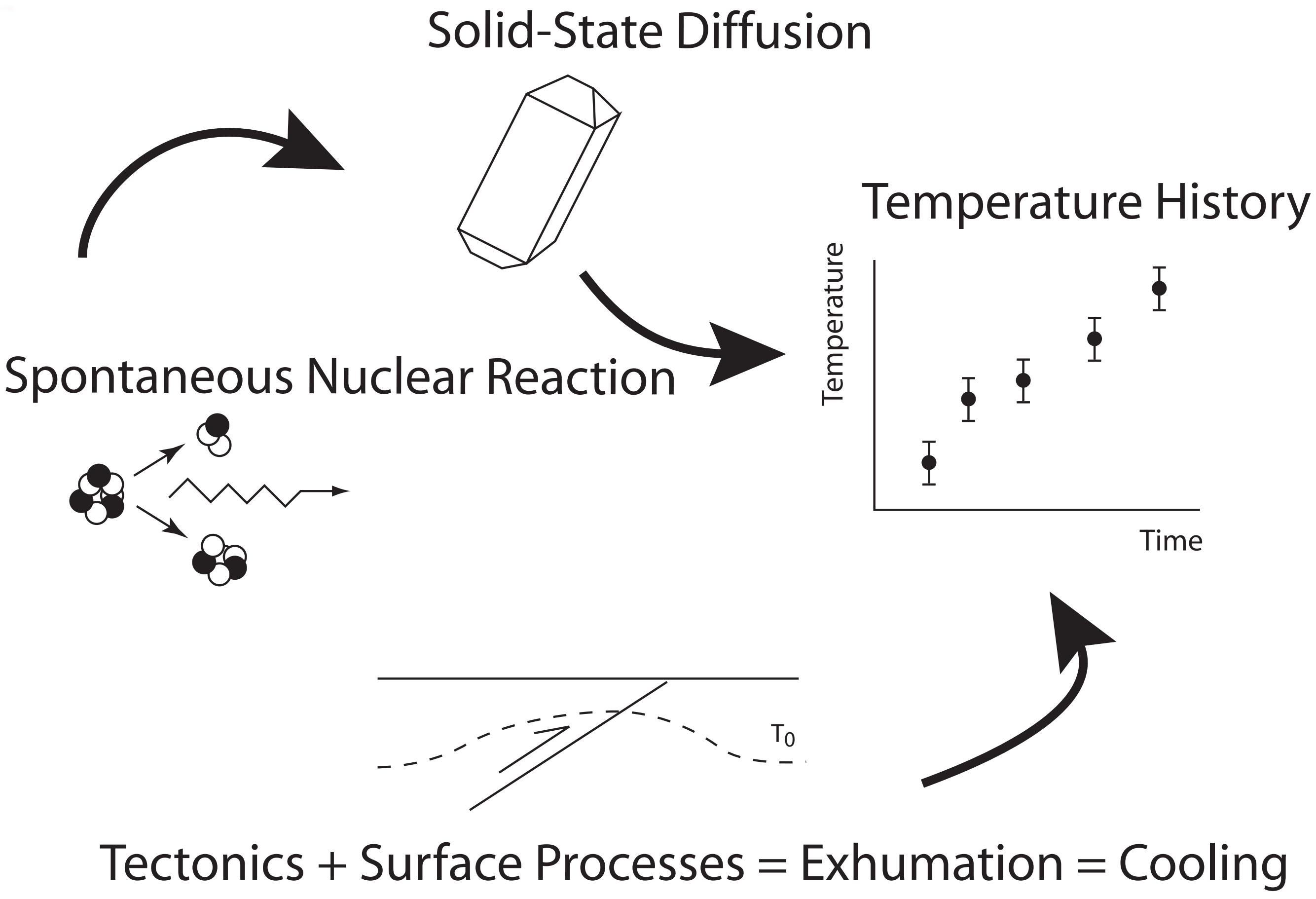


Fig 1.1, Braun et al., 2006

- **Thermochronometry**
  The analysis, practice, or application of a thermochronometer to understand thermal histories of rocks or minerals
- **Thermochronology**
  The thermal history of a rock, mineral, or geologic terrane

The aim of thermochronology



Solid-State Diffusion

Temperature History

Spontaneous Nuclear Reaction

Tectonics + Surface Processes = Exhumation = Cooling

Fig 1.1, Braun et al., 2006

- In most modern applications of thermochronology, the goal is to use the recorded thermal history to provide insight into past tectonic or erosional (surface) processes
- To do this, it is essential to link the temperature to which a thermochronometer is sensitive to a depth in the Earth
  - This is not easy, and the field of quantitative thermochronology is growing rapidly as a result

The essence of thermochronology

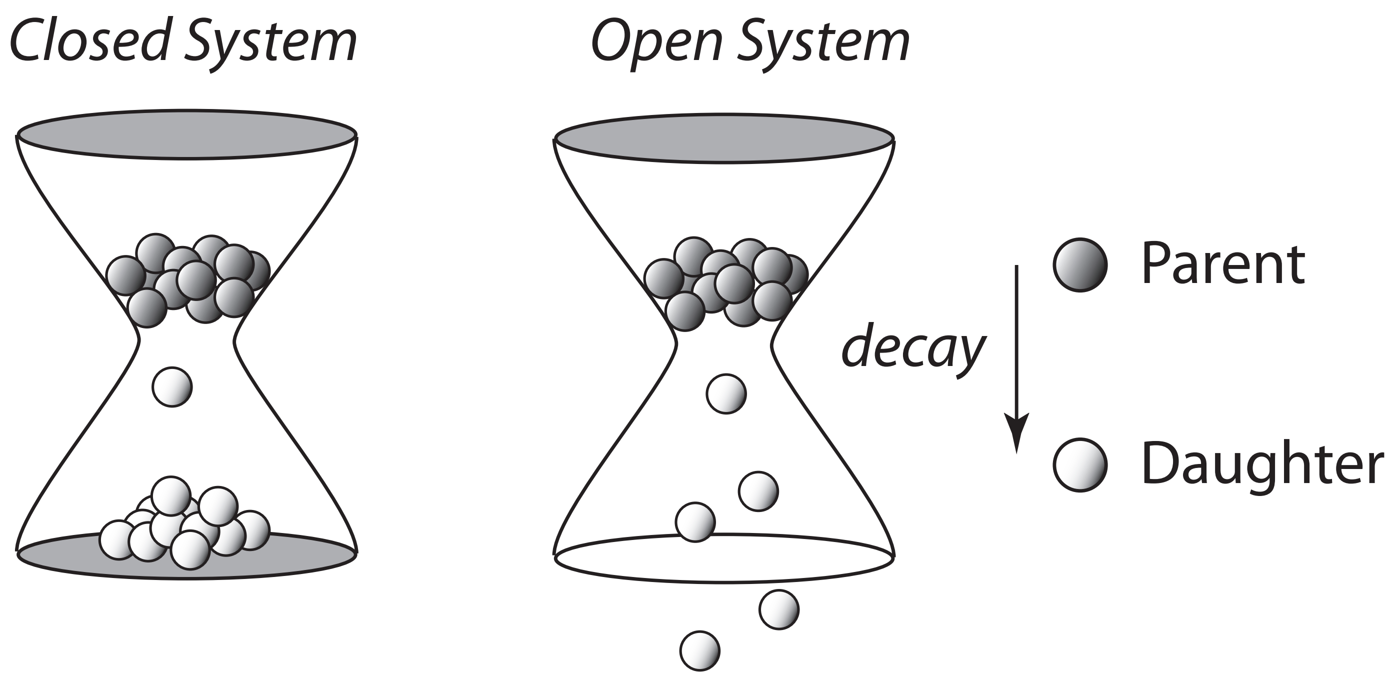
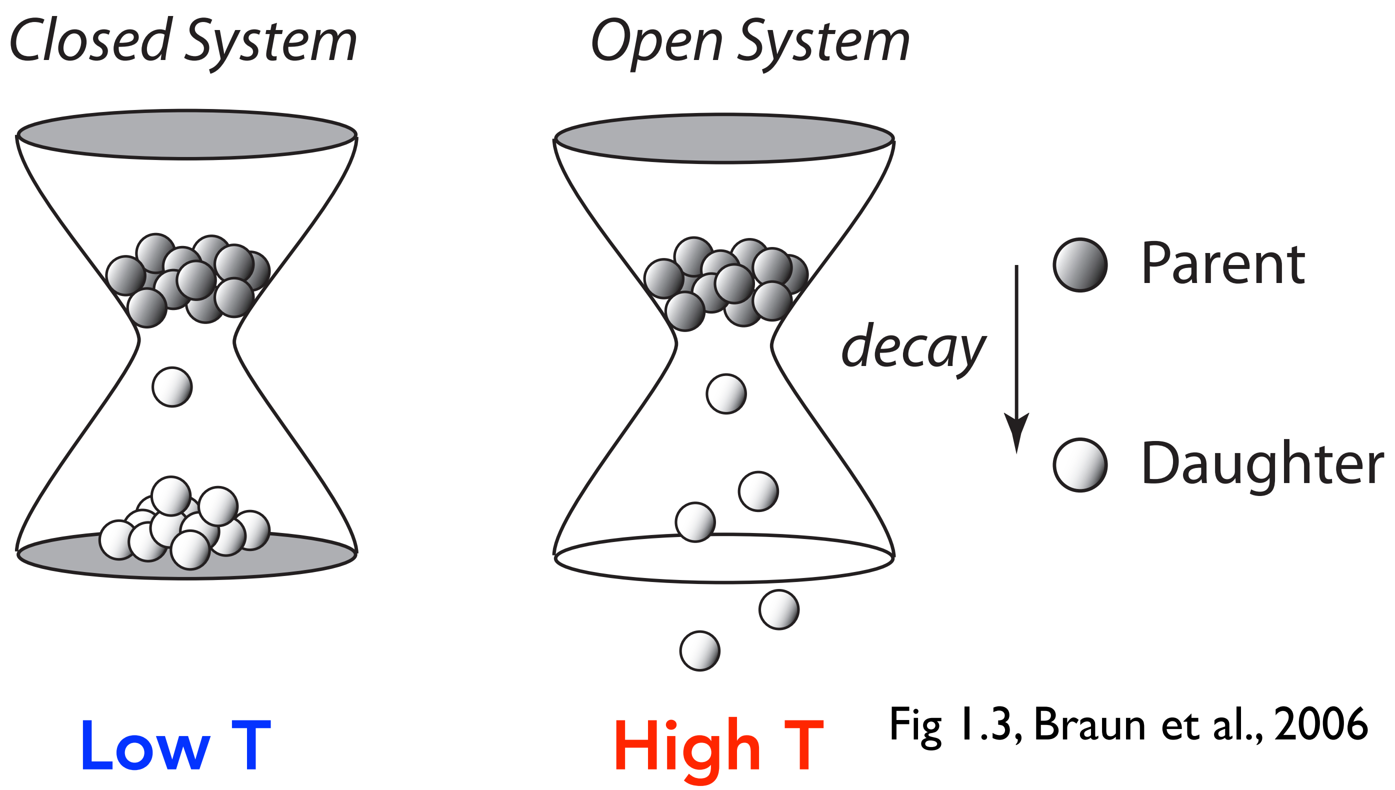


Fig 1.3, Braun et al., 2006

- **Daughter products** are <u>continually produced</u> within a mineral as a result of radioactive decay
- Daughter products <u>may be lost due to thermally activated diffusion</u>
  - The temperature below which the daughter product is retained depends on the daughter product and host mineral

The essence of thermochronology



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The concept of a closure temperature

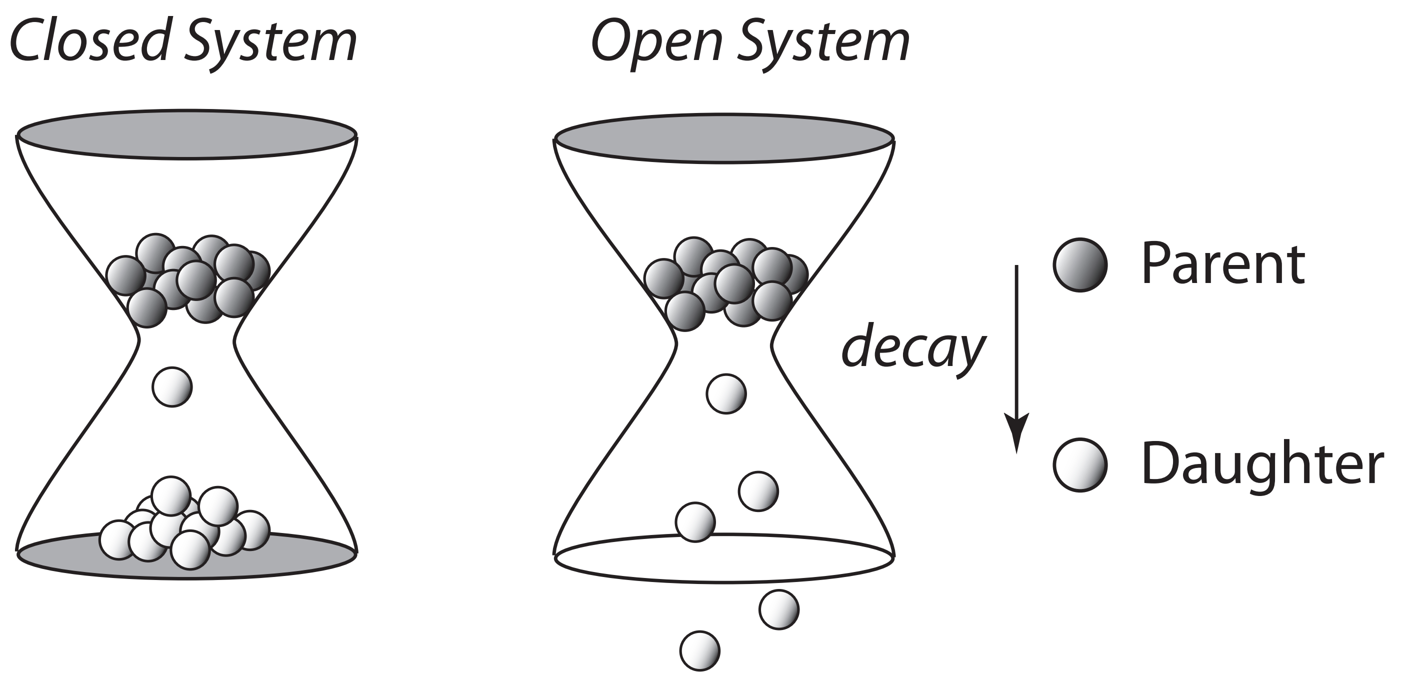


Fig 1.3, Braun et al., 2006

- The transition from an open to a closed system does not occur instantaneously at a given temperature, but rather over a temperature range known as the **partial retention** (or **partial annealing**) **zone**

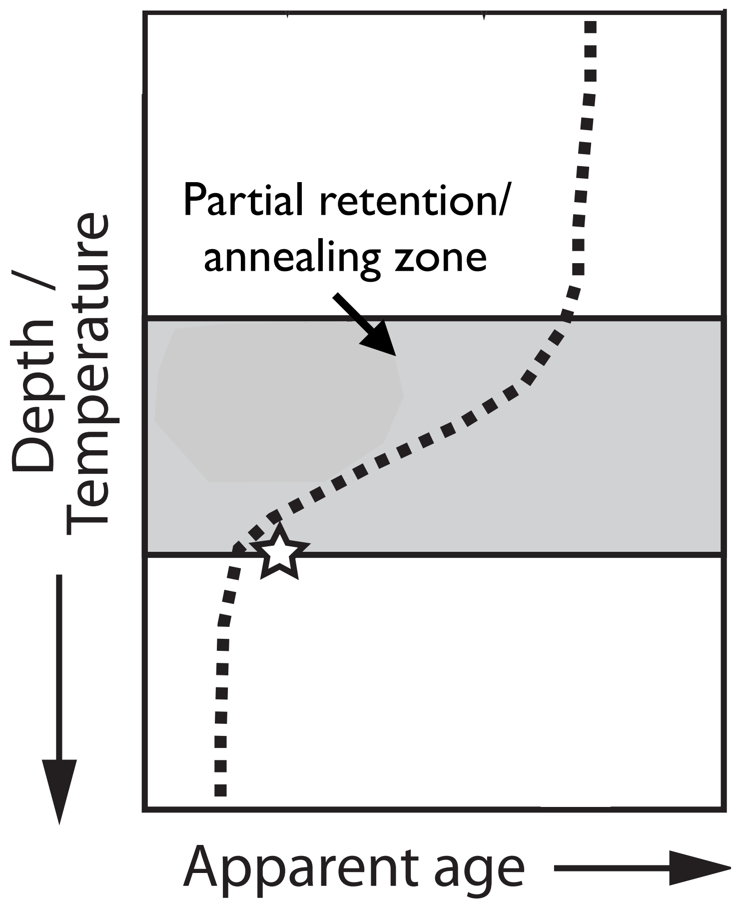
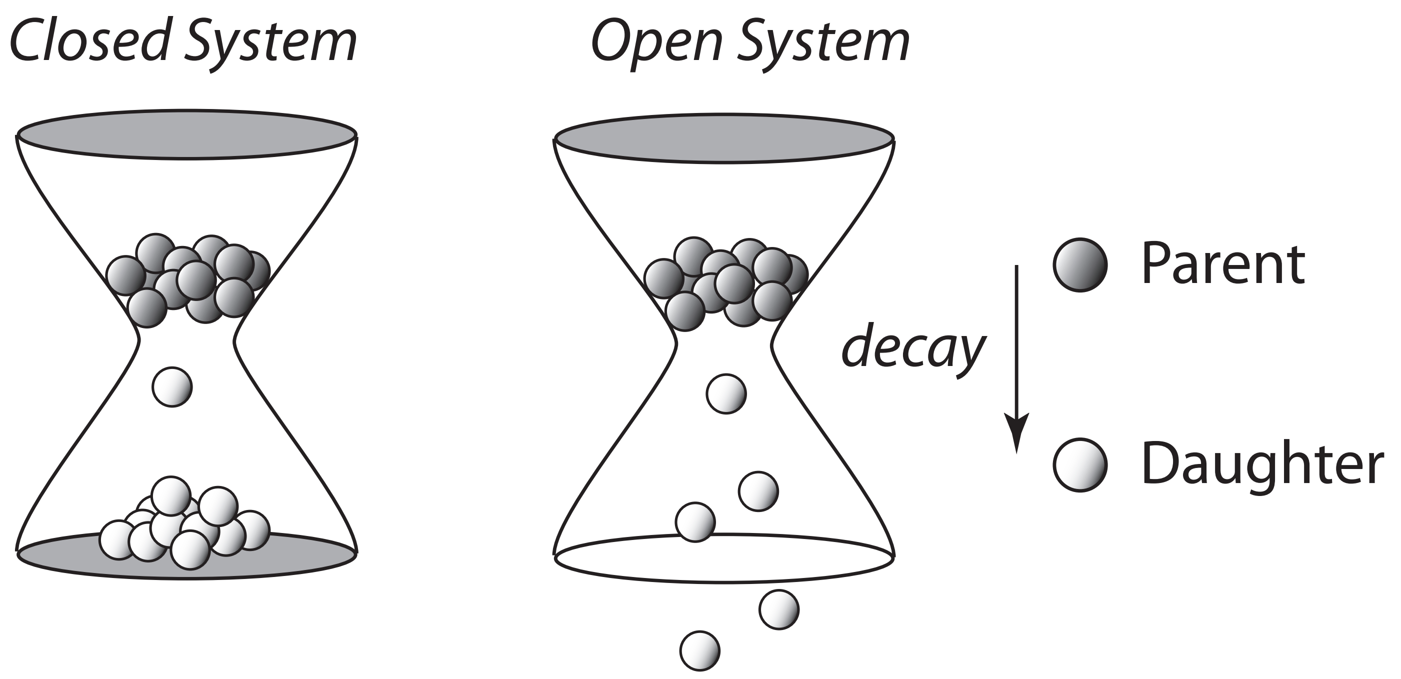


Fig 1.6a, Braun et al., 2006

The concept of a closure temperature



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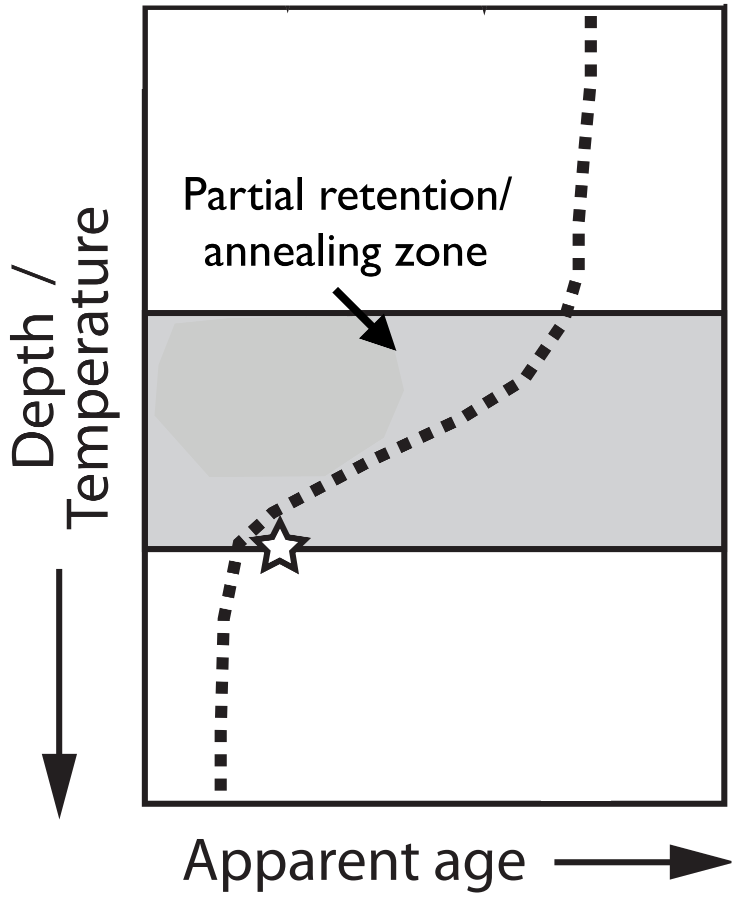
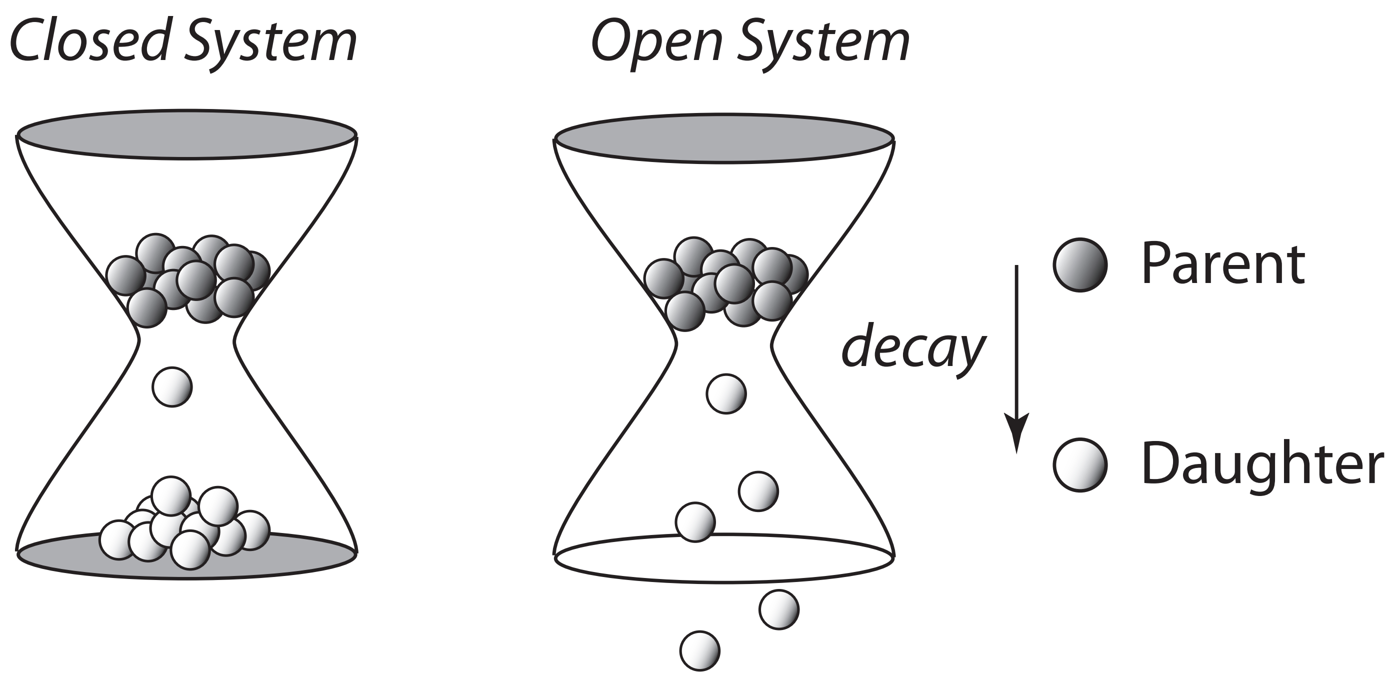


Fig 1.6a, Braun et al., 2006

- The transition from an open to a closed system does not occur instantaneously at a given temperature, but rather over a temperature range known as the **partial retention** (or **partial annealing**) **zone**

- The **partial retention zone** temperature range spans from the point at which nearly all produced daughter products are lost to diffusion to where they are nearly all retained

The concept of a closure temperature



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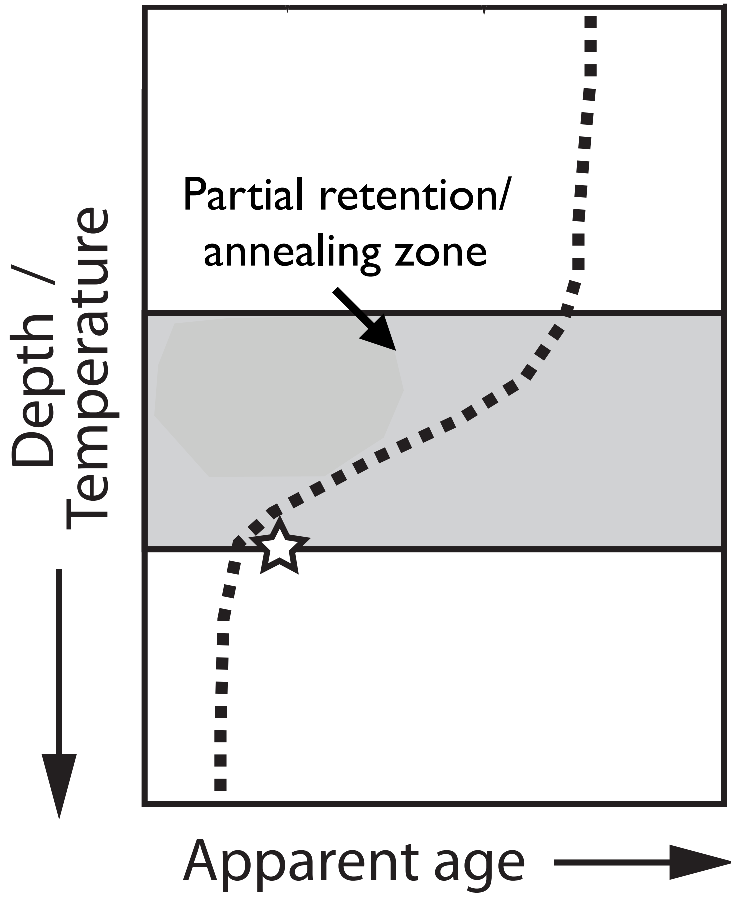


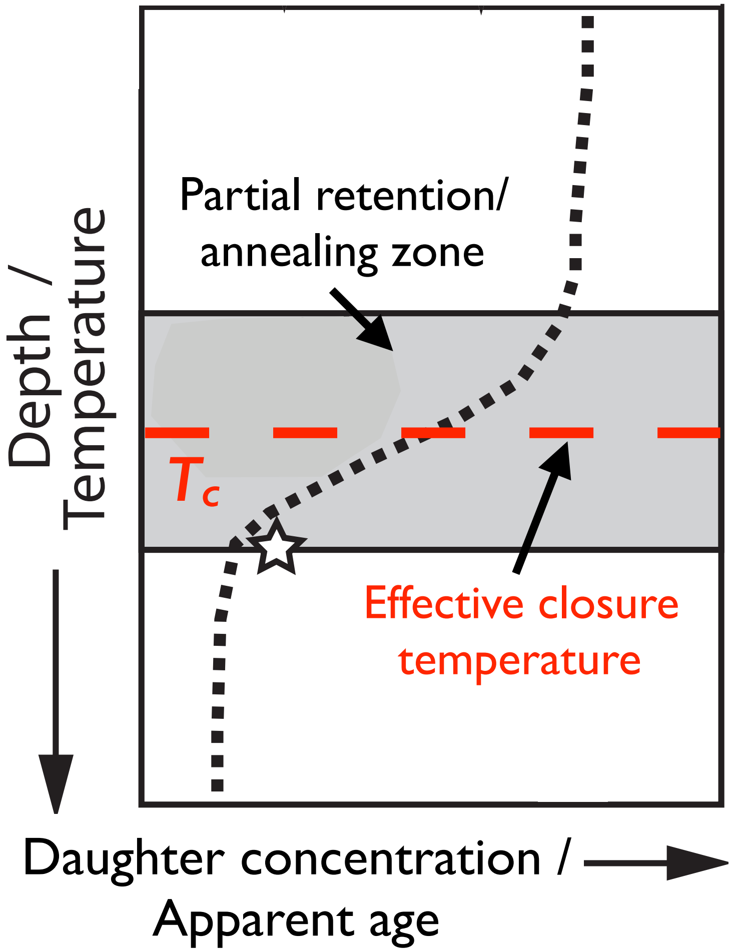
Fig 1.6a, Braun et al., 2006

- **Why do you think there is a partial retention/annealing zone?**

Effective closure temperature

- Defined by Dodson (1973), the **closure temperature** (T_c) is the "temperature of a thermochronological system at the time corresponding to its apparent age"

- This concept is quite useful, as we can thus relate a measured age to a temperature in the Earth



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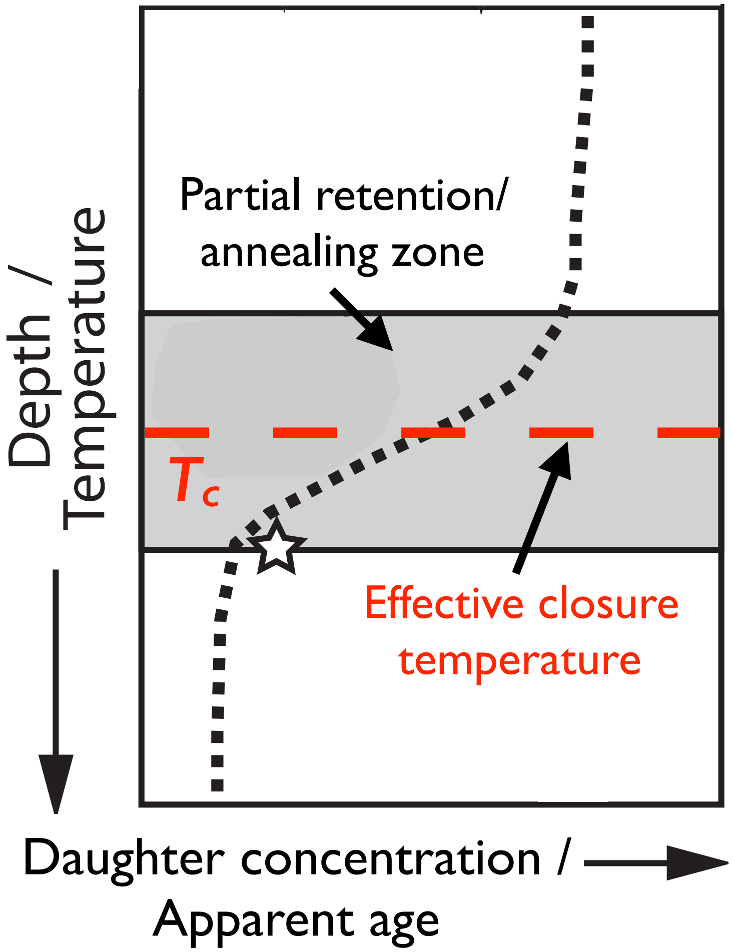
- Unfortunately, closure temperatures vary as a function of the thermochronological system, mineral size, chemical composition and cooling rate
  - This definition also only works when cooling is monotonic (no reheating)



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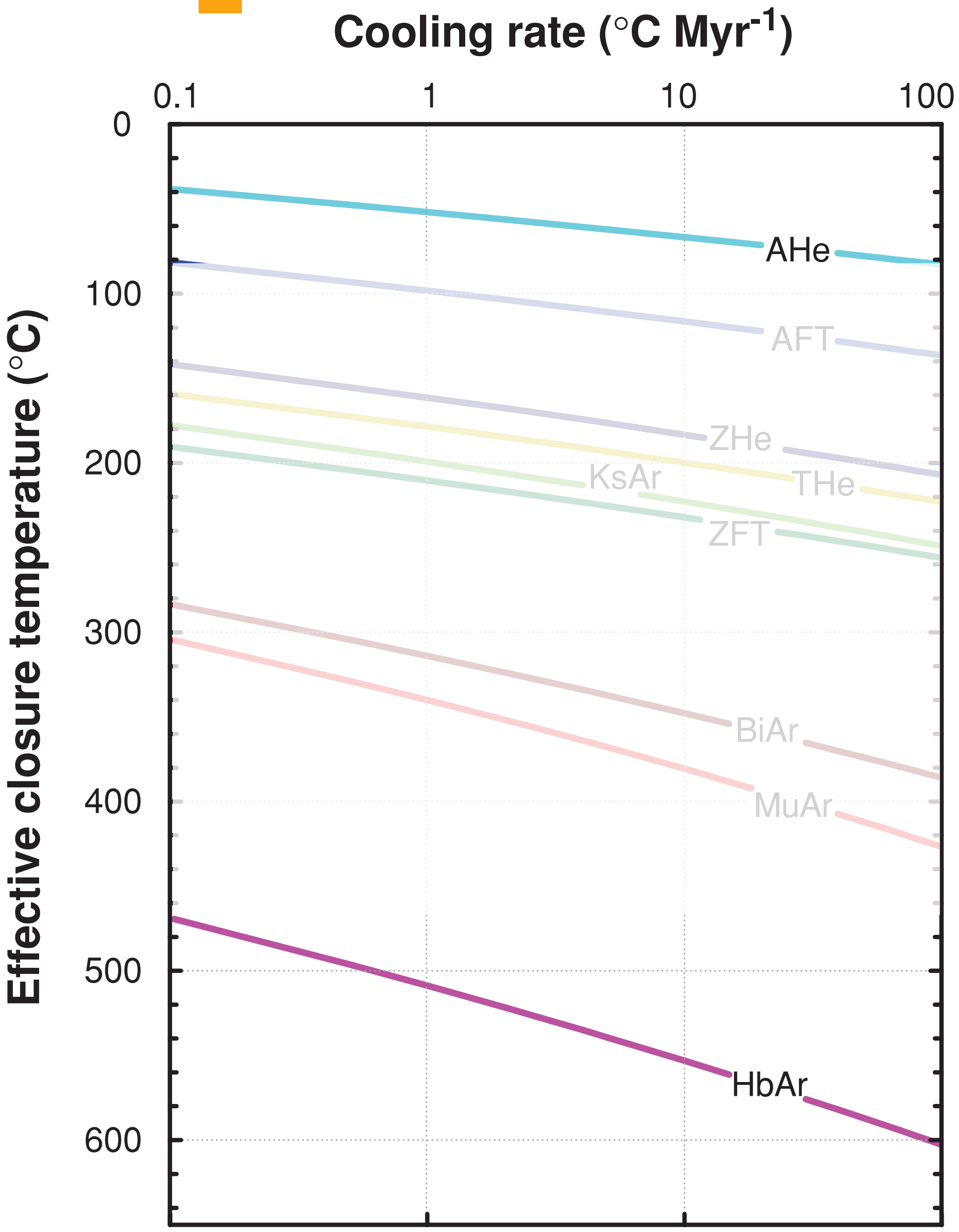
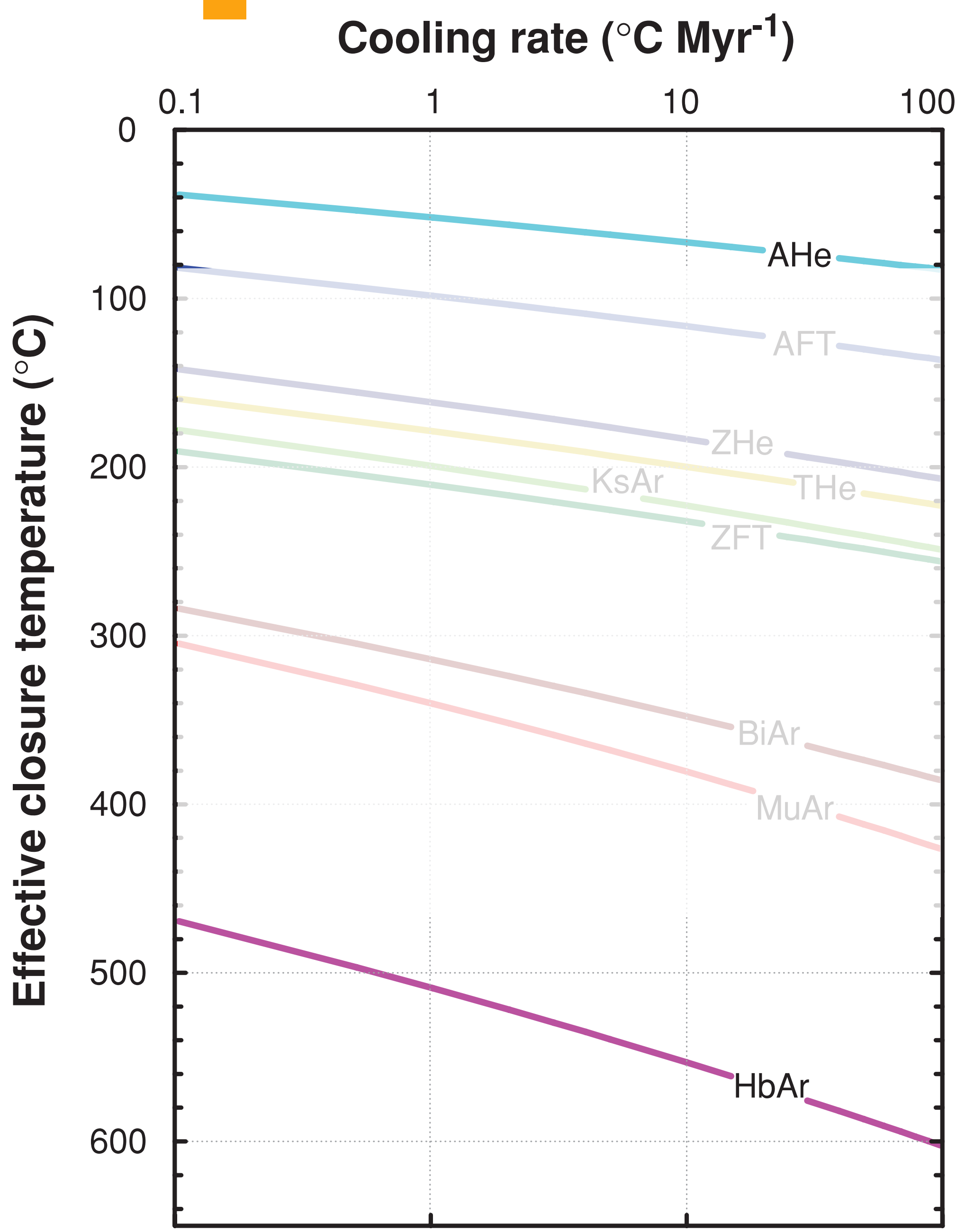
The effect of cooling rate



Reiners and Brandon, 2006

- In general, the effective closure temperature for a given thermochronometer system will increase with increasing cooling rate
    - For the retention of ^{4}He in apatite, the effective closure temperature is ~40°C at a cooling rate of 0.1 °C Ma^{-1} and ~80°C at a rate of 100°C Ma^{-1}
- 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

The effect of cooling rate



Reiners and Brandon, 2006

- Considering that the daughter product diffuses out of mineral crystals above the effective closure temperature, **why would the closure temperature increase for faster cooling rates?**

Estimating thermochronometer ages

- Let's ignore the cooling rate effect for the moment. The apatite (U-Th)/He thermochronometer has an effective closure temperature of 75±5°C (previous slide)
- Using the mean value, calculate the cooling age for rocks with the following thermal histories (each is 100 Ma long)

1. Rapid cooling from 500 to 15°C, 40 Ma ago
2. Monotonic cooling from 135 to 15°C over 100 Ma
3. Rapid cooling from 60 to 15°C 20 Ma ago
4. Slow cooling from 100 to 60°C over 25 Ma, isothermal conditions at 60°C for 50 Ma, then slow cooling to 15°C over the last 25 Ma
5. Slow monotonic heating from 15 to 65°C during the first 95 Ma, followed by rapid cooling to 15°C over the last 5 Ma

Solutions?

Scenario	Estimated age [Ma]
1	40.0
2	50.0
3	—
4	
5	—

- Clearly, the observed age will have some dependence on the cooling history
- It is also clear that estimating the effective closure temperature is a critical step in the interpretation of any real dataset

Solutions?

Scenario	Estimated age [Ma]	F.D. estimate [Ma]
1	40.0	39.5
2	50.0	39.3
3	—	42.1
4	~85.0	40.5
5	—	39.9

- Clearly, the observed age will have some dependence on the cooling history
- It is also clear that estimating the effective closure temperature is a critical step in the interpretation of any real dataset

What causes cooling?

- With the idea of an effective closure temperature, we now have the main concept of thermochronology - a date will ideally reflect the time since the rock sample was at T_c
- But, what causes cooling?

Erosion, exhumation, and uplift, oh my!

- For rock samples collected at the Earth’s surface, cooling is almost always the result of **exhumation**
    - Exhumation is often used interchangeably with other “erosion-like” terms…we need a few definitions[1]

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- **Exhumation**: The unroofing history of a rock, as caused by tectonic and/or surficial processes
- **Erosion**: The surficial removal of mass at a spatial point in the landscape by both mechanical and chemical processes
- **Denudation**: The removal of rock by tectonic and/or surficial processes at a specified point at or under the Earth's surface

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Erosion, exhumation, and uplift, oh my!

- Another inconsistently used term, which is important for many thermochronological applications, is **uplift**[1]
    - We can distinguish between several different types of uplift depending on what moves and our reference frame

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- **Rock uplift**: Vertical motion of rock relative to sea level
- **Surface uplift**: Vertical movement of the Earth's surface relative to sea level

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- **Rock uplift**: Vertical motion of rock relative to sea level
- **Surface uplift**: Vertical movement of the Earth's surface relative to sea level
  - Exhumation results from differences in the rates of rock and surface uplift at a given point

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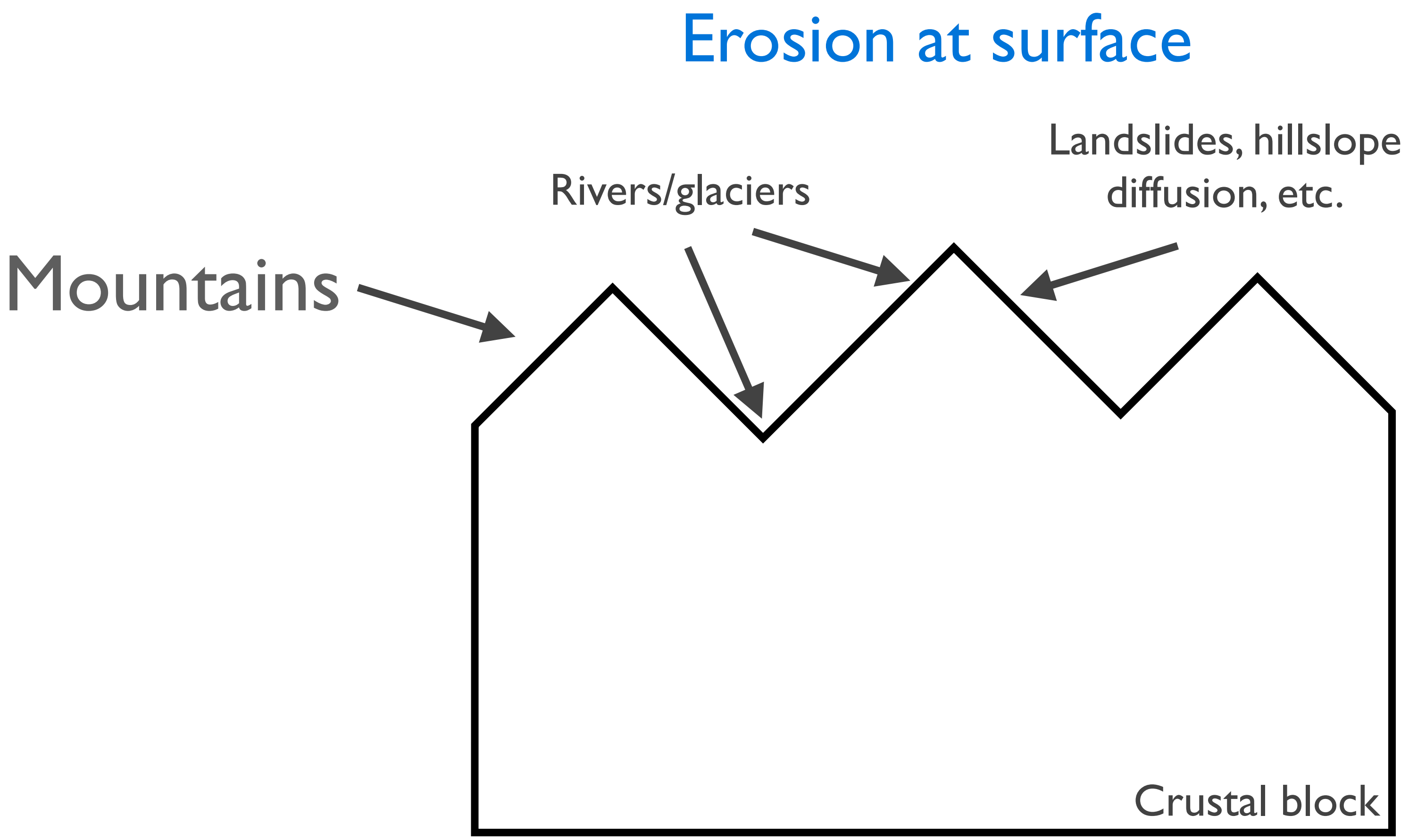
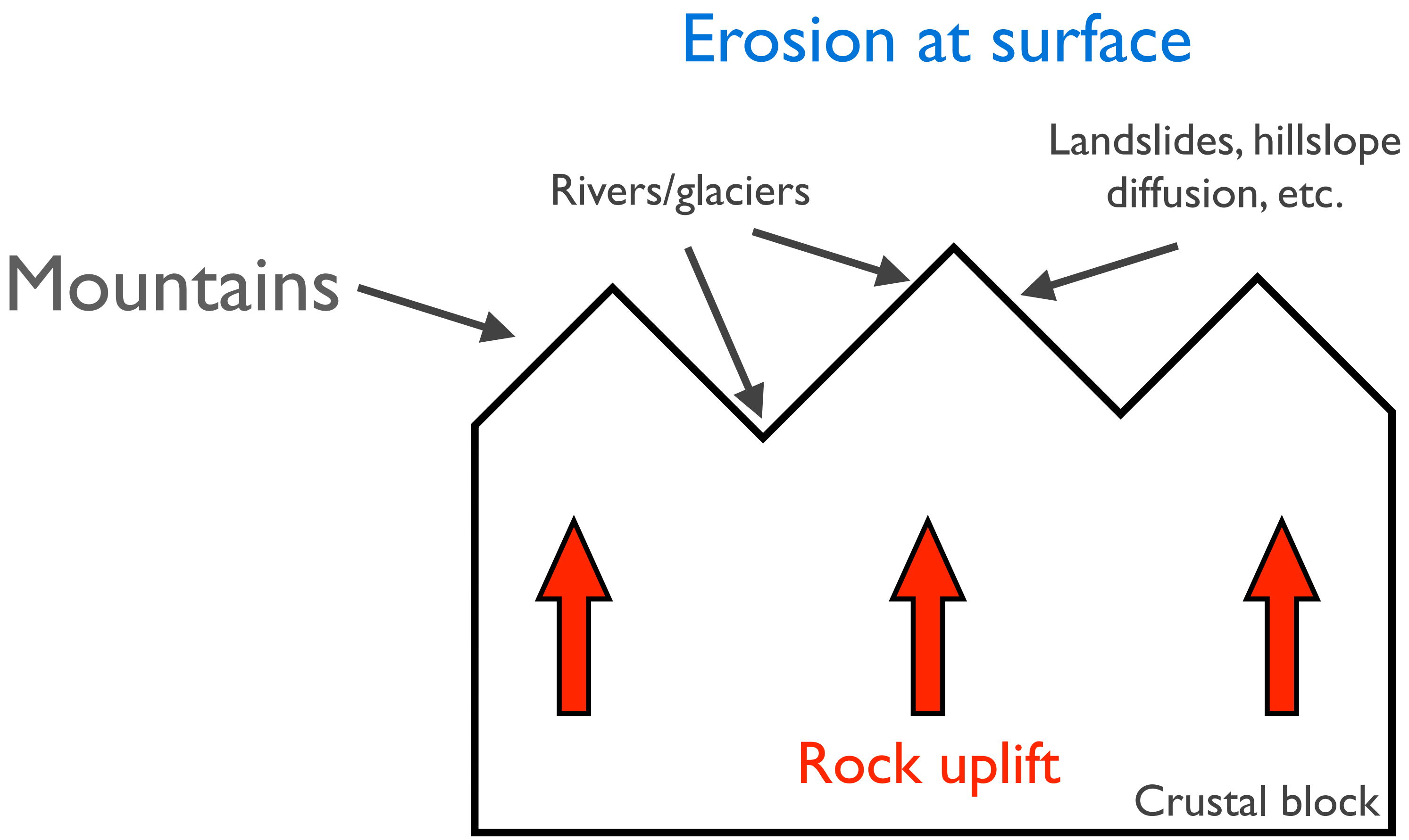
Erosional exhumation



- Occurs as a result of erosion and removal of overlying rock bringing relatively warm rock to the surface
- Can take place in convergent, extensional, strike-slip or inactive tectonic settings
- Most common "cooling type" for thermochronology

Erosional exhumation



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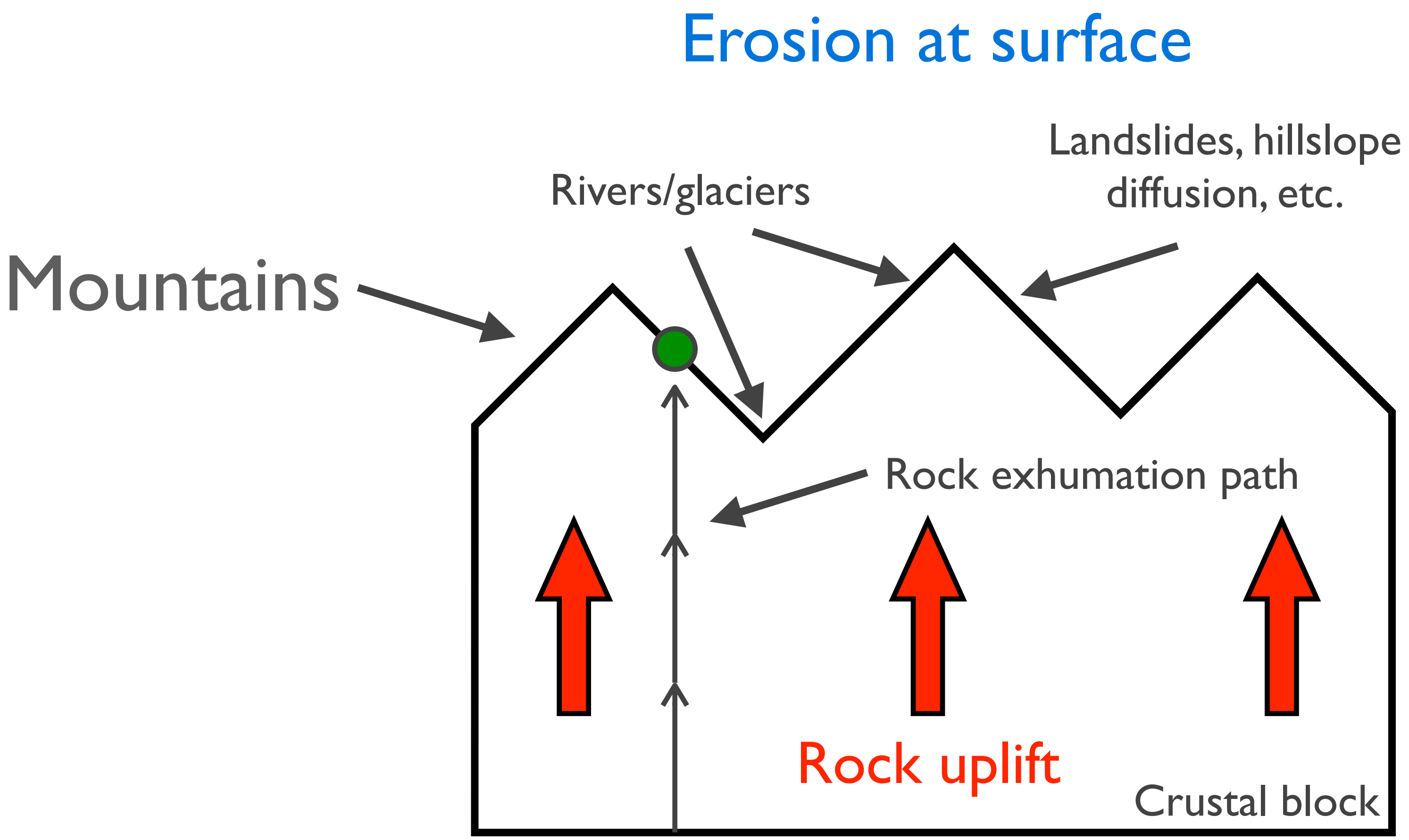

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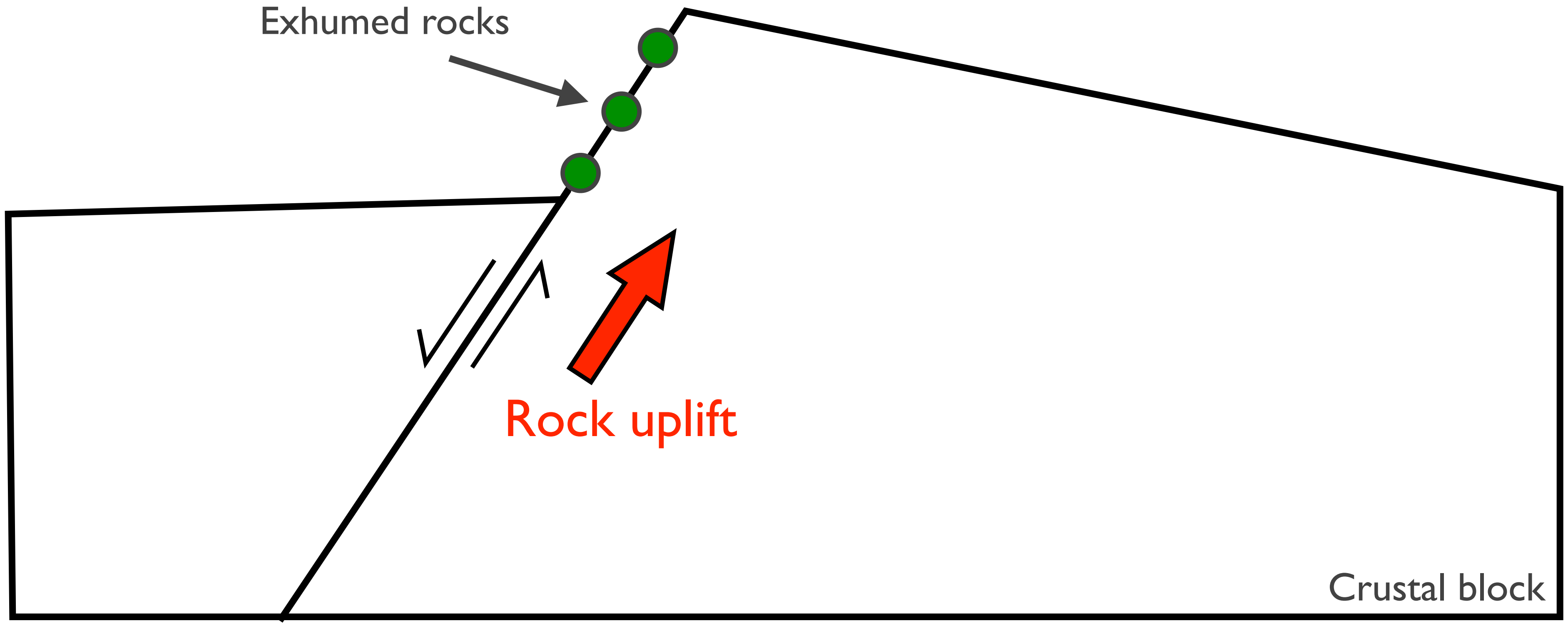
Tectonic exhumation



- Generally occurs in extensional settings
- Uplifted footwall will also experience some erosional exhumation in most cases

Other cases of rock cooling

- Rock cooling can also occur
  - Following emplacement of an igneous body or volcanic deposit
    - Typically, thermochronology is not useful in these cases as the cooling is rapid and geochronological and thermochronological ages will be similar
- Following reheating by
  - Burial in a sedimentary basin and subsequent exhumation
  - Emplacement of proximal igneous intrusions or volcanics

Radioisotopic chronometer ages

- The general equation for an isotopic age is

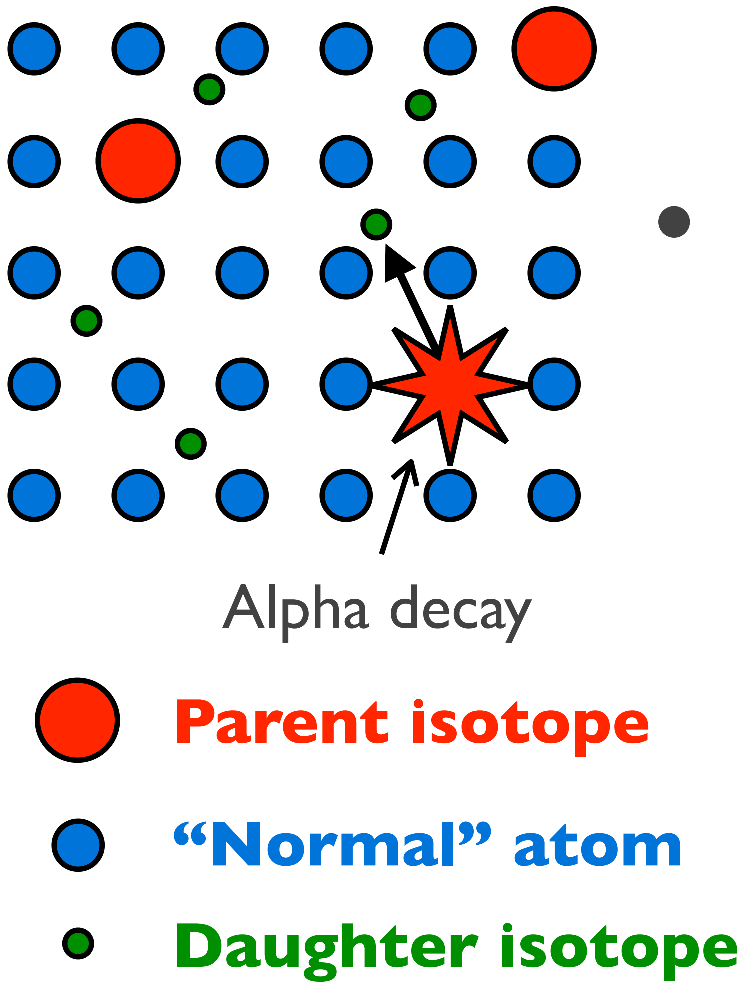
  $$t = \frac{1}{\lambda} \ln\left(1 + \frac{N_\mathrm{d}}{N_\mathrm{p}}\right)$$

  where t is the isotopic age, λ is the radioactive decay constant, N_d is the concentration of the daughter product and N_p is the concentration of the parent isotope

- For thermochronometers, we know that the <u>concentration of the daughter product will vary</u> not only <u>as a result of radioactive decay</u>, but also <u>due loss via solid-state diffusion</u>

Solid-state diffusion

Parent and daughter isotopes in a crystal



- Thermochronometer daughter products are <u>not suitable to be incorporated in the host mineral’s crystal lattice</u>
  - As ‘foreign’ isotopes, they are thus <u>mobile and will diffuse within the crystal</u>
- Their diffusion can be modelled using the standard **diffusion equation**

$$\frac{\partial N_\mathrm{d}}{\partial t} = D(T)\frac{\partial^2 N_\mathrm{d}}{\partial x^2} + P \qquad \textbf{1-D}$$

where $D(T)$ is the temperature dependent diffusivity (see next slide), $\partial^2 N_\mathrm{d}/\partial x^2$ is the second derivative of the daughter product concentration and P is the daughter production rate (often assumed to be constant over the age of a sample)

Temperature-dependent diffusion

- **Temperature dependence** for diffusion is typically modelled as

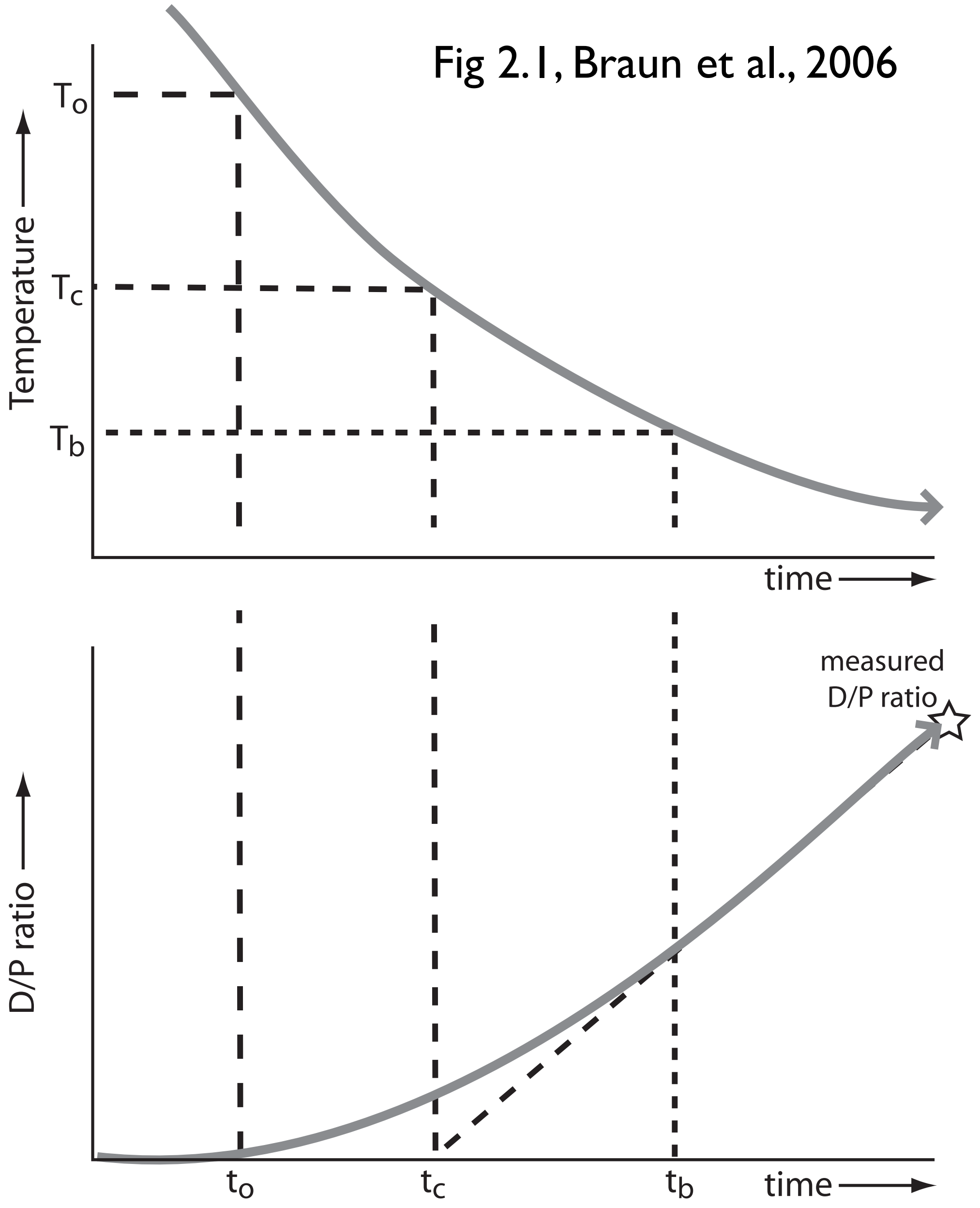
$$\frac{D(T)}{a^2} = \frac{D_0}{a^2} \mathrm{e}^{-E_\mathrm{a}/(RT_\mathrm{K})}$$

  where D_0 is the diffusivity at infinite temperature (diffusion constant), a is the diffusion domain, E_a is the activation energy, R is the gas constant and T_K is temperature in Kelvins

- For simple systems, the diffusion domain a is typically the size of the mineral itself

- The activation energy E_a is the minimum energy that must be put into the system in order for diffusion to occur

Temperature-dependent diffusion



- With the temperature-dependent diffusion concept in mind, there are essentially 3 different temperatures we might consider
  - **The 'open system' temperature T_o**
    The time/temperature that corresponds to the lower limit to the fully open system
  - **The closure temperature T_c**
    The temperature of the system at the time corresponding to its age (Dodson)
  - **The blocking temperature T_b**
    The upper temperature limit of fully closed system behavior

Dodson's effective closure temperature

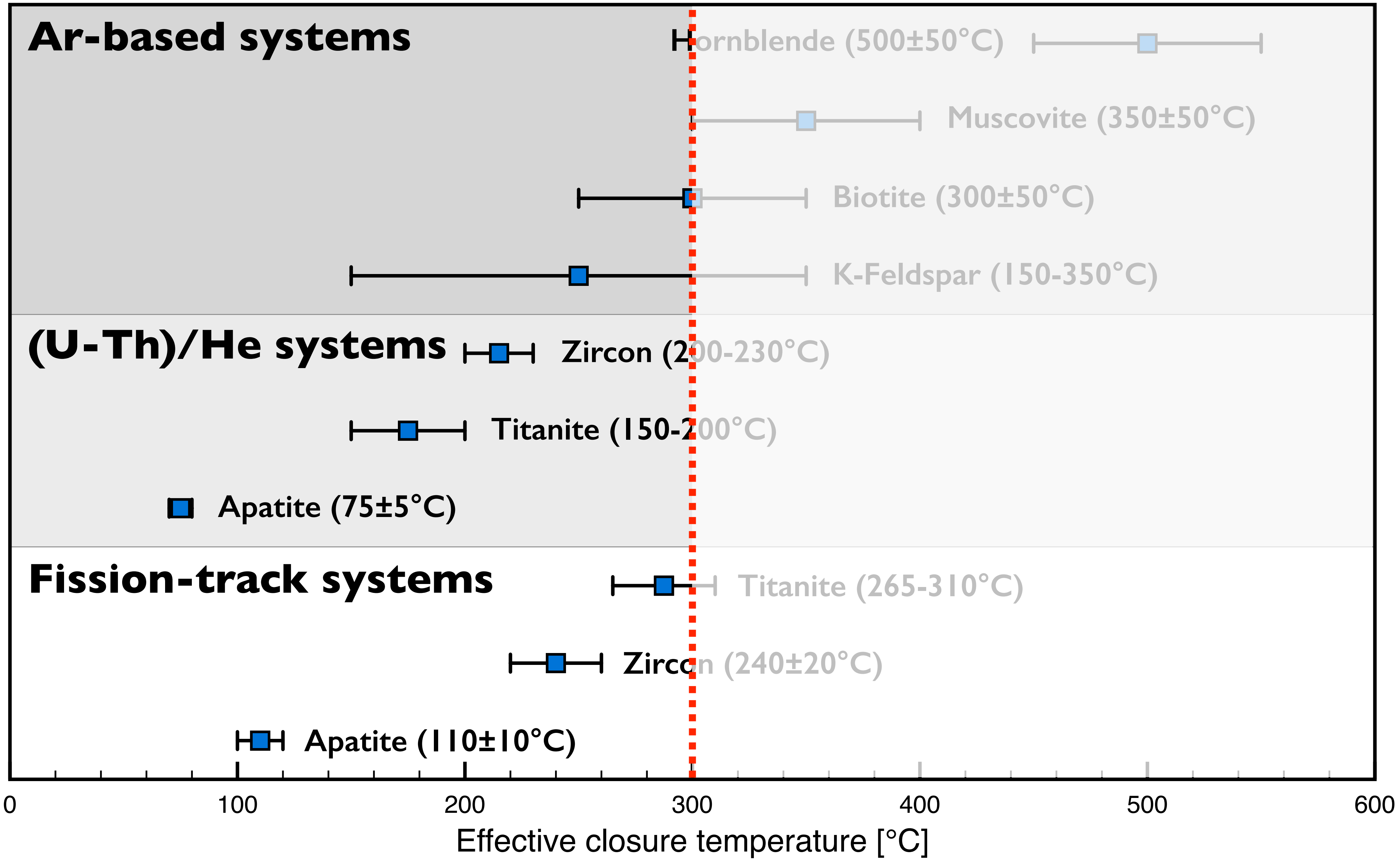
- Dodson (1973) introduced a method for calculating the closure temperature of a thermochronological system based on the observed diffusion parameters and the rock/mineral cooling rate

- We'll see more of this and explore how it the Dodson's equations work tomorrow

Low-temperature thermochronology?

- Now that we have some idea of what a thermochronometer is and what they can record, it is worthwhile to revisit the idea of *low-temperature thermochronology*
  - A **low-temperature thermochronometer** is a thermochronometer with an effective closure temperature **below ~300°C**

Low-temperature thermochronology?



Why is *low-T* thermochronology useful?

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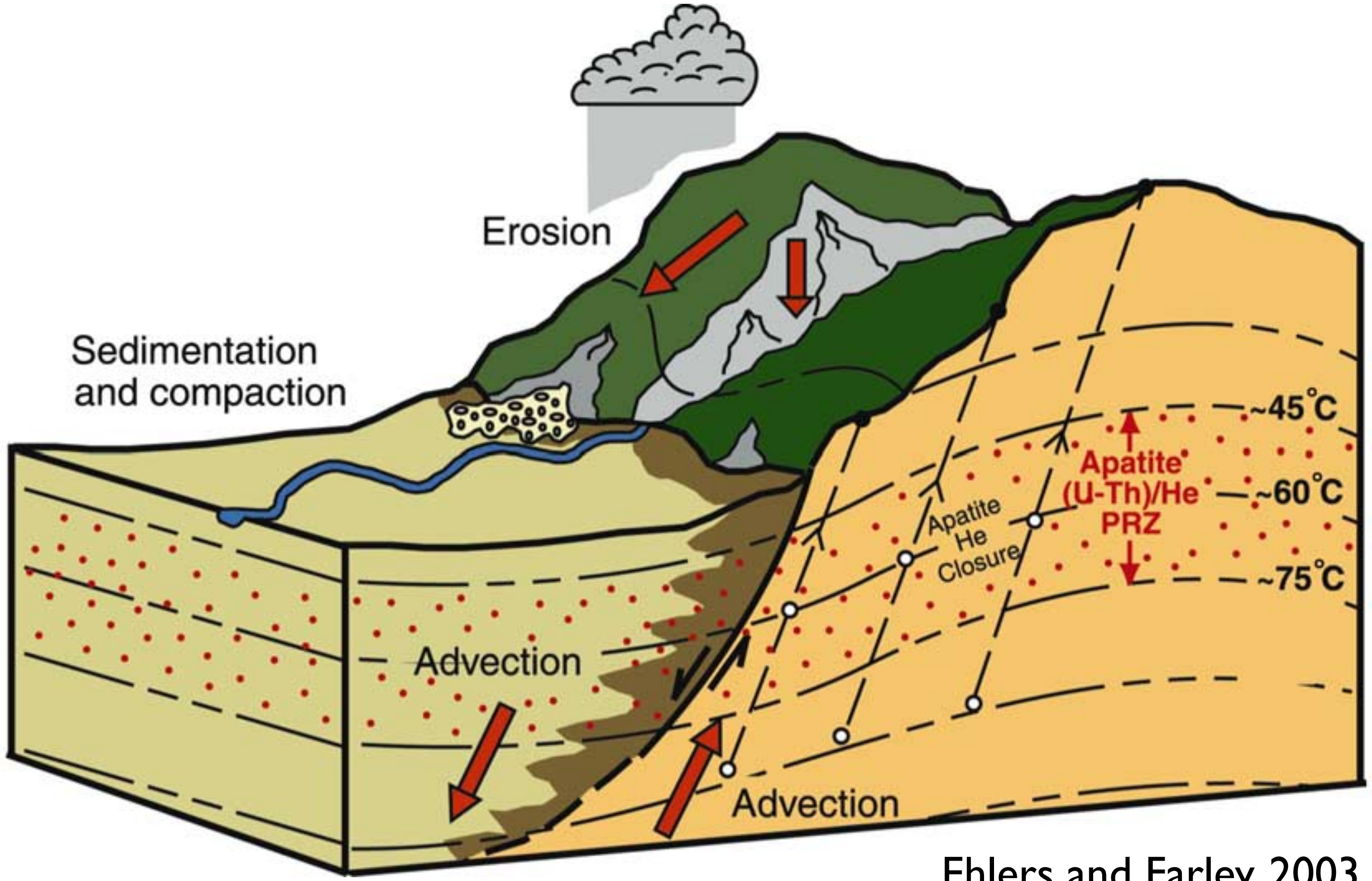
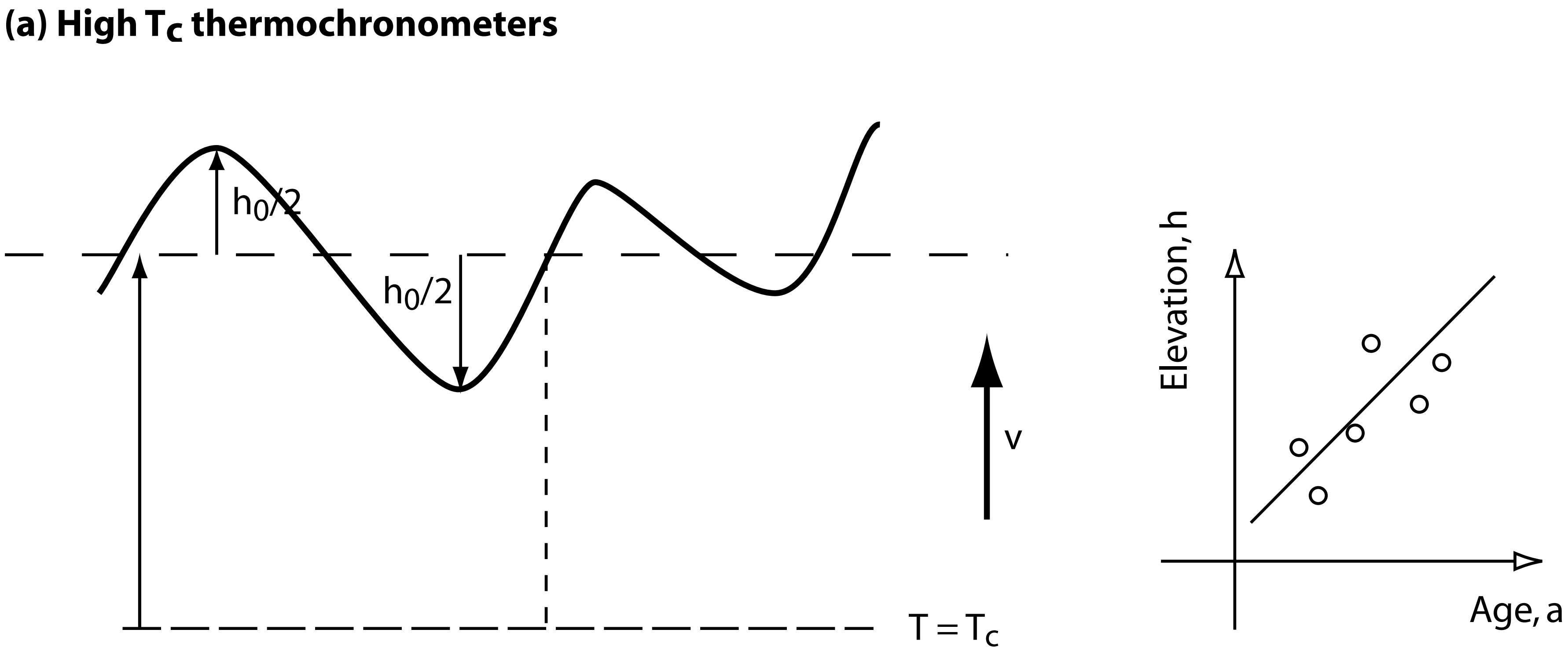


Ehlers and Farley, 2003

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

High T = No topographic sensitivity

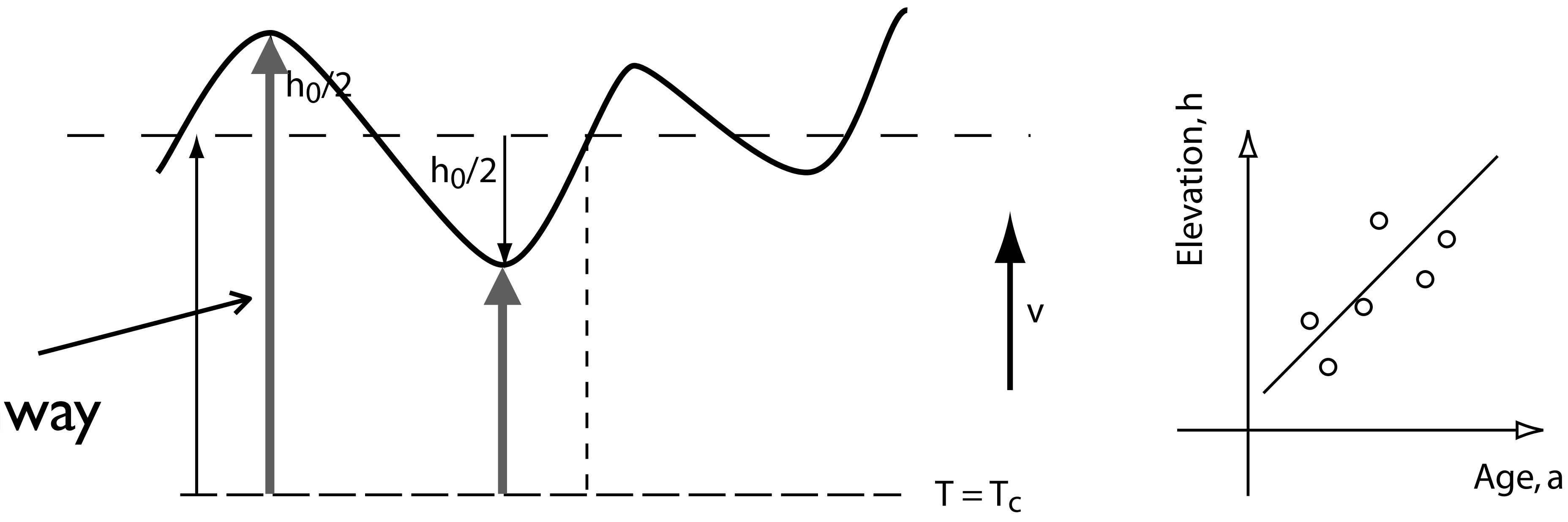


Braun, 2002

- 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 T = No topographic sensitivity



(a) High T_c thermochronometers

Exhumation pathway

Braun, 2002

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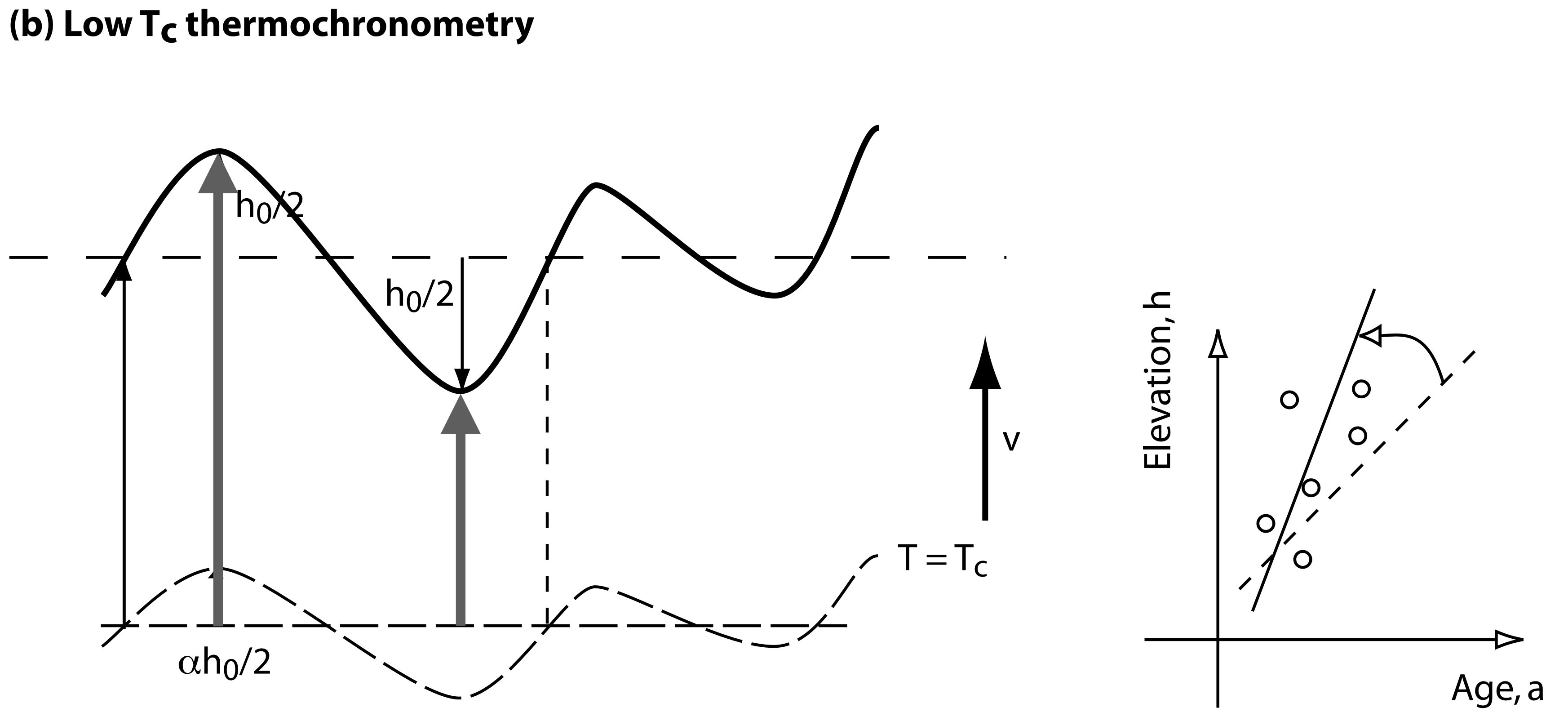
Low T = Sensitive to topography



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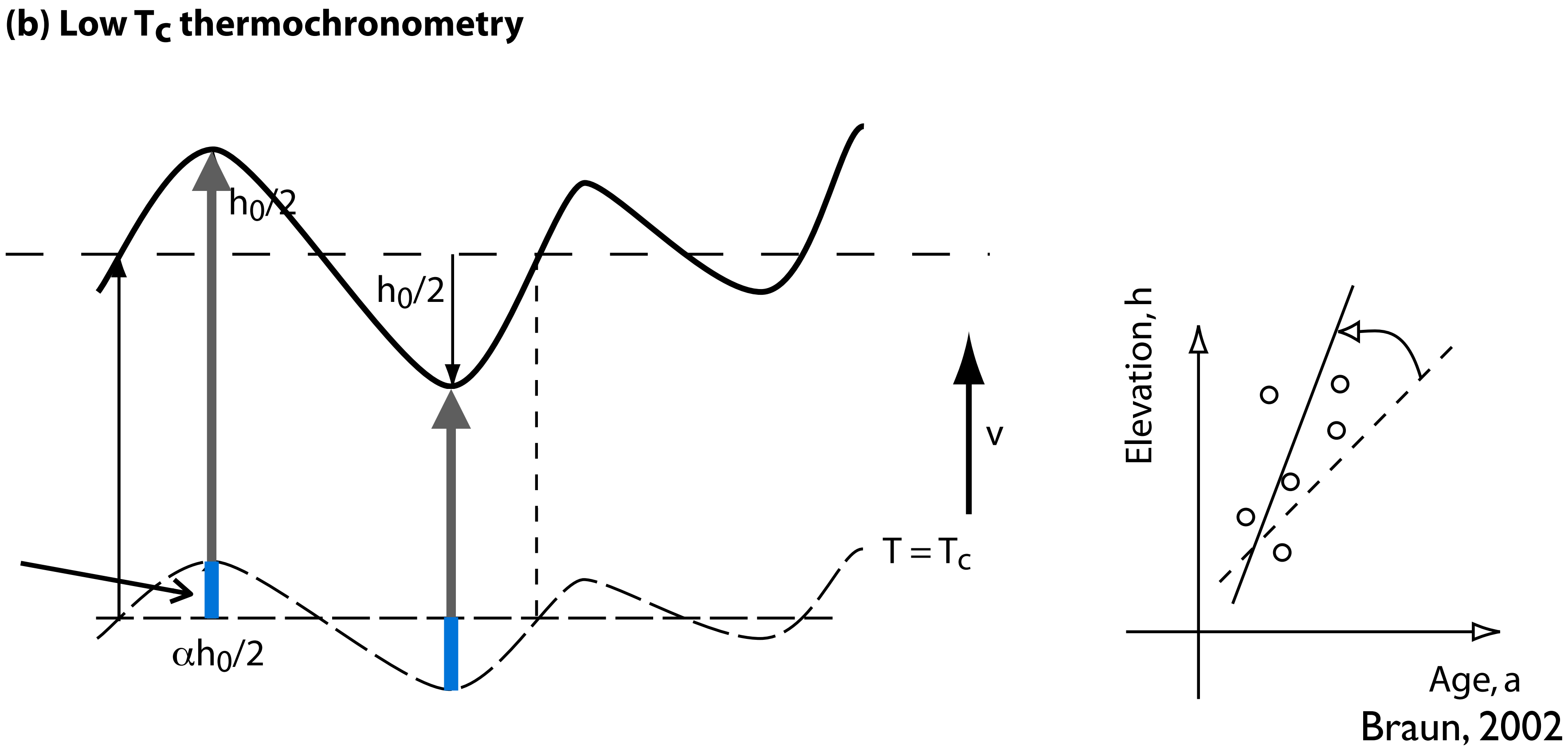
- The effective closure temperature isotherm for low-temperature thermochronometers <u>will generally be "bent" by the surface topography</u>, changing the age-elevation trend
  - The lower the value of T_c, the more its geometry will resemble the surface topography

Low T = Sensitive to topography



Change in pathway

Braun, 2002

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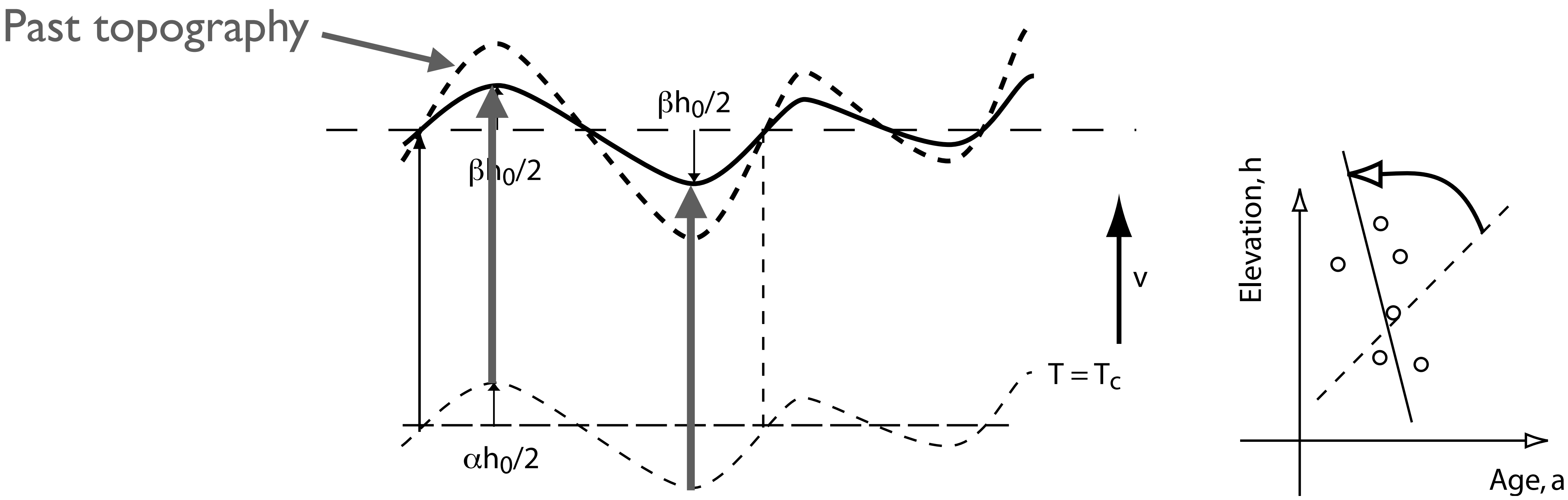
Sensitivity to changing topography



(c) Low T_c thermochronometry + Relief change

Past topography

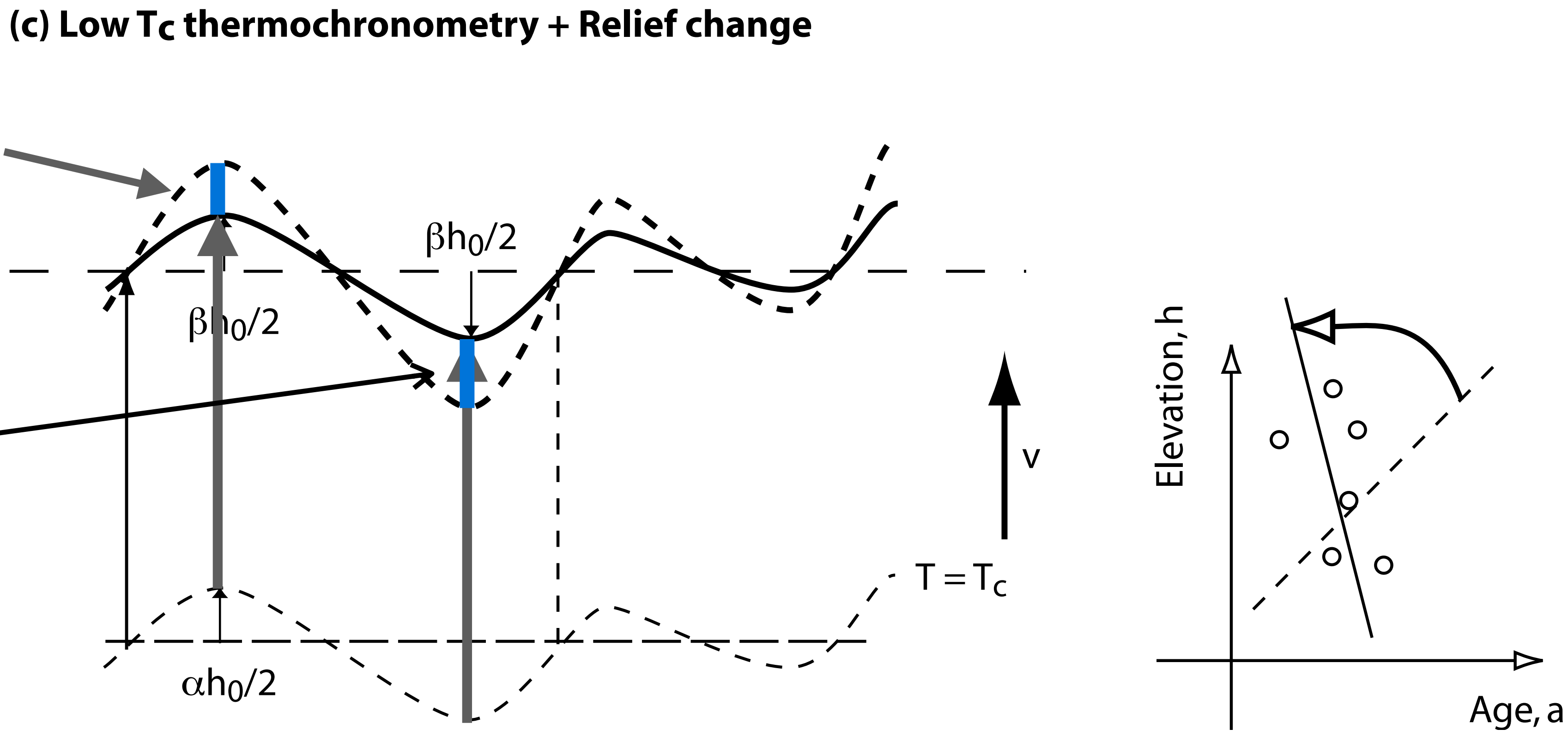
Braun, 2002

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

Sensitivity to changing topography

Past topography

Change in pathway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Summary

- **How does thermochronology differ from geochronology?**
- What is a closure temperature?
- What kinds of things can we study with low-temperature thermochronology?

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