Introduction to Quantitative Geology
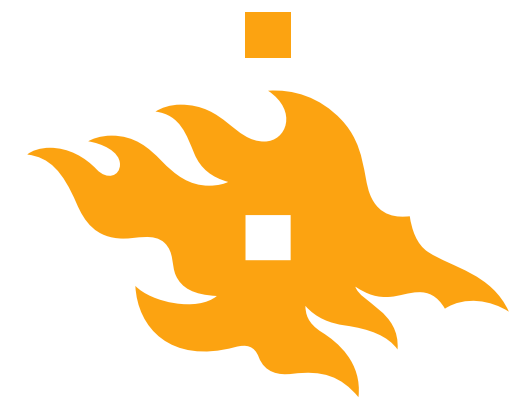
Basic concepts of thermochronology

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Goals of this lecture

- Introduce the basic concepts of **thermochronology**

- Discuss the **closure temperature** concept and how closure temperatures are estimated

Why thermochronology?

- Popular dating technique for studying **long-term tectonic and erosional processes** (typically over millions of years)

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)
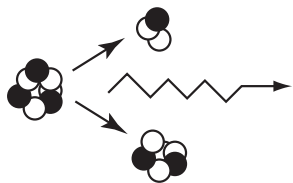
General thermocronology terms

Solid-State Diffusion
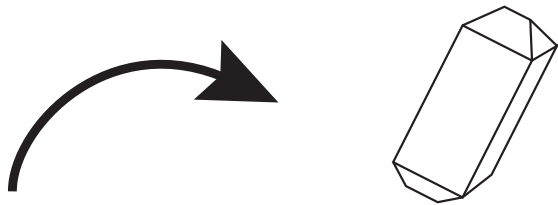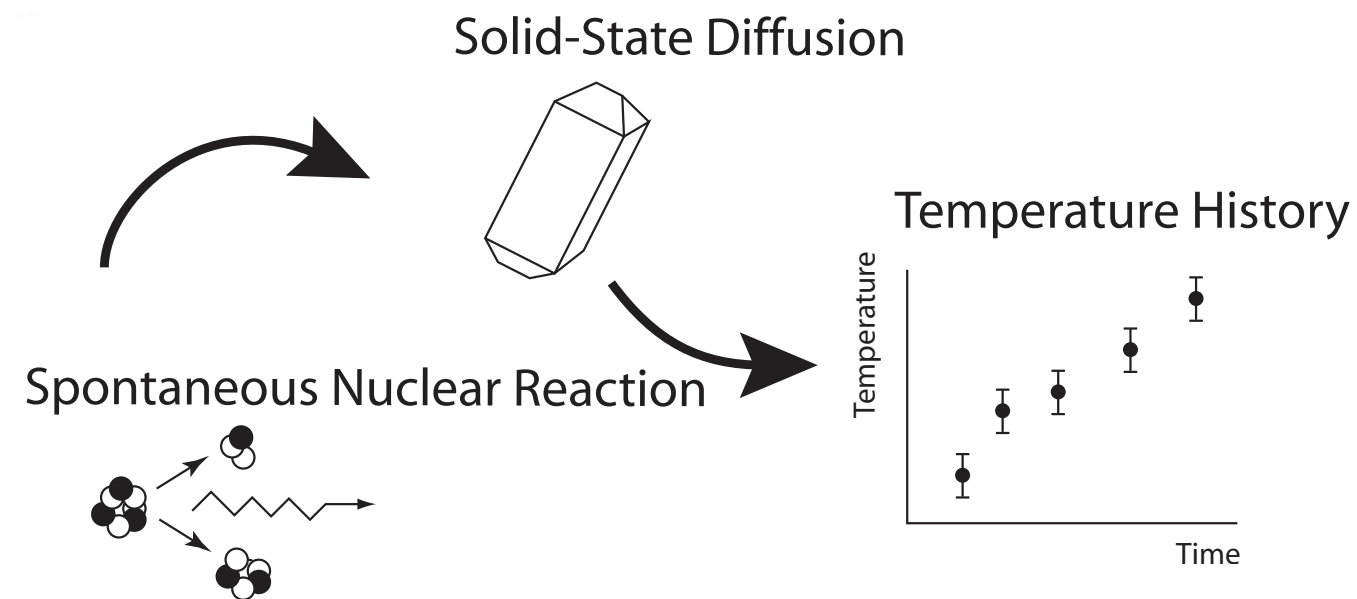
Spontaneous Nuclear Reaction

- **Thermochronometer**
  A radioisotopic system consisting of:

  - a radioactive parent

  - a radiogenic daughter isotope or crystallographic feature

  - the mineral in which they are found

Fig 1.1, Braun et al., 2006

General thermochronology terms

Solid-State Diffusion

Spontaneous Nuclear Reaction
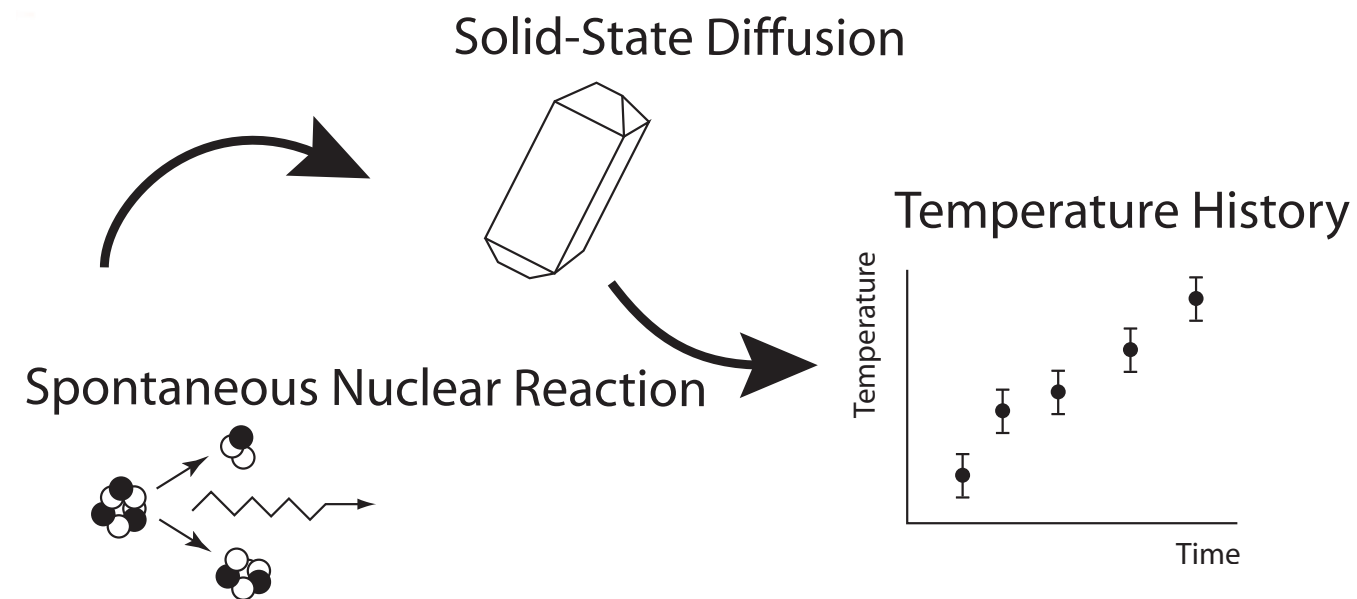
Temperature History

Temperature

Time

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

Fig 1.1, Braun et al., 2006

General thermochronology terms

Solid-State Diffusion

Temperature History

Spontaneous Nuclear Reaction

Time

- **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.

Fig 1.1, Braun et al., 2006

The aim of thermochronology

Solid-State Diffusion

Spontaneous Nuclear Reaction

Temperature History
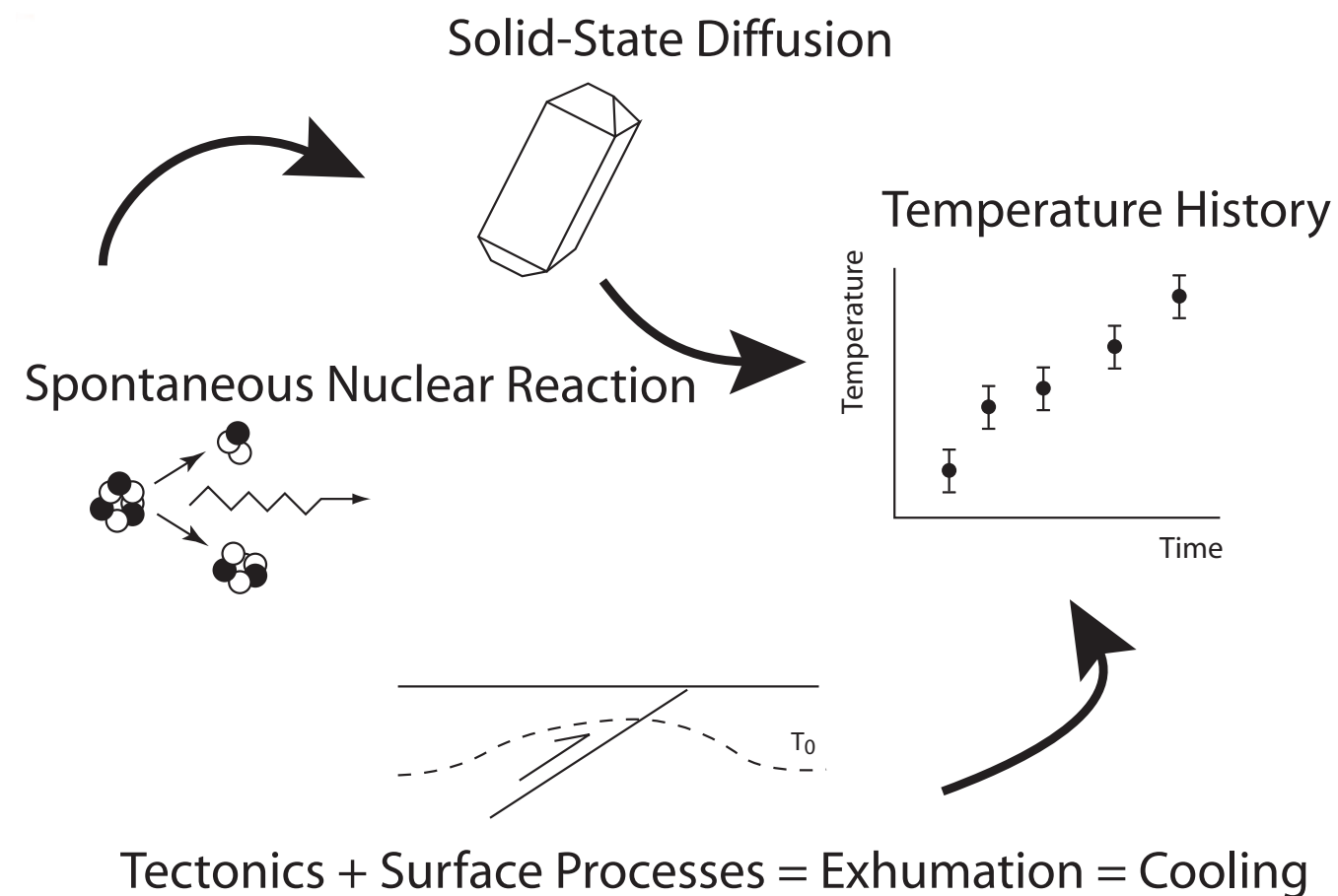
Tectonics + Surface Processes = Exhumation = Cooling

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

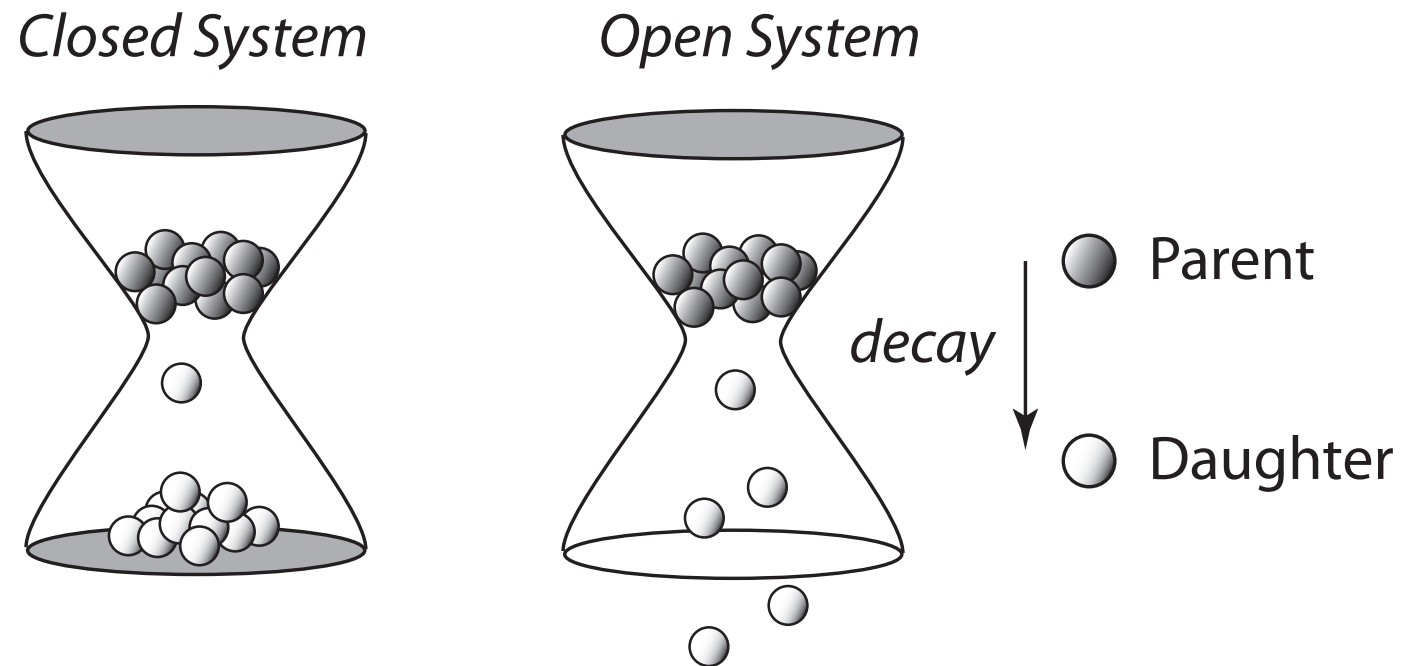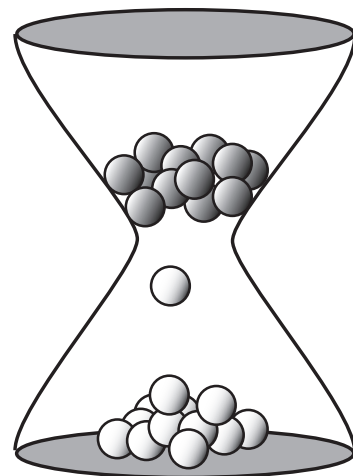Closed System   Open System

decay

Parent

Daughter

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** may be <u>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

Closed System   Open System

decay

Parent

Daughter

Low T   High T   Fig 1.3, Braun et al., 2006

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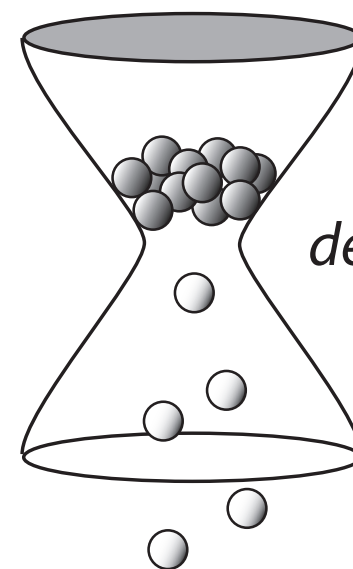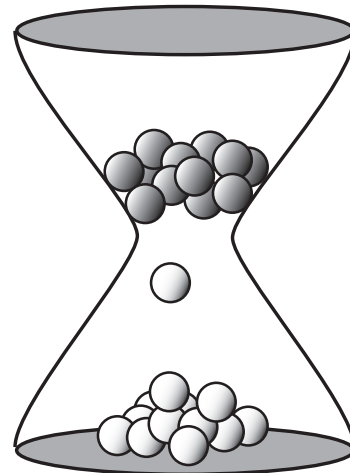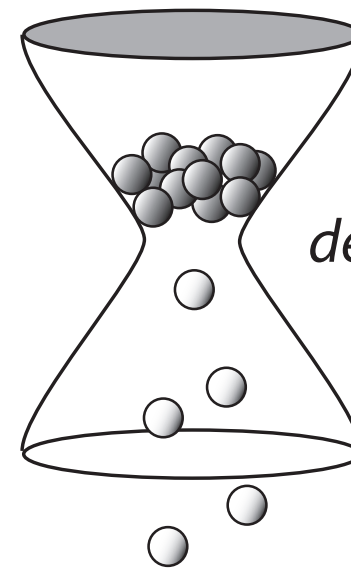
The concept of a closure temperature

Closed System   Open System

Parent

decay

Daughter

Fig 1.3, Braun et al., 2006

Partial retention/
annealing zone

Depth /
Temperature

Daughter concentration /
Apparent age

Fig 1.6a, Braun et al., 2006

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

The concept of a closure temperature

Closed System   Open System

Parent

decay

Daughter

Fig 1.3, Braun et al., 2006

Partial retention/
annealing zone

Depth /
Temperature

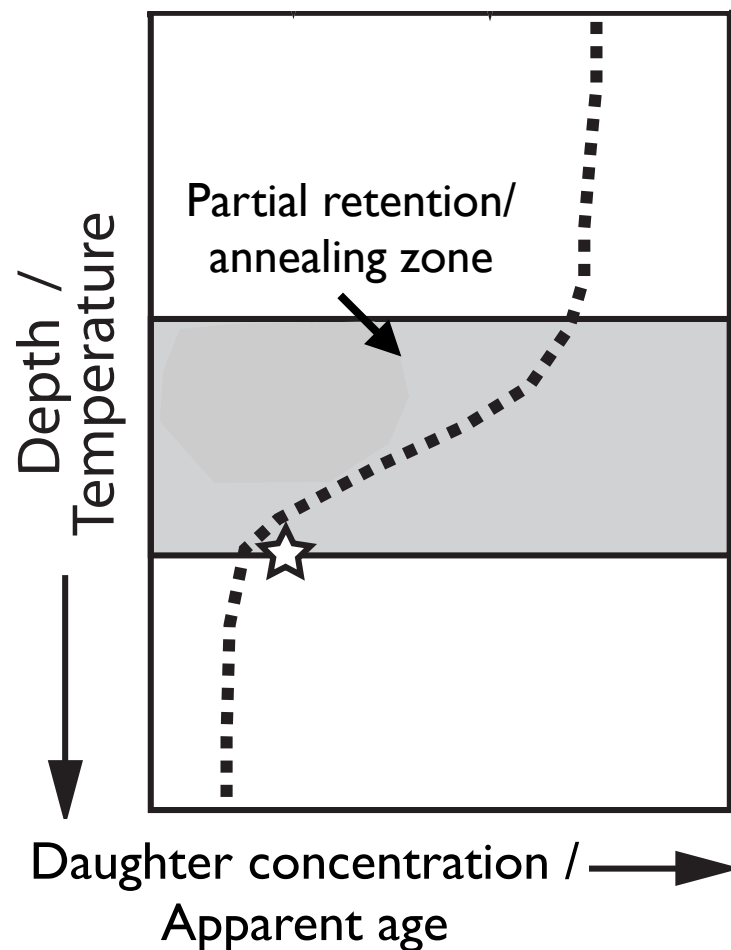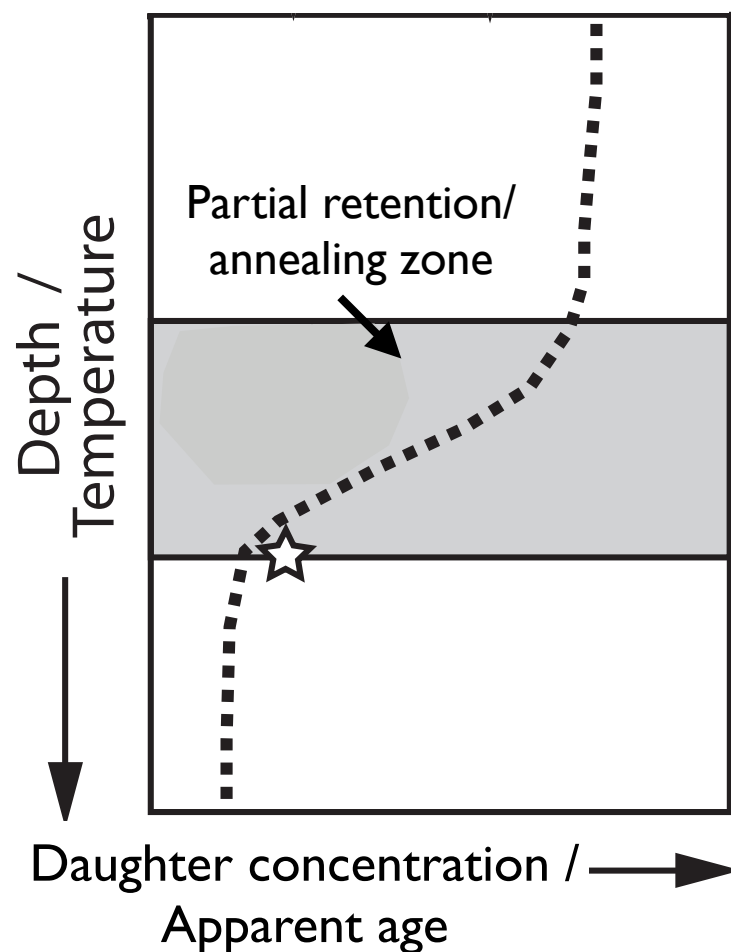Daughter concentration /
Apparent age

Fig 1.6a, Braun et al., 2006

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

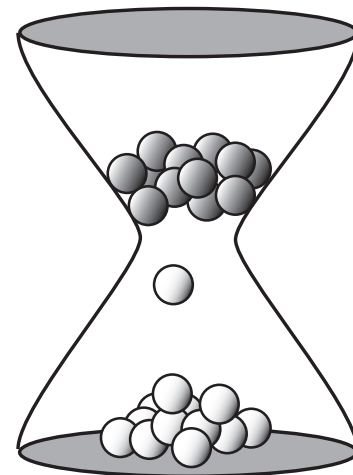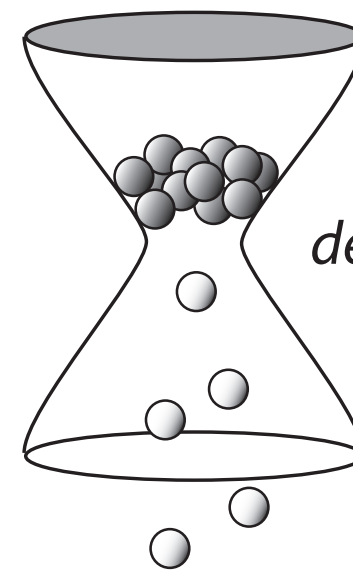- The **partial retention zone** temperature range spans from the point at which <u>nearly all produced daughter products are lost</u> to diffusion to where they are <u>nearly all retained</u>

Effective closure temperature, defined

Partial retention/
annealing zone

Depth / Temperature

T_c

Effective closure temperature

Daughter concentration /
Apparent age

Fig 1.6a, Braun et al., 2006

- Defined by Dodson (1973), the **closure temperature** 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

- 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)
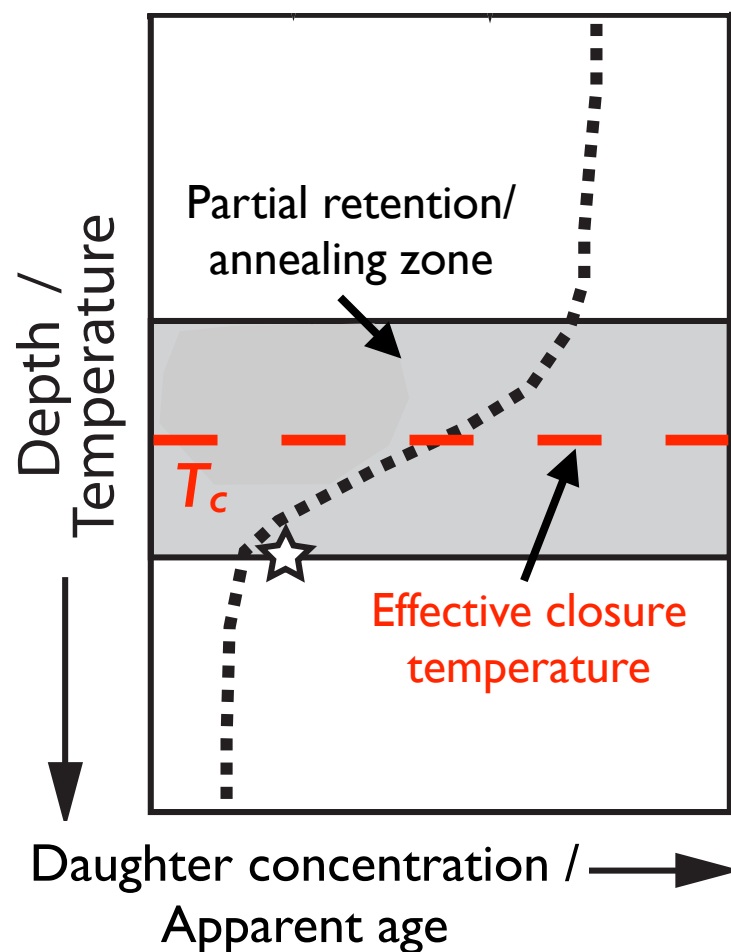
Influence of cooling rate on effective T_c

Reiners and Brandon, 2006
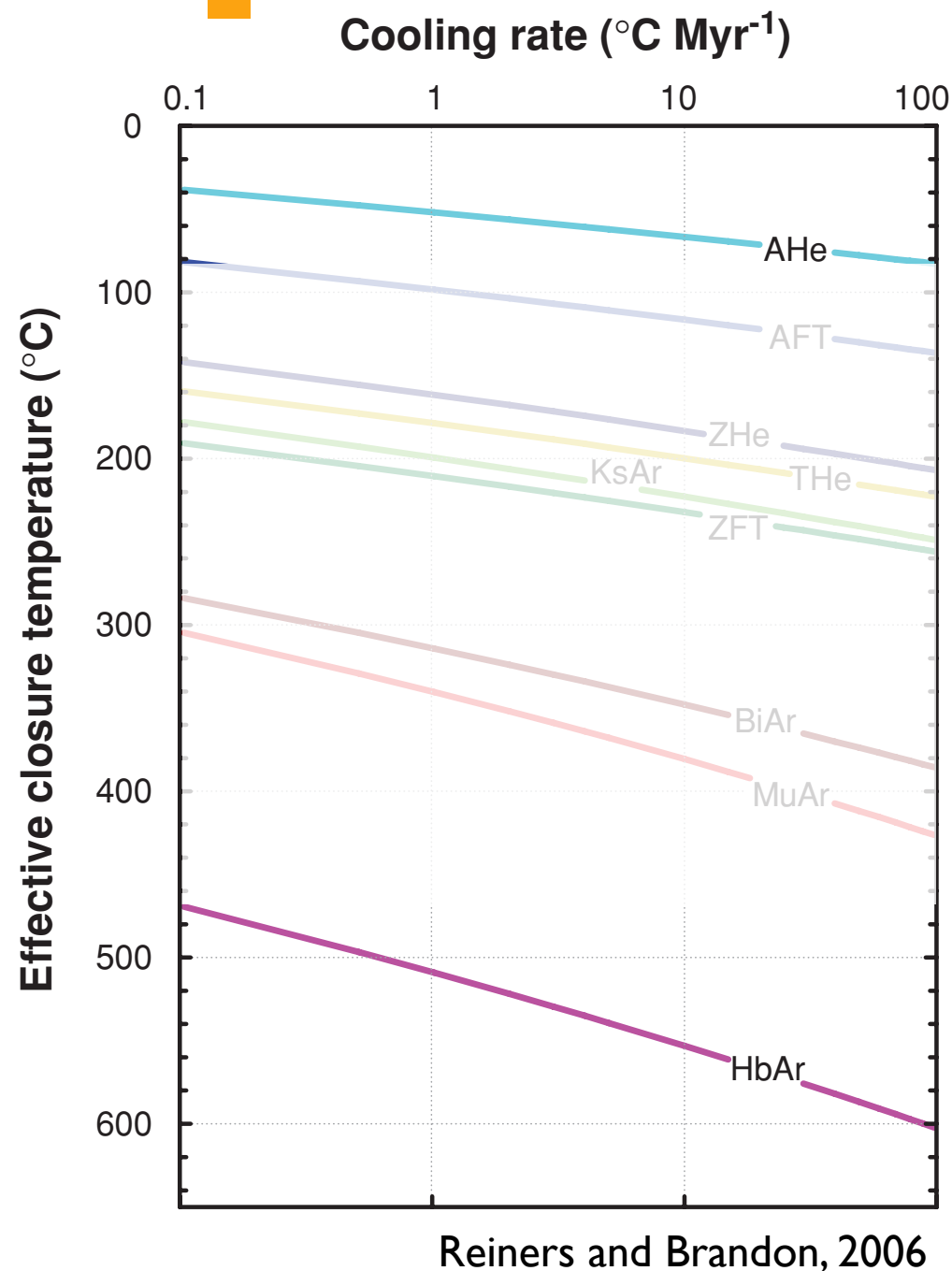
- In general, <u>the effective closure temperature for a given thermochronometer system will increase with increasing cooling rate</u>

  - 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

Radioisotopic chronometer ages

- The general equation for an isotopic age is

$$t = \frac{1}{\lambda} \ln \left(1 + \frac{N_d}{N_p} \right)$$

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
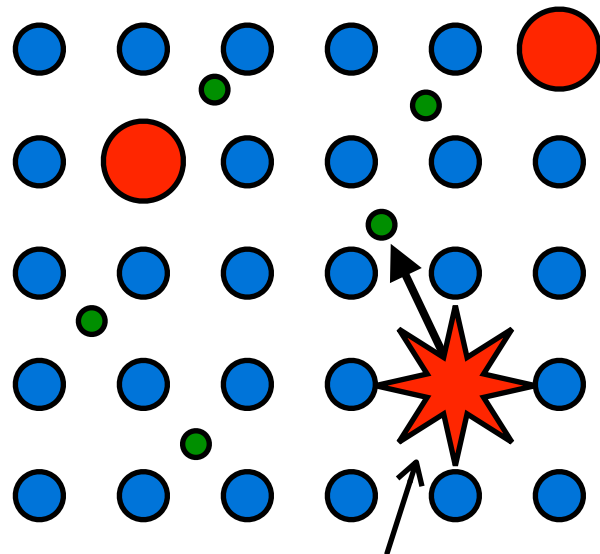
Alpha decay

🔴 **Parent isotope**

🔵 **"Normal" atom**

🟢 **Daughter isotope**

- 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)
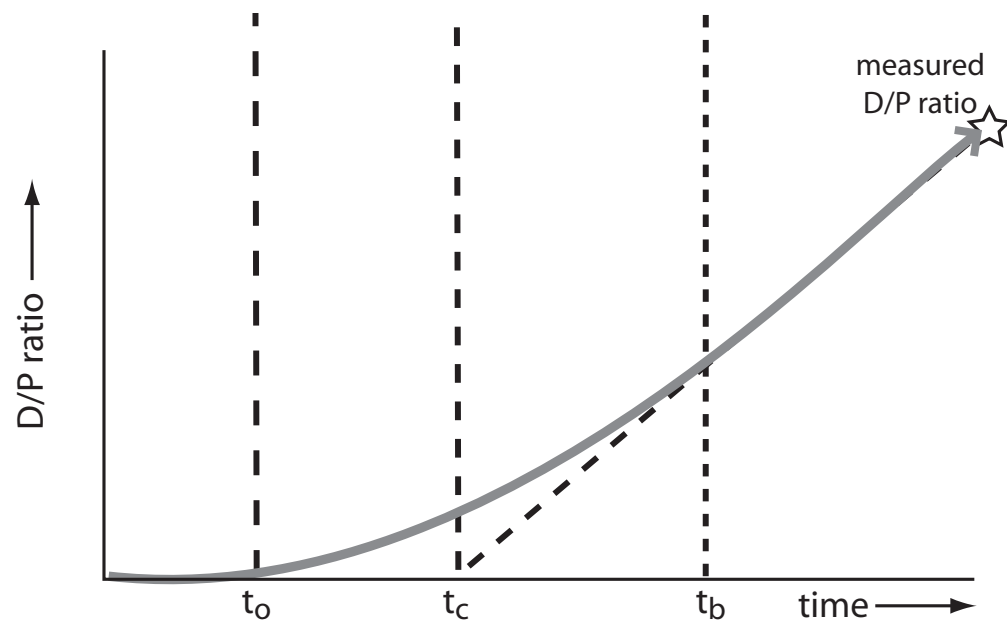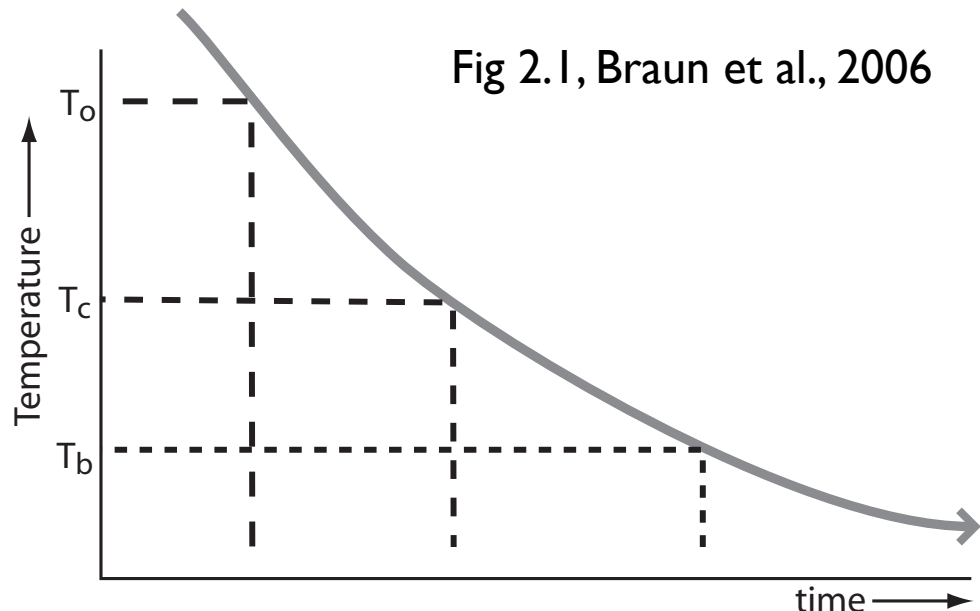
Temperature-dependent diffusion

- **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

Fig 2.1, Braun et al., 2006

- With the temperature-dependent diffusion concept in mind, there are essentially <u>3 different temperatures</u> 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 <u>calculating the closure temperature of a thermochronological system</u> based on the observed diffusion parameters and the rock/mineral cooling rate

- If we assume that once a rock enters the partial retention zone, the <u>temperature will vary as the inverse of time ($T \propto 1/t$)</u>, it is possible to find an approximate solution to the <u>temperature-dependent diffusion equation</u> with a diffusivity

$$D(t) = D(0)\mathrm{e}^{-t/\tau}$$

where τ is is the time taken for the diffusivity to <u>decrease by a factor of 1/e</u>

Dodson's effective closure temperature

- After some mathematical manipulation we can solve for τ and find

$$\tau = -\frac{RT^2}{E_{\mathrm{a}}\dot{T}}$$

  where $\dot{T}$ is the cooling rate (negative by convention)

- **Dodson's closure temperature** equation is

$$T_{\mathrm{c}} = \frac{E_{\mathrm{a}}}{R\ln(A\tau D_0/a^2)}$$

  where A is a geometry factor (25 for a sphere, 27 for a cylinder and 8.7 for a plane sheet)

- We can find the closure temperature as a function of cooling rate by <u>assuming $T = T_{\mathrm{c}}$ in the equation for τ and iterating</u>

Pseudo-code for solving Dodson's equation

- Define constants

- Define initial "guess" for value of T_c

- Loop over some range to iterate on values of τ and T_c

  - Calculate new τ with current value of T_c

  - Calculate new value of T_c for new τ value

  - Check to see how much value of T_c has changed since last iteration

    - If value has not changed more than some very small number, exit loop and output calculated 'final' T_c value
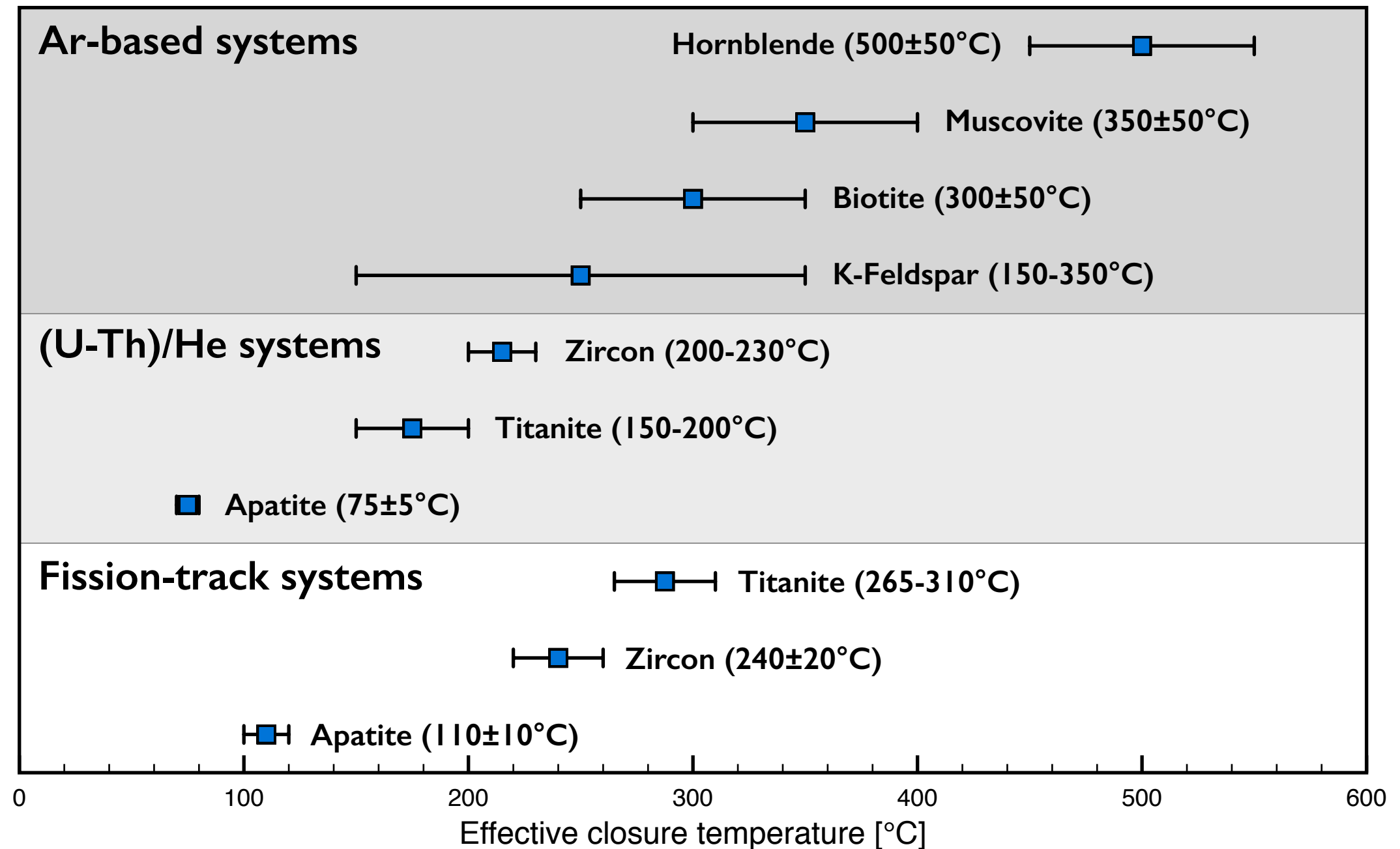
Dodson's effective closure temperature

Estimated T_c for apatite (U-Th)/He

Fig 2.3, Braun et al., 2006
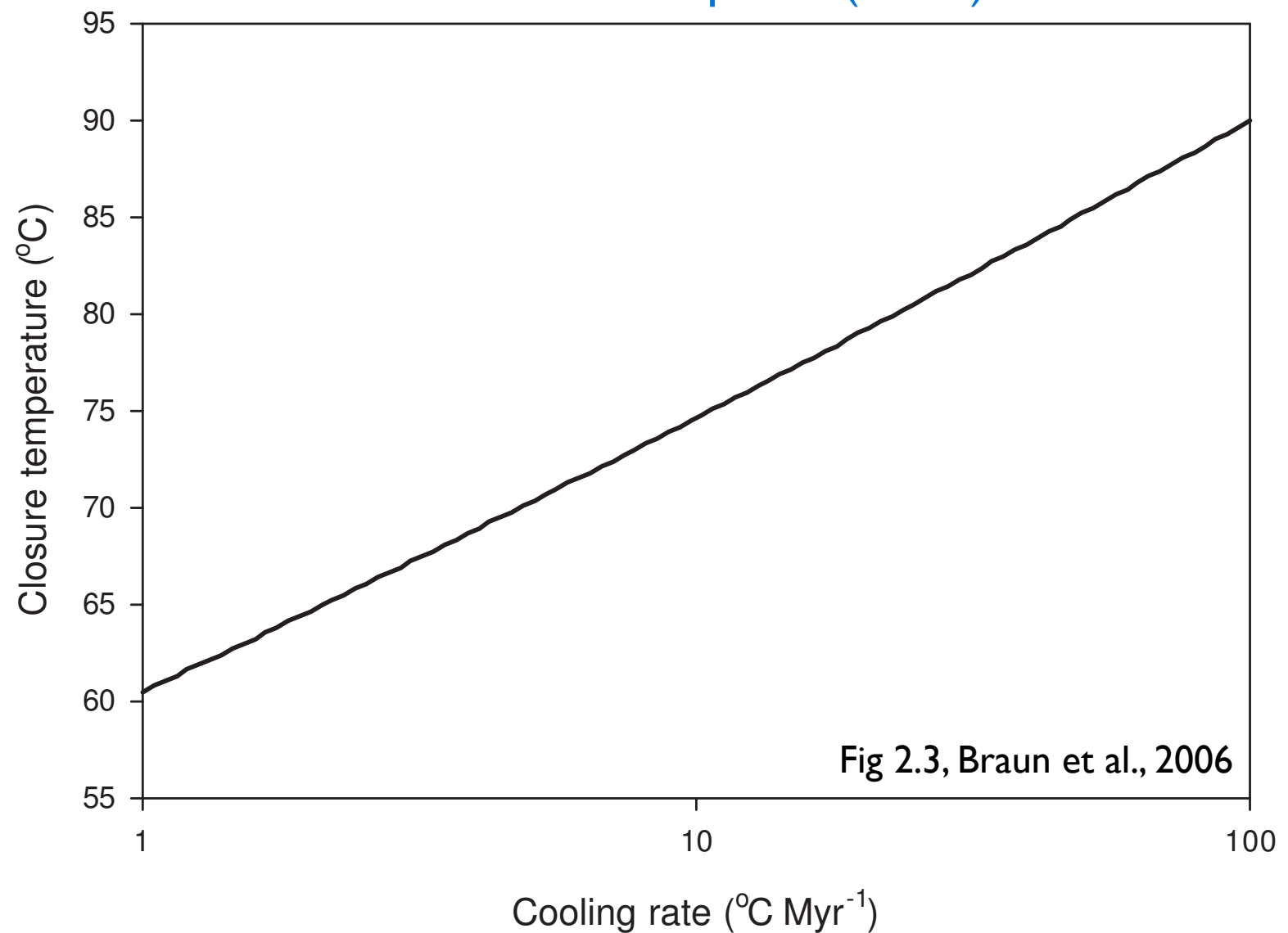
- The effective closure temperature T_c <u>increases significantly at higher cooling rates</u>

Common thermochronometers

Recap

- **What is the basic idea for thermochronology?**

- What is an effective closure temperature and how does it relate to the rate of cooling of a mineral sample?

Recap

- What is the basic idea for thermochronology?

- **What is an effective closure temperature and how does it relate to the rate of cooling of a mineral sample?**

References

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

Reiners, P. W., and M. T. Brandon (2006), Using Thermochronology to Understand Orogenic Erosion, *Annual Review of Earth and Planetary Sciences*, *34*, 419–466.