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 6.1
Basic concepts of thermochronology

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2.12.19

Goals of this lecture

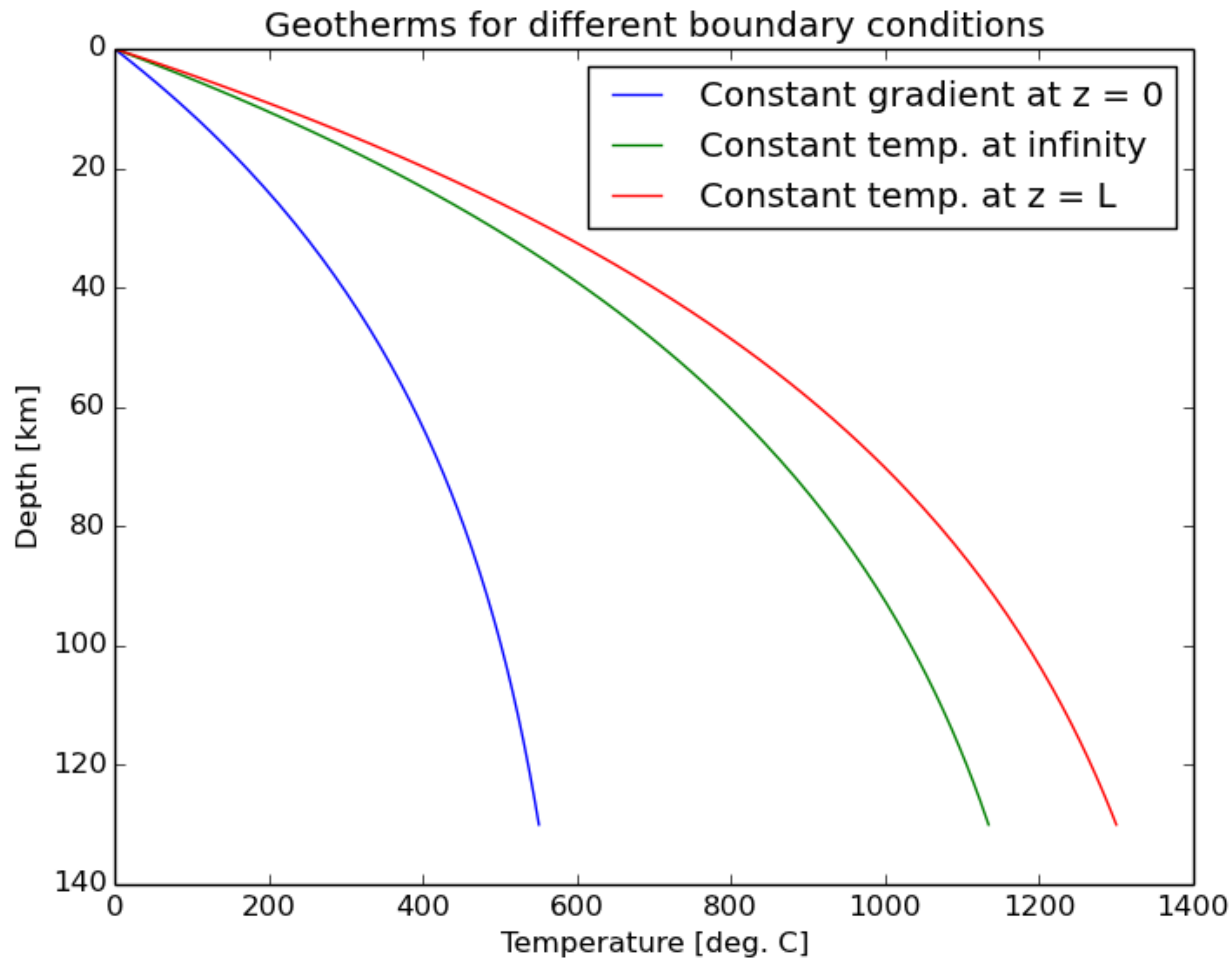
- Introduce the basic concepts of **thermochronology**
- Discuss the **closure temperature** concept and how closure temperatures are estimated

Why thermochronology?

Spanish Pyrenees

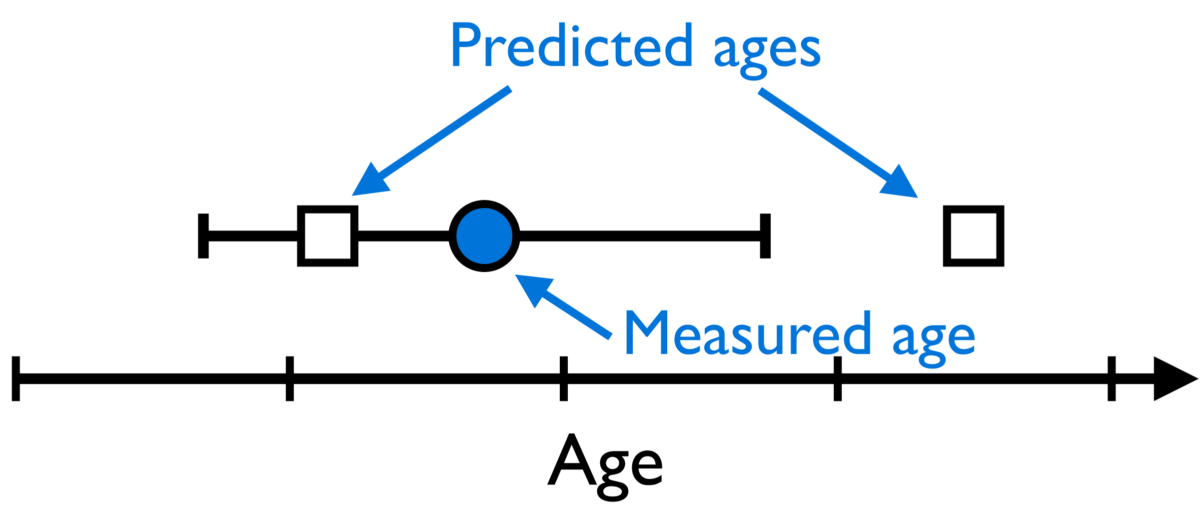
- Popular dating technique for studying **long-term tectonic and erosional processes** (i.e., stuff we've been learning)

Why thermochronology?



- Inherently linked to **crustal heat transfer processes** (advection, diffusion, production, etc.)

Why thermochronology?



$$\chi^2 = \sum \frac{(O_i - E_i)^2}{\sigma_i^2}$$

- Incorporates **many equations we've seen** and many other concepts presented earlier in the course (hillslope processes, river erosion, heat conduction/advection, basic geostatistics)

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 thermochronology terms

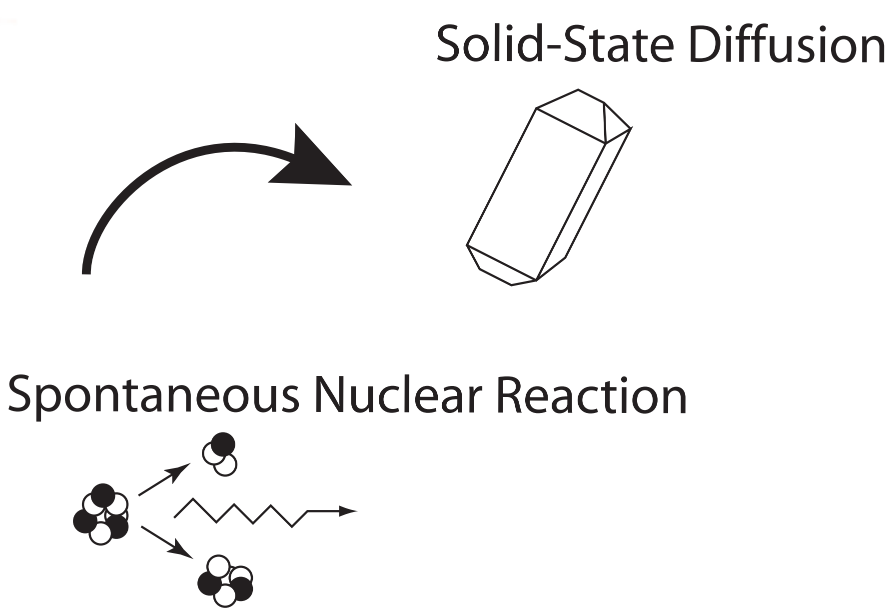
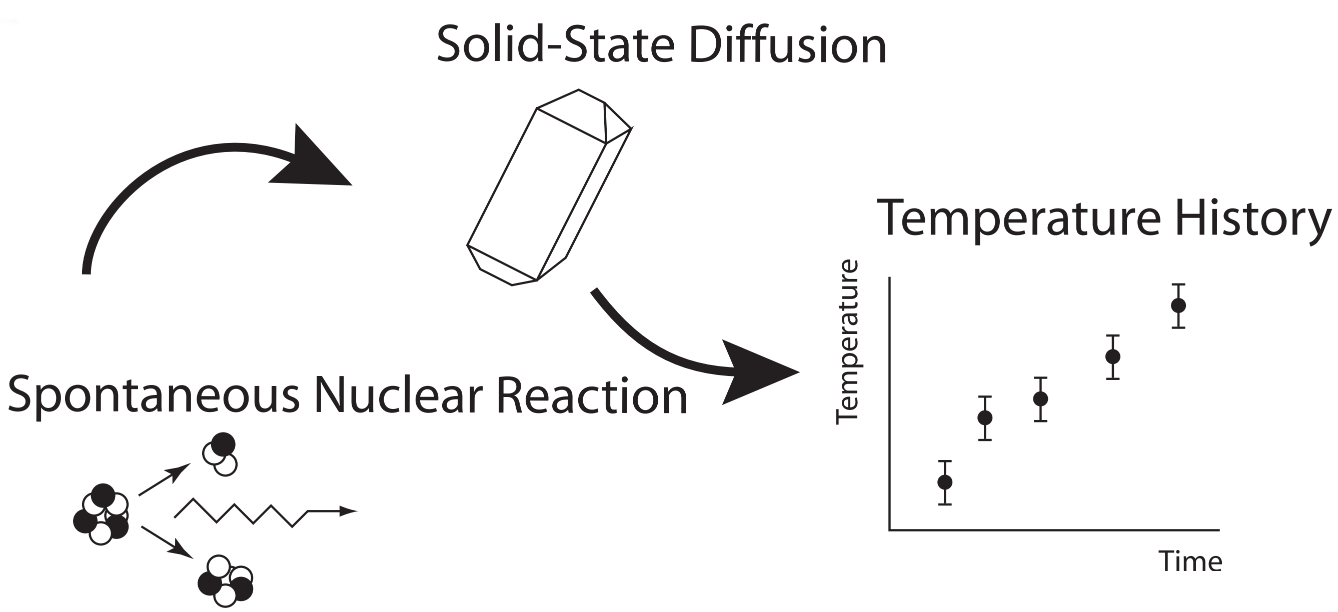


Fig 1.1, Braun et al., 2006

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

General thermochronology terms



- **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

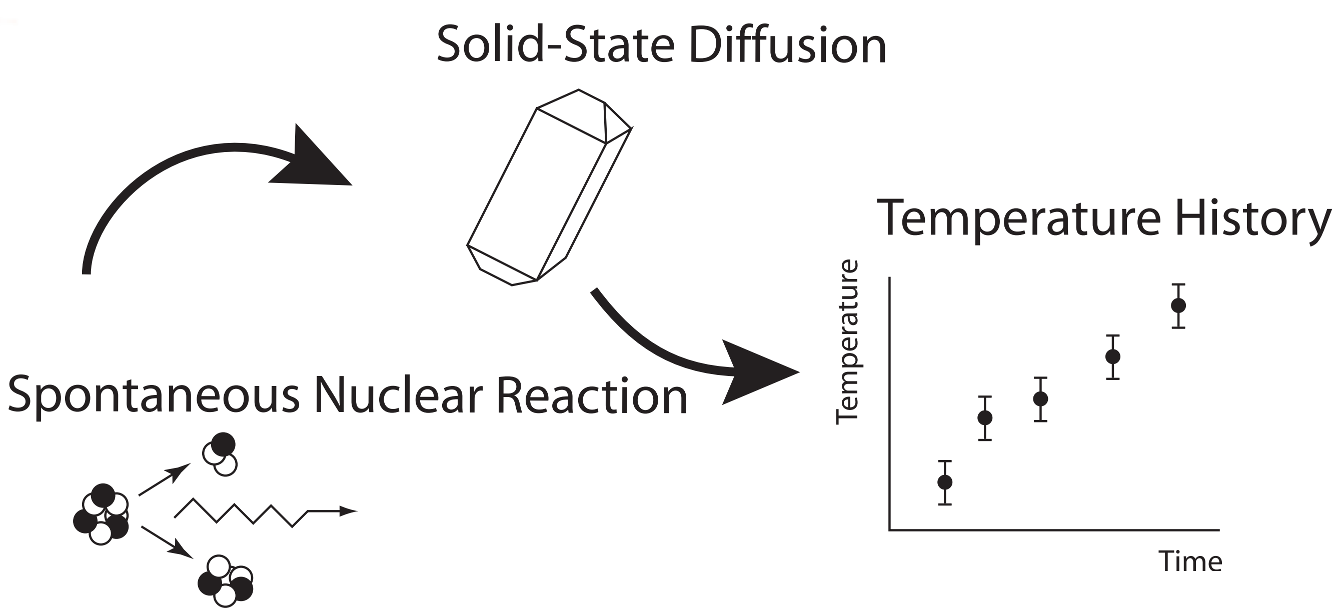


Fig 1.1, Braun et al., 2006

- **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

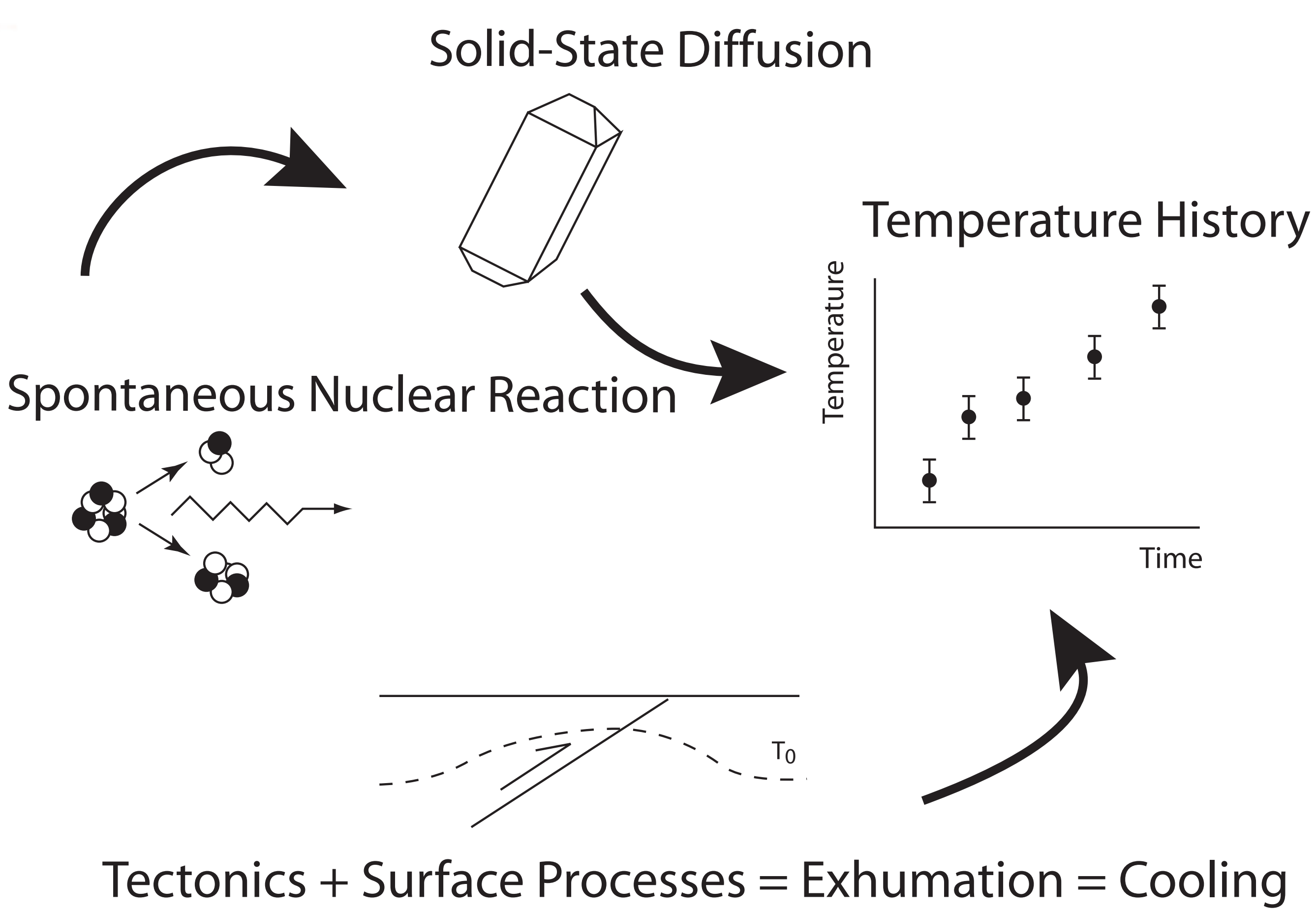


Fig 1.1, Braun et al., 2006

- 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

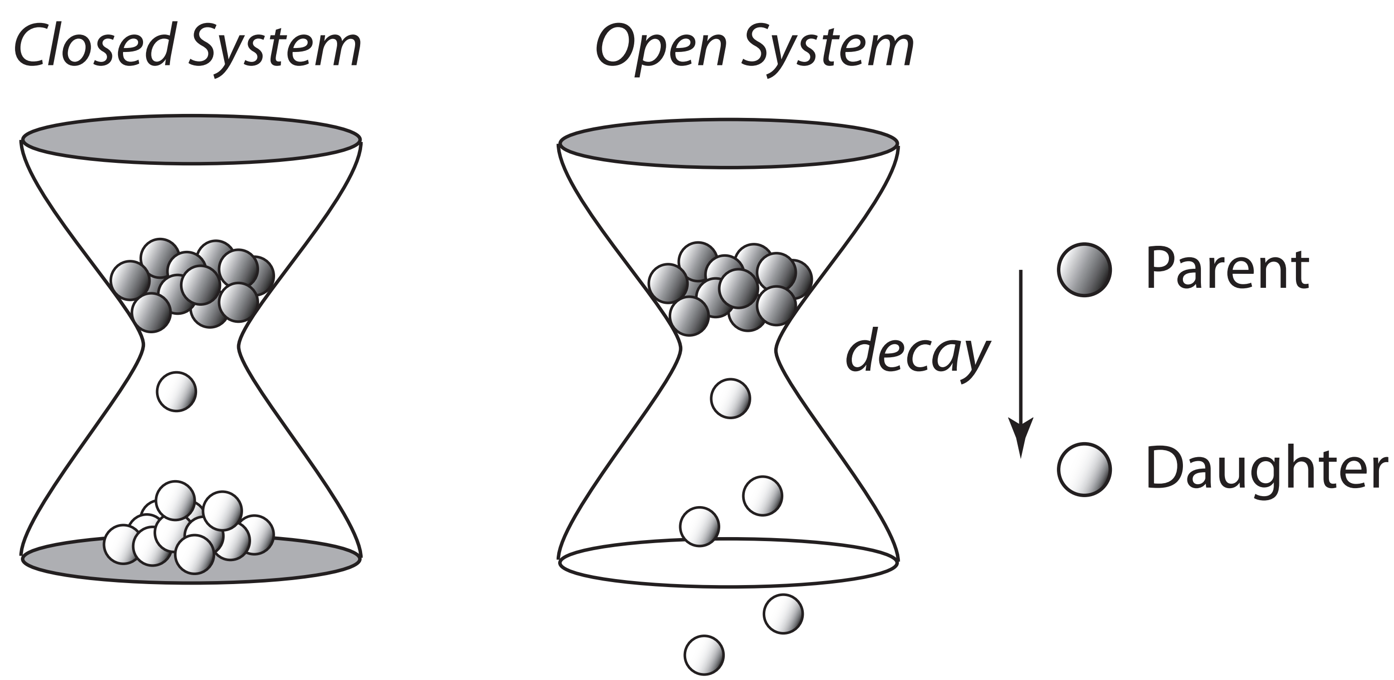
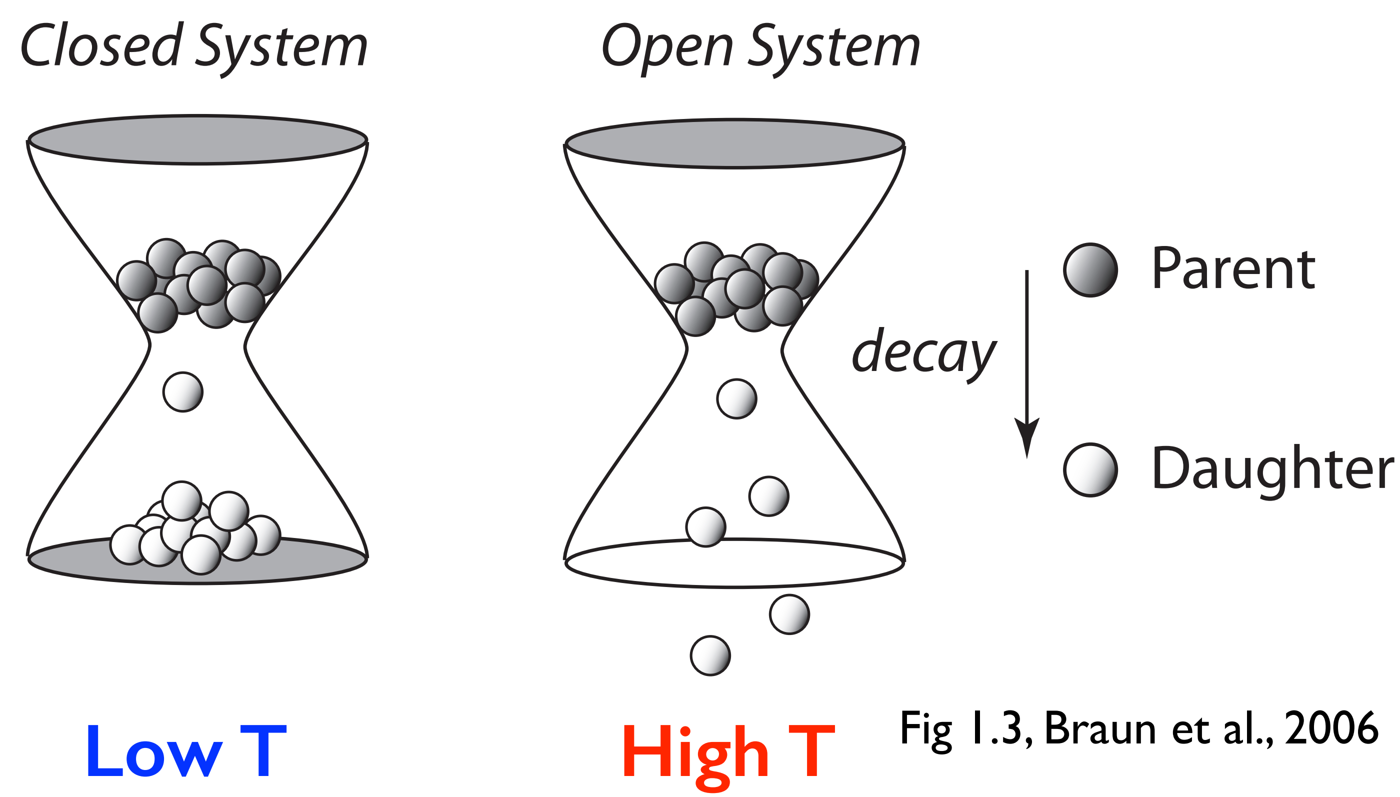


Fig 1.3, Braun et al., 2006

- **Daughter products** are continually produced within a mineral as a result of radioactive decay
- **Daughter products** may be lost due to thermally activated diffusion
    - 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

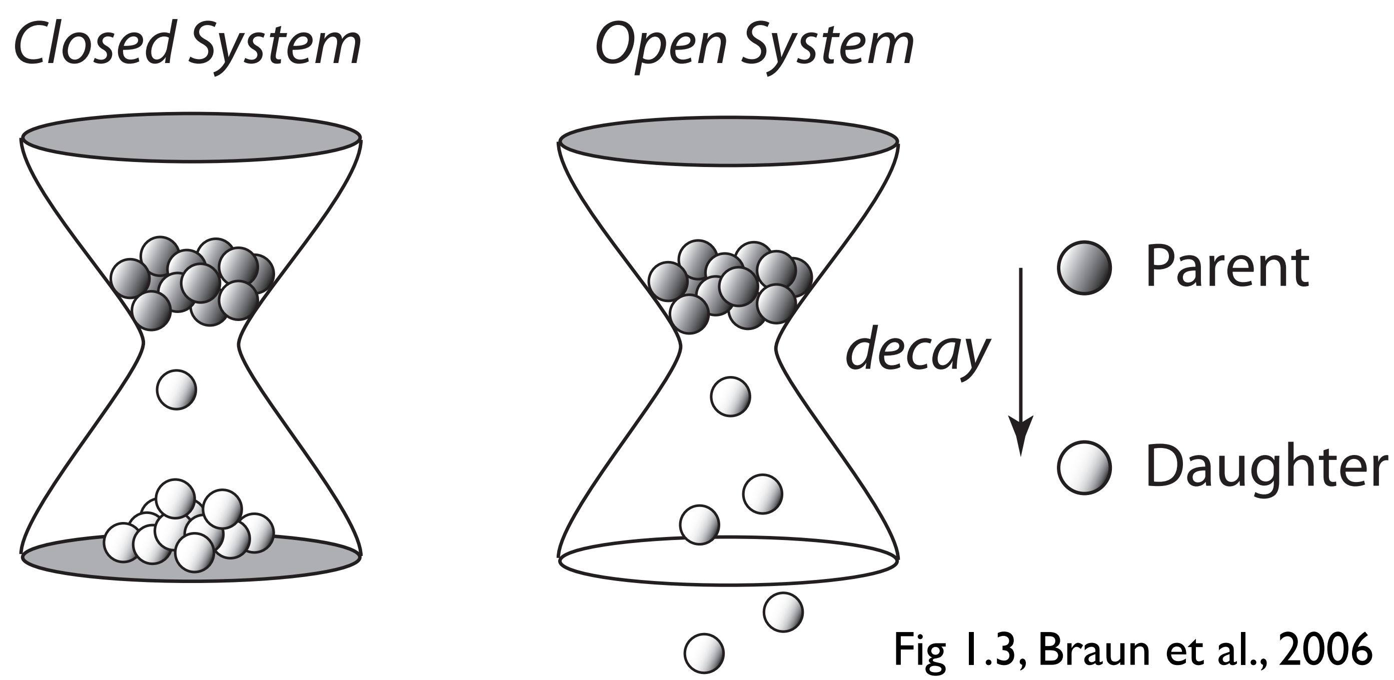


Fig 1.3, Braun et al., 2006

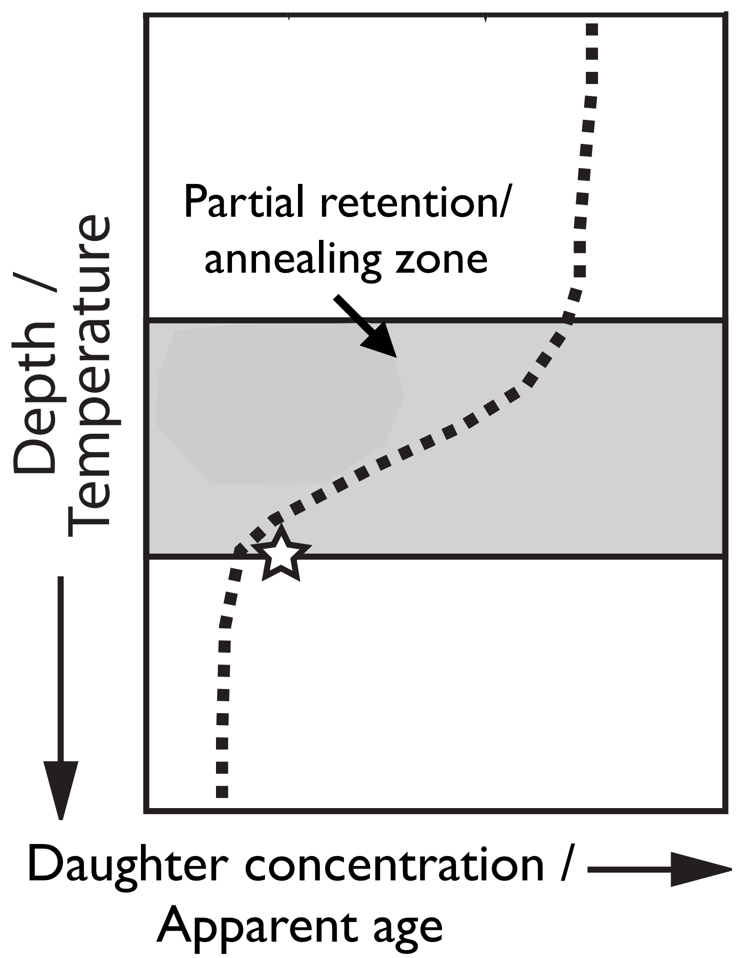
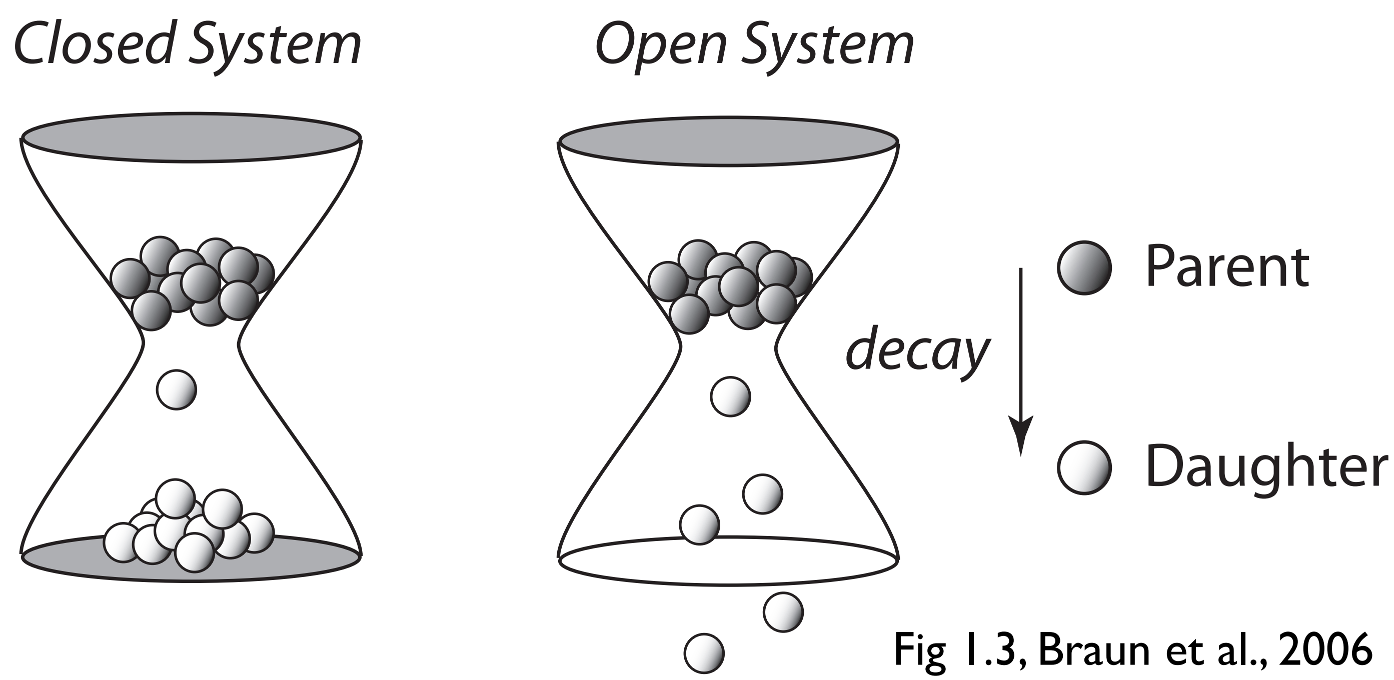


Fig 1.6a, Braun et al., 2006

- 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



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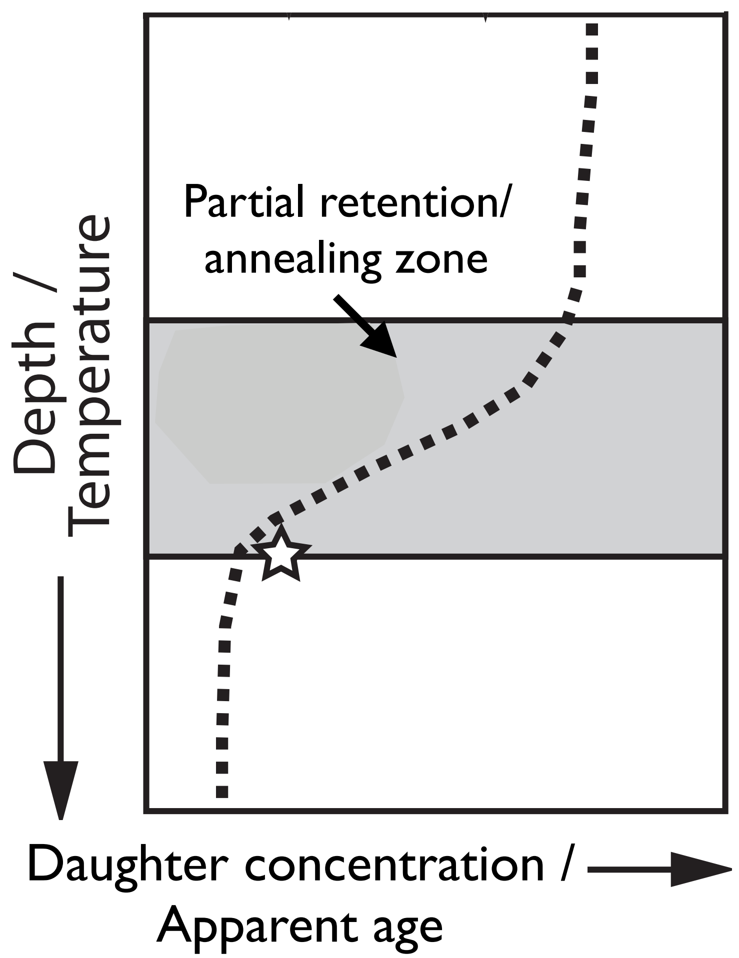

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- The transition from an open to a closed system <u>does not occur instantaneously at a given temperature</u>, but rather over a temperature range known as the **partial retention** (or **partial annealing**) **zone**

- 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

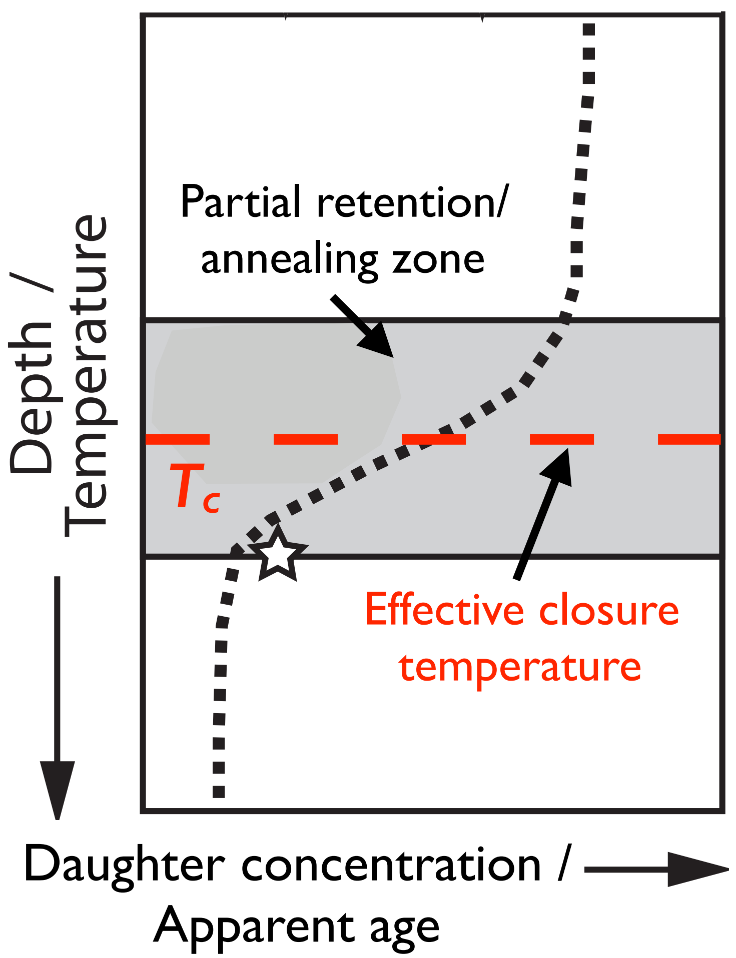
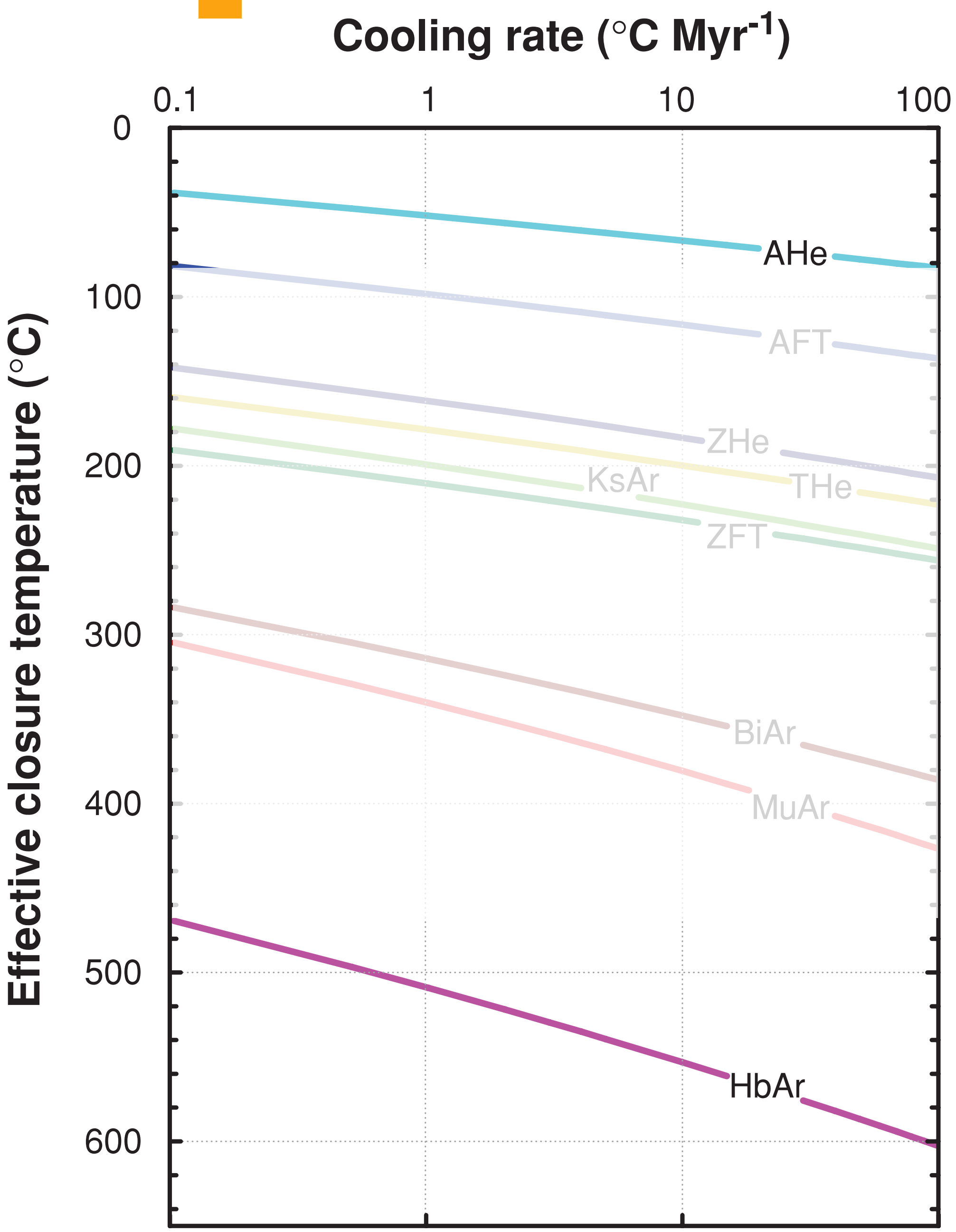


Fig 1.6a, Braun et al., 2006

- Defined by Dodson (1973), the **closure temperature** is the '<u>temperature of a thermochronological system at the time corresponding to its apparent age</u>'
- This concept is quite useful, as we can thus <u>relate a measured age to a temperature</u> 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 <u>cooling is monotonic</u> (no reheating)

Influence of cooling rate on effective T_c



Reiners and Brandon, 2006

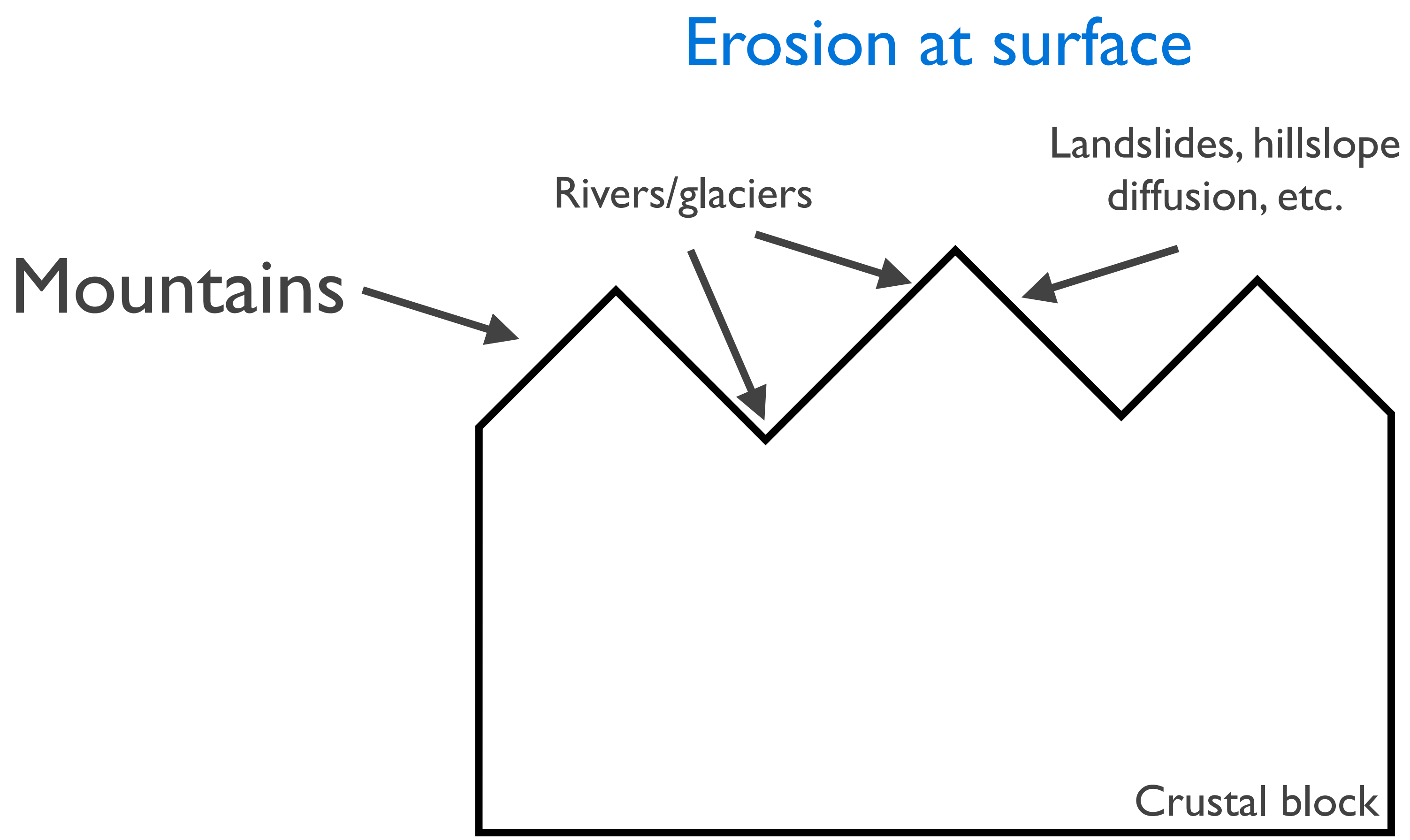
- In general, <u>the effective closure temperature for a given thermochronometer system will increase with increasing cooling rate</u>
    - For the retention of ^{4}He in apatite, the effective closure temperature is ~40°C at a cooling rate of 0.1 °C/Ma and ~80°C at a rate of 100°C/Ma
- The absolute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

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

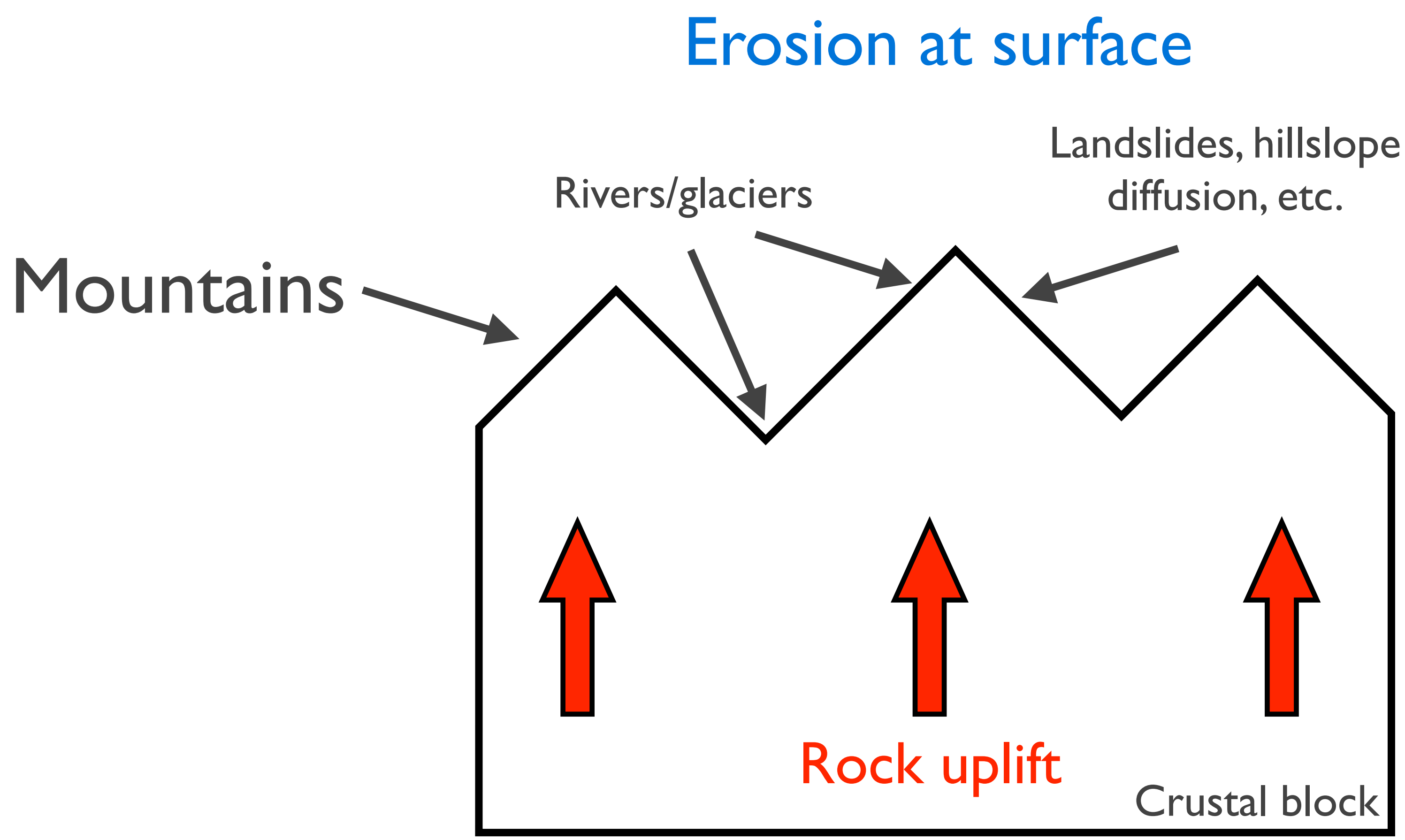
- But, what causes cooling?

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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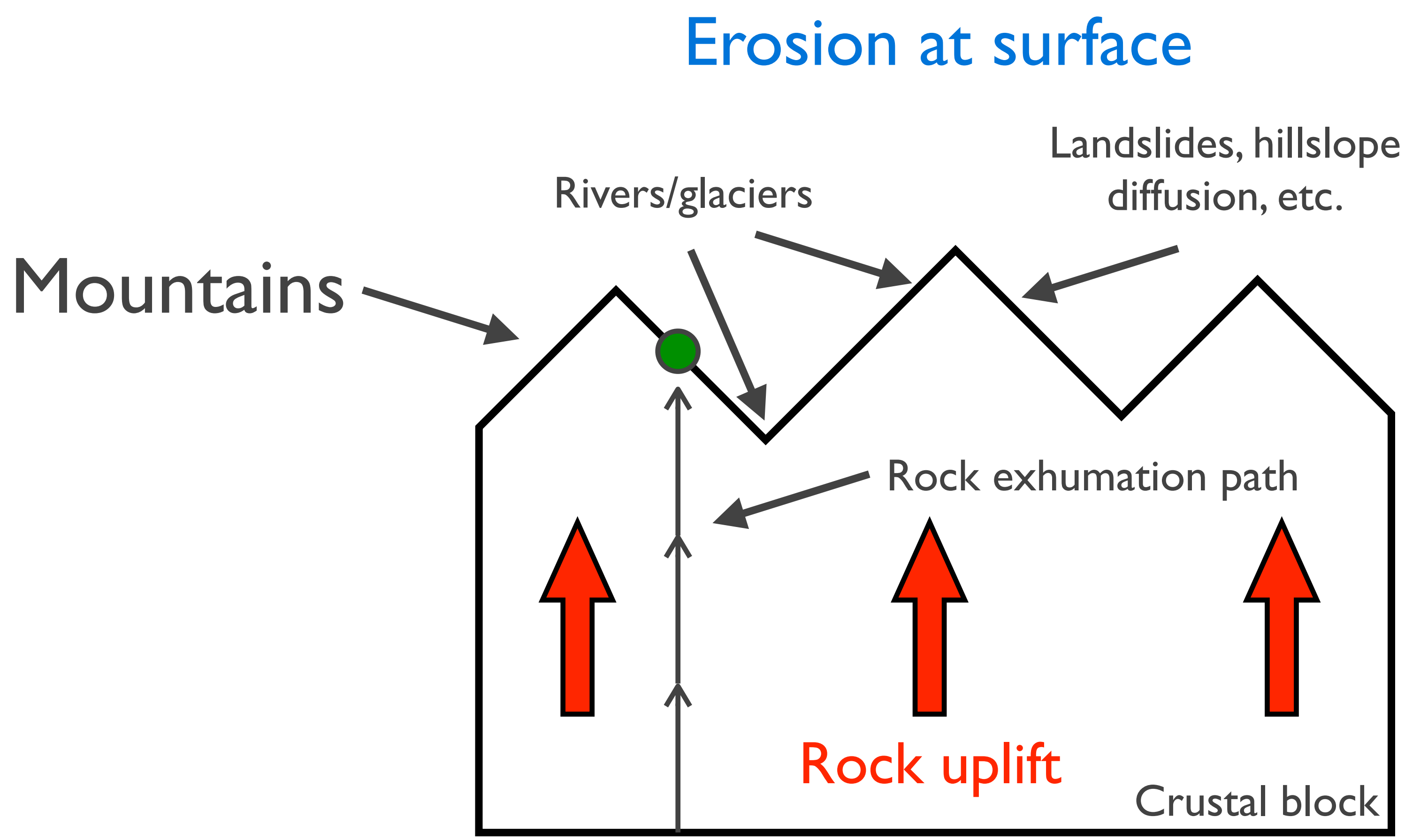

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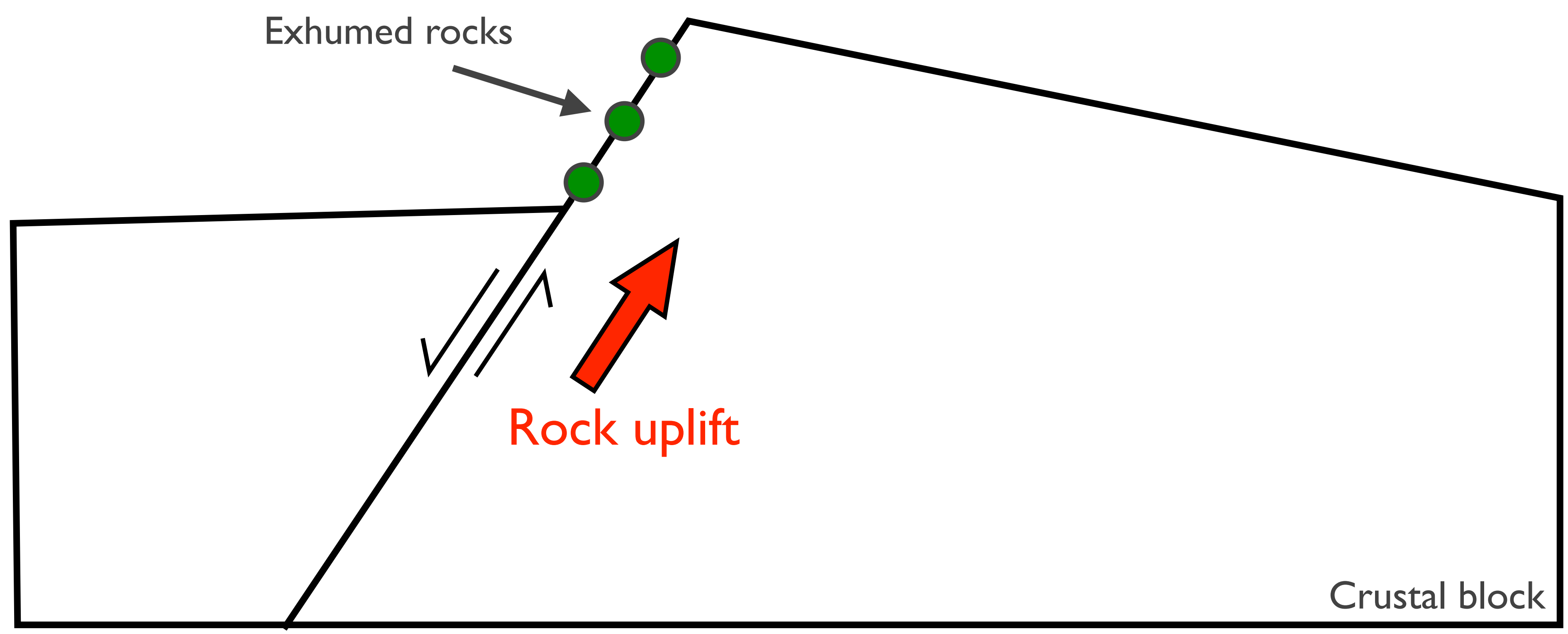
Tectonic exhumation



- 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

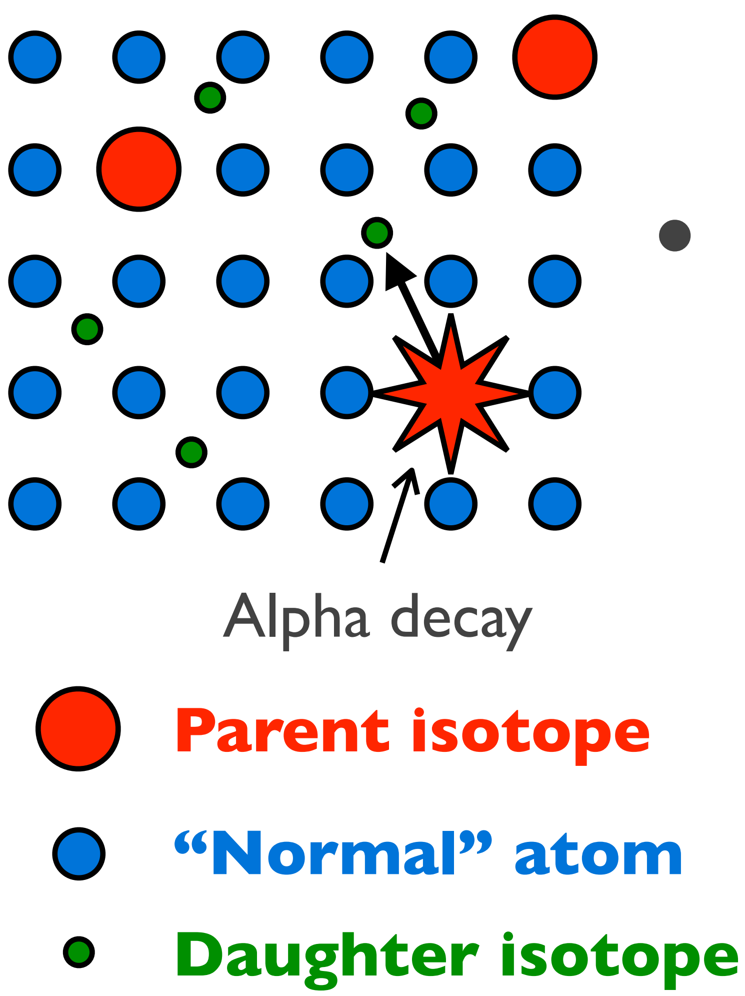
$$t = \frac{1}{\lambda} \ln \left(1 + \frac{N_\mathrm{d}}{N_\mathrm{p}} \right)$$

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 concentration of the daughter product will vary not only as a result of radioactive decay, but also due loss via solid-state diffusion

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

Temperature-dependent diffusion

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

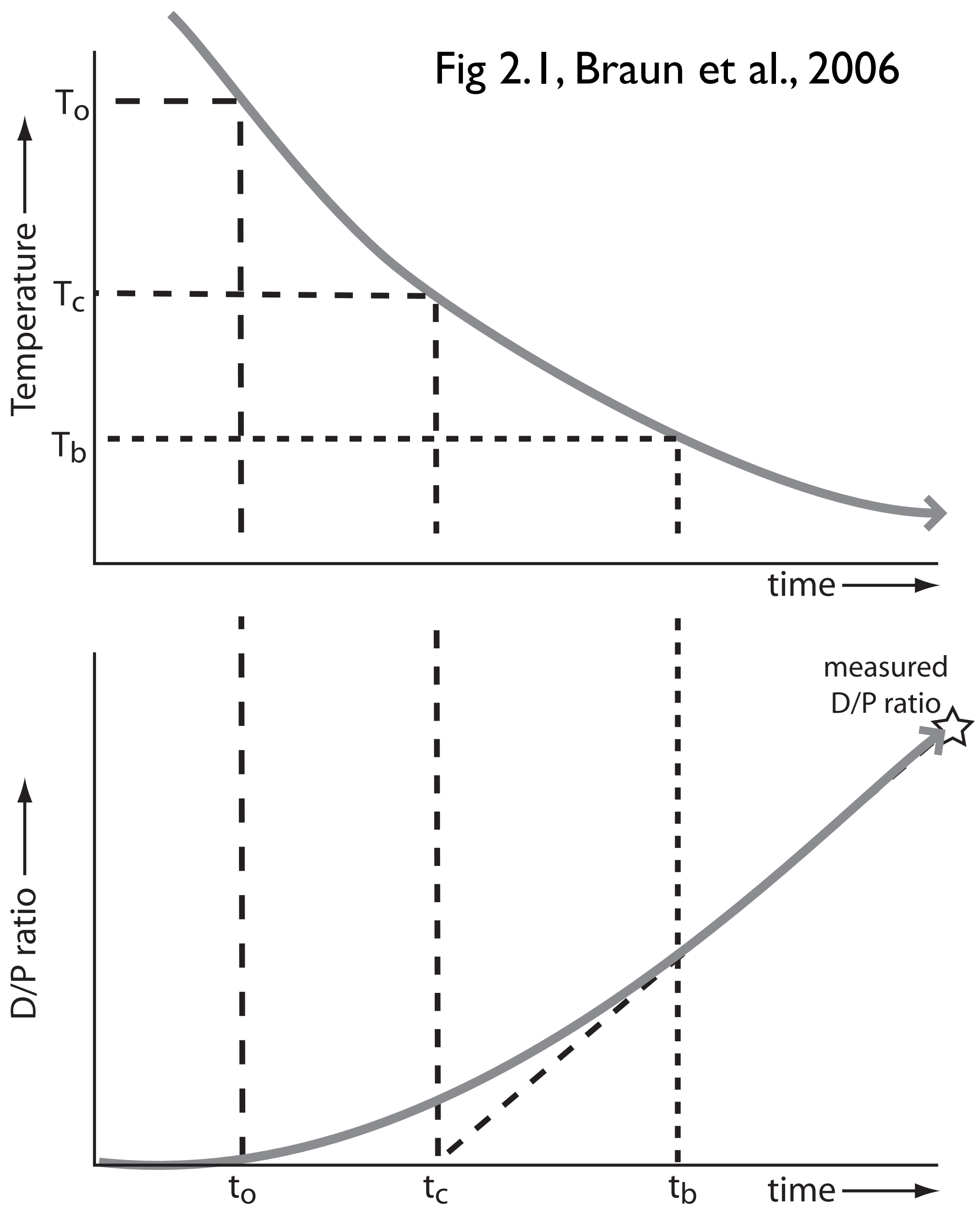
$$\frac{D(T)}{a^2} = \frac{D_0}{a^2} e^{-E_\mathrm{a}/(RT_\mathrm{K})}$$

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 <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 calculating the closure temperature of a thermochronological system 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 temperature will vary as the inverse of time ($T \propto 1/t$), it is possible to find an approximate solution to the temperature-dependent diffusion equation with a diffusivity

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

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

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

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

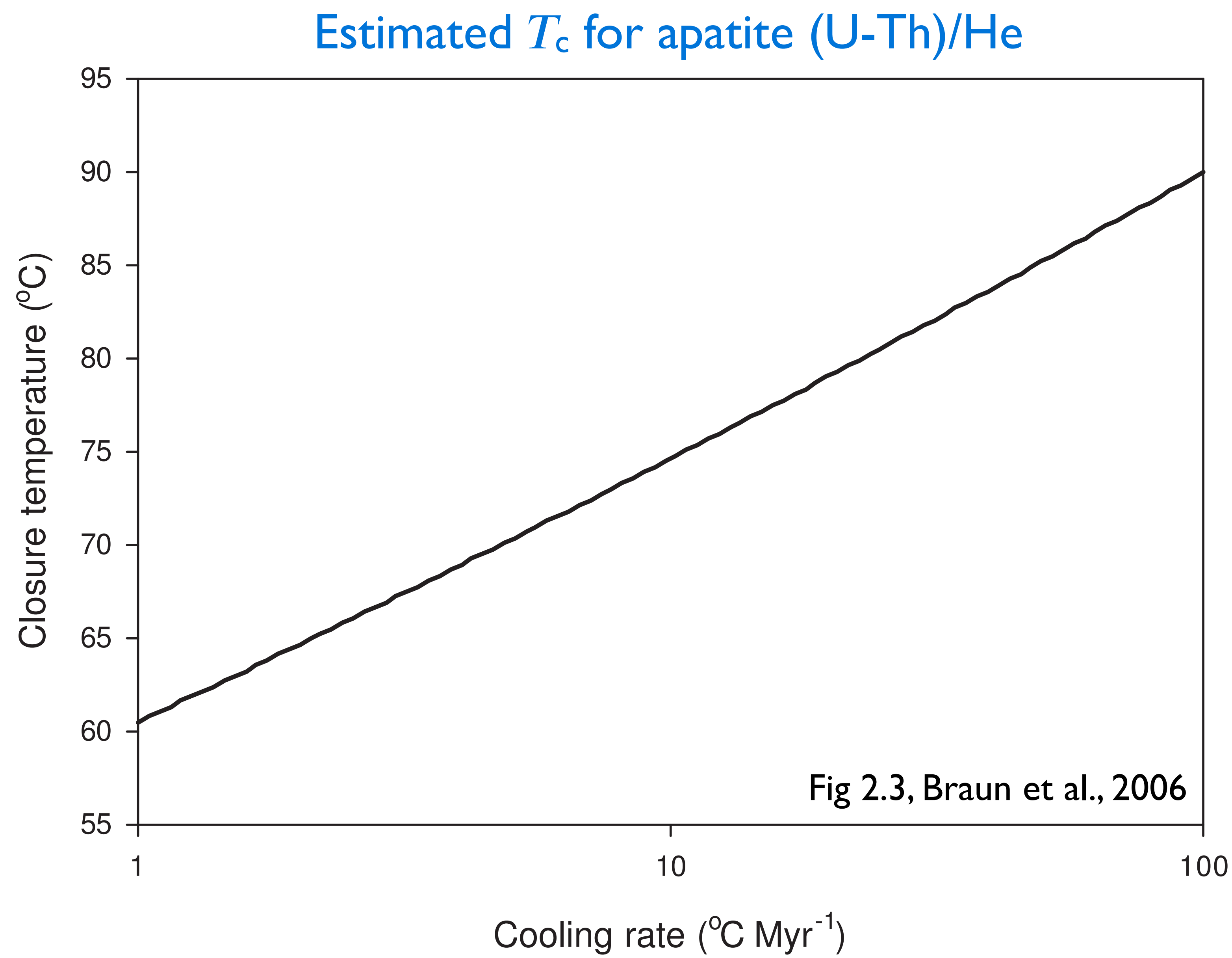
  where A is a geometry factor (25 for a sphere, 27 for a cylinder and 8.7 for a plane sheet)

- We can find the closure temperature as a function of cooling rate by <u>assuming T=T_c in the equation for τ and iterating</u>

Pseudo-code for solving Dodson's equation

- Define constants
- Define initial "guess" for value of τ
- Loop over some range to iterate on values of τ and T_c
    - Calculate new T_c with current value of τ
    - Calculate new value of τ for new T_c 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



- The effective closure temperature T_c <u>increases significantly at higher cooling rates</u>

From age to process

- Using **Dodson's equations**, we're able to calculate closure temperatures as a function of cooling rate
  - This does not provide any information about the depth of the closure temperature in the Earth

- There are several possibilities for determining the depth (or position) of T_c, such as assuming a constant geothermal gradient
  - As quantitative geologists, we can do better…

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.