



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 6.1

Basic concepts of thermochronology

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3.12.18



Goals of this lecture

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



Why thermochronology?

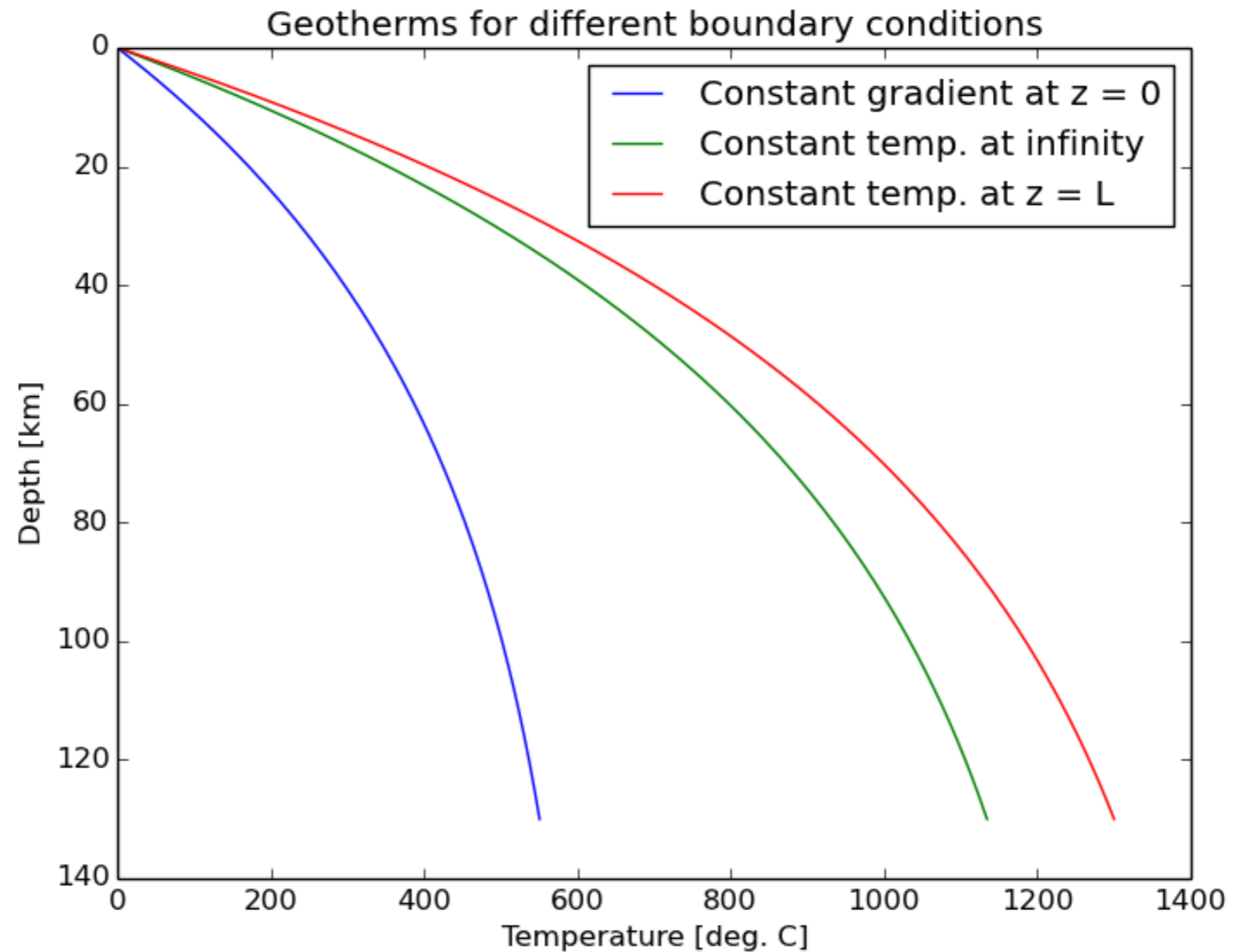


- Popular dating technique for studying **long-term tectonic and erosional processes** (i.e., stuff we've been learning)

Spanish Pyrenees



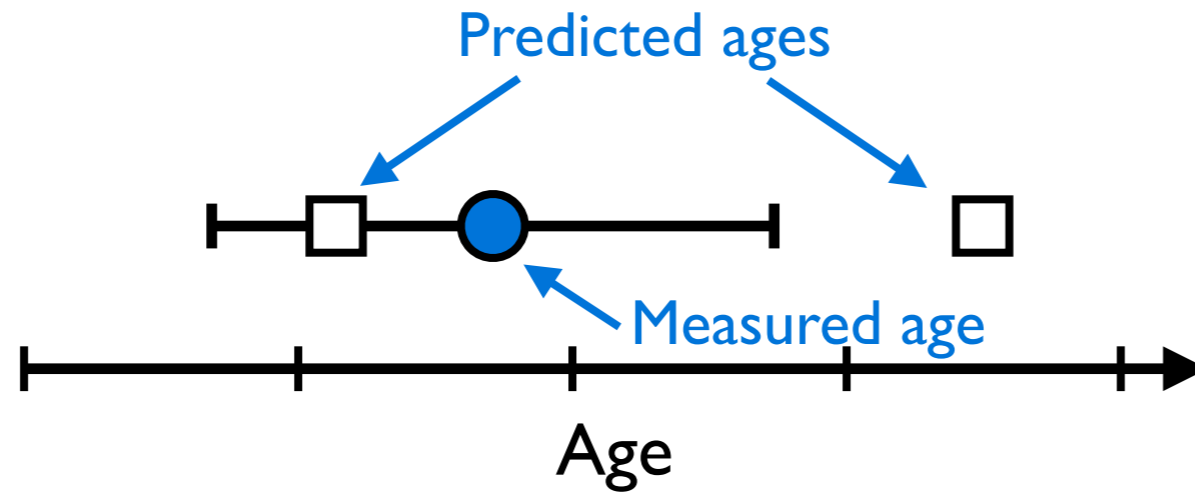
Why thermochronology?



- 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)



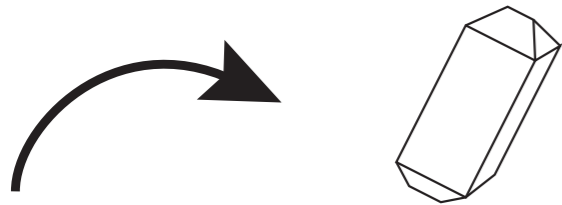
Geochronology versus thermochronology

- **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)

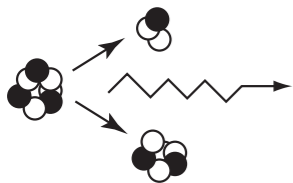


General thermochronology terms

Solid-State Diffusion



Spontaneous Nuclear Reaction

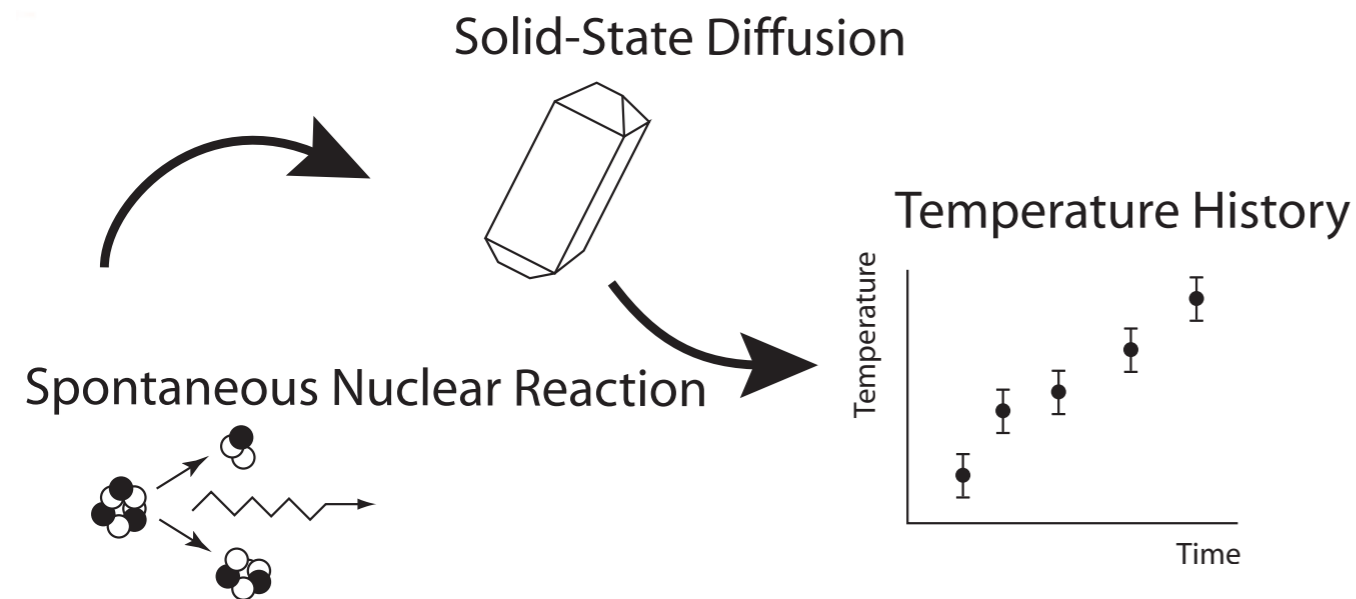


- **Thermochronometer**
A radioisotopic system consisting of:
 - a radioactive parent
 - a radiogenic daughter isotope or crystallographic feature
 - the mineral in which they are found

Fig 1.1, Braun et al., 2006



General thermochronology terms

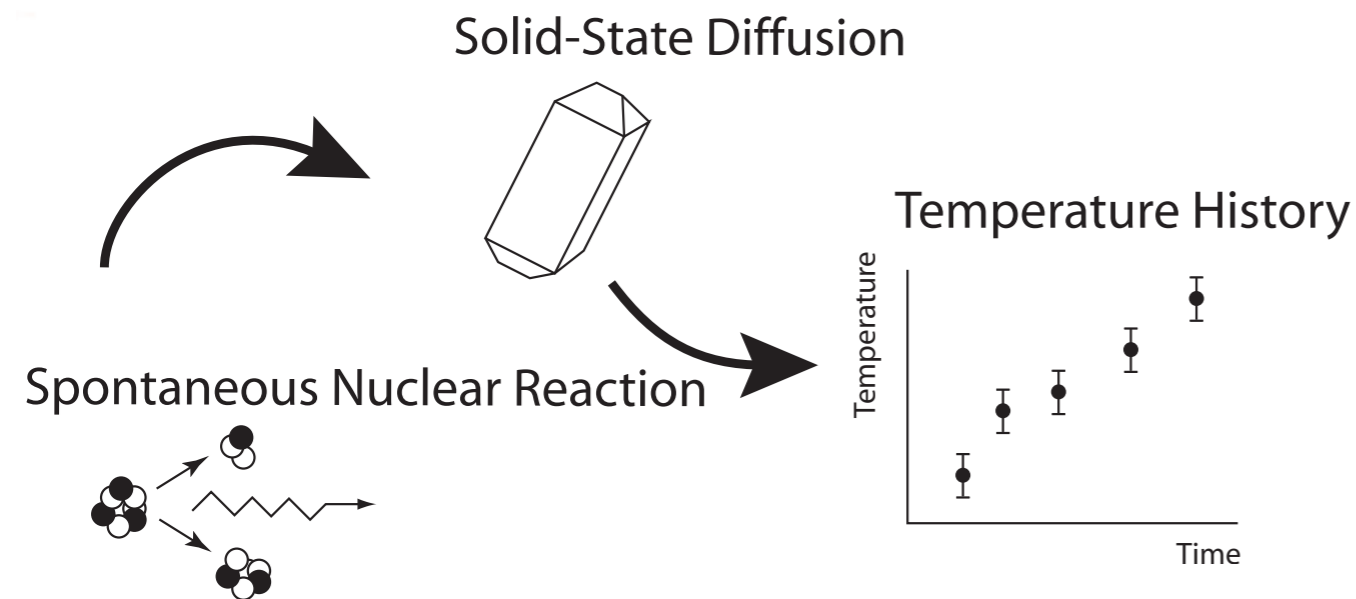


- **Thermochronometry**
The analysis, practice, or application of a thermochronometer to understand thermal histories of rocks or minerals

Fig 1.1, Braun et al., 2006



General thermochronology terms



- **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

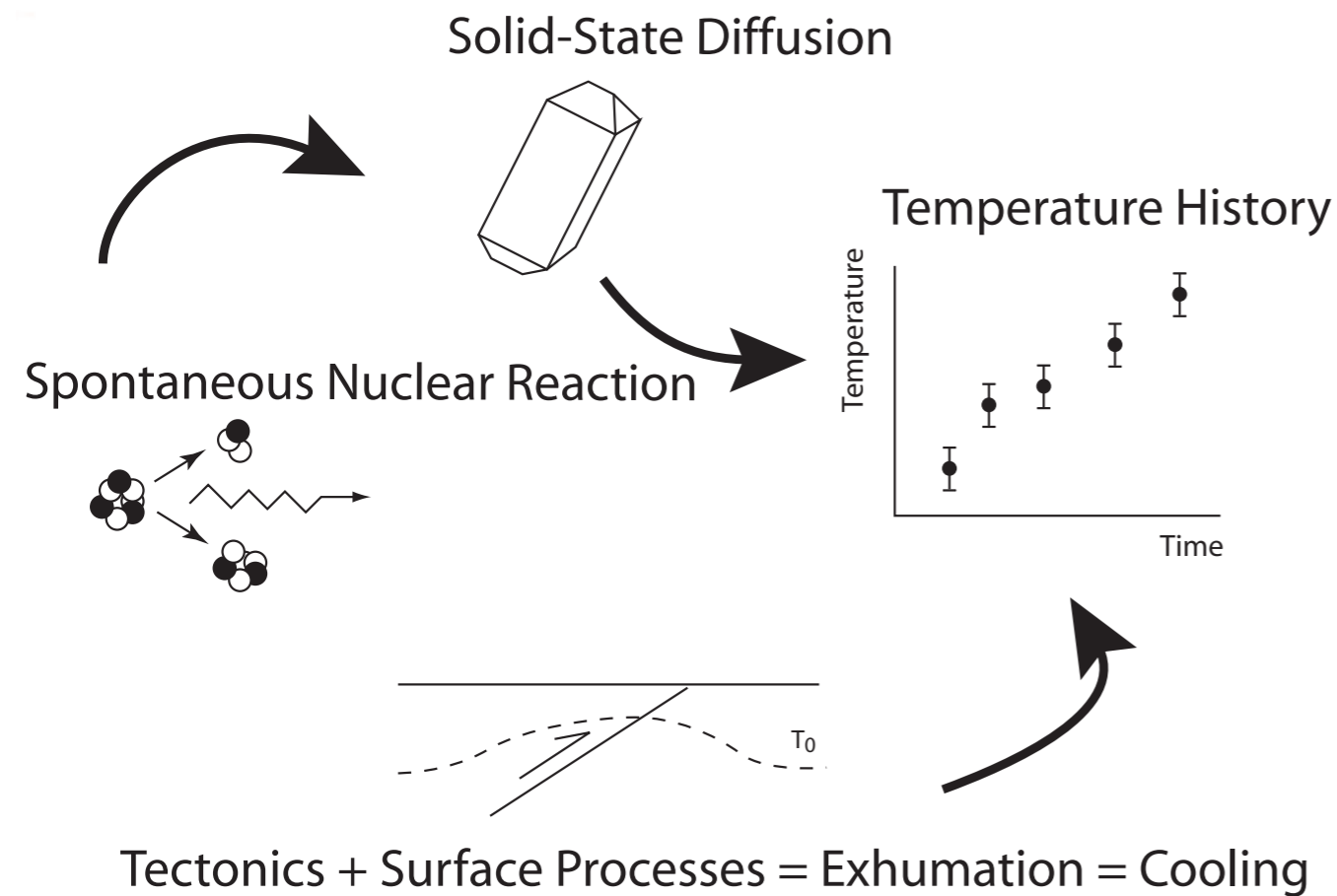


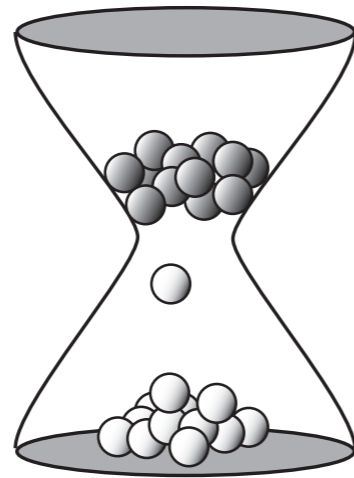
Fig 1.1, Braun et al., 2006

- 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

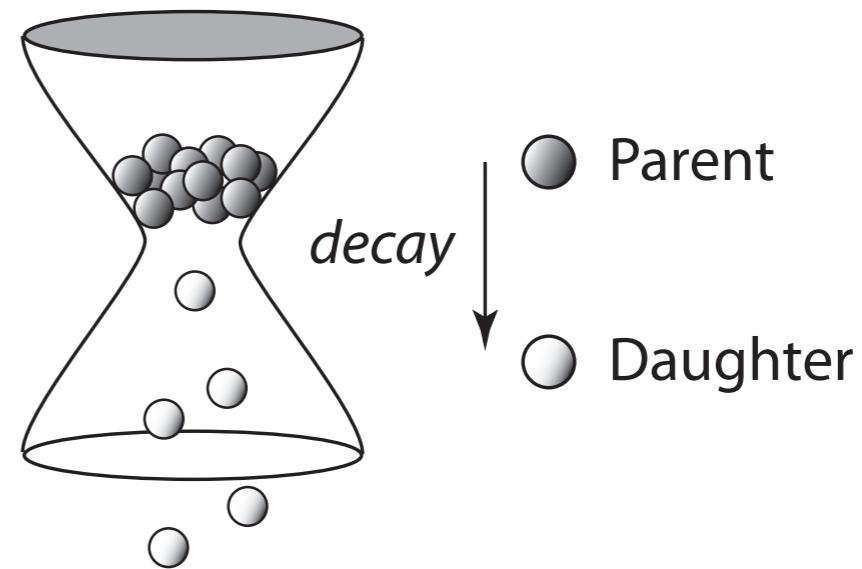


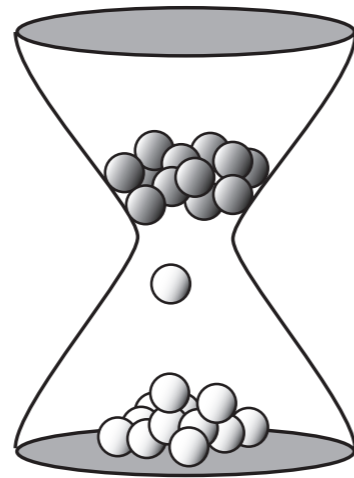
Fig 1.3, Braun et al., 2006

- **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



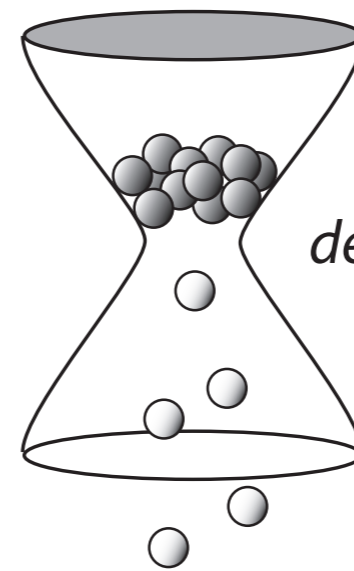
The essence of thermochronology

Closed System



Low T

Open System



High T

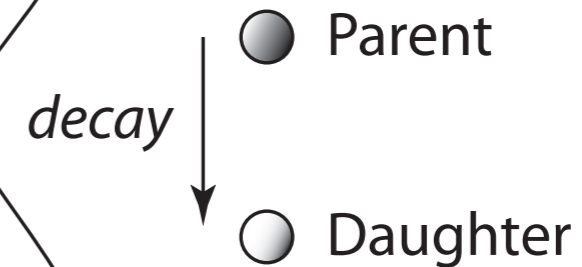


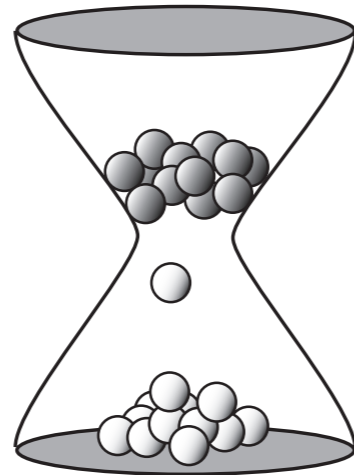
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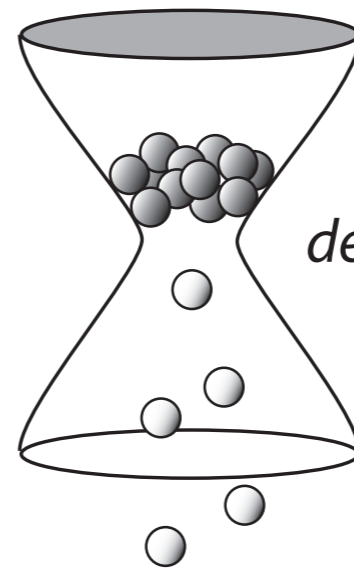


The concept of a closure temperature

Closed System



Open System



● Parent
○ Daughter

Fig 1.3, Braun et al., 2006

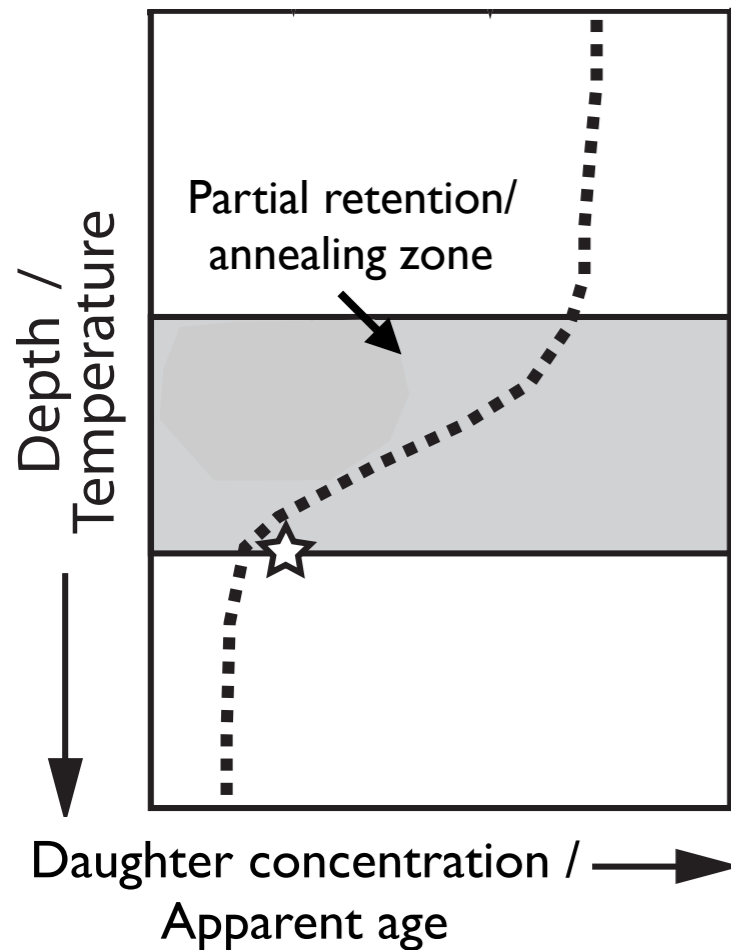


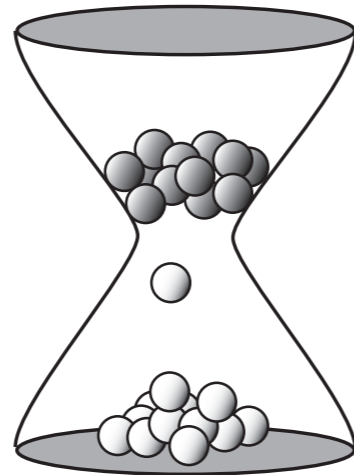
Fig 1.6a, Braun et al., 2006

- 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**

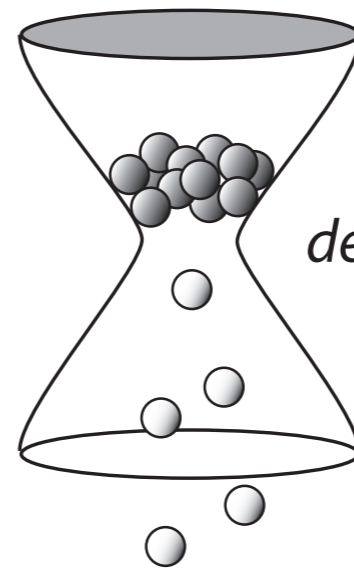


The concept of a closure temperature

Closed System



Open System



● Parent
○ Daughter

Fig 1.3, Braun et al., 2006

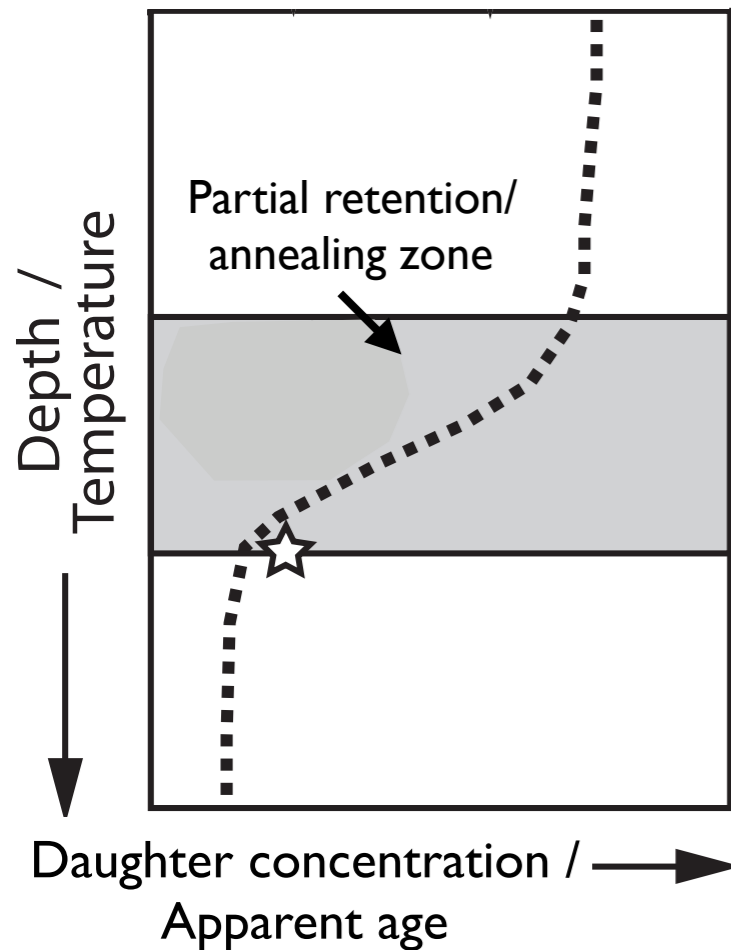


Fig 1.6a, Braun et al., 2006

- 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



Effective closure temperature, defined

- 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)

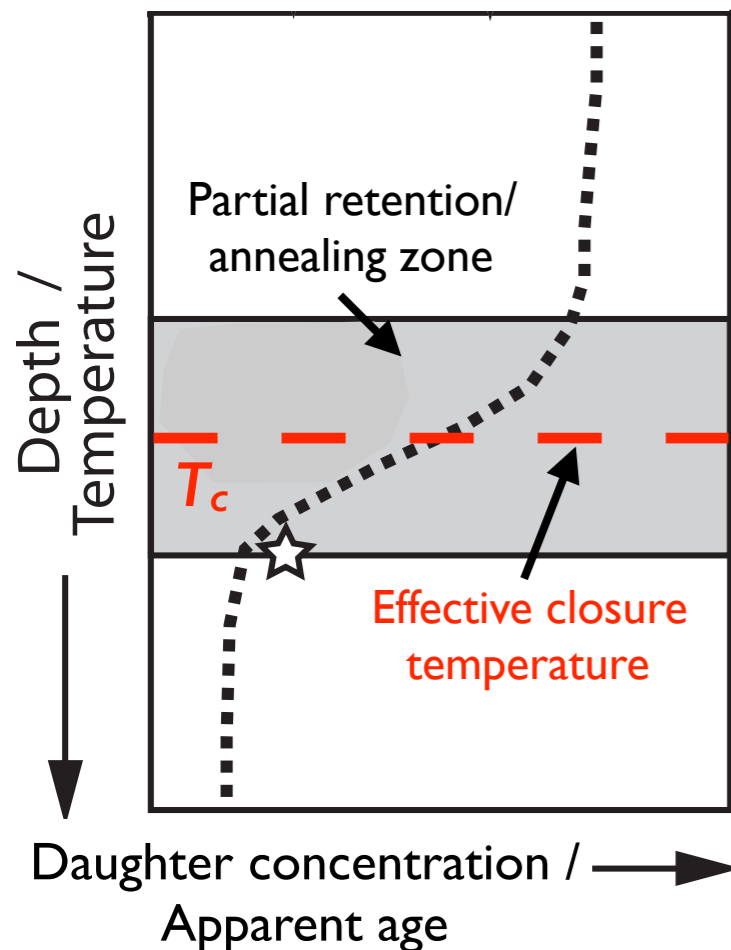
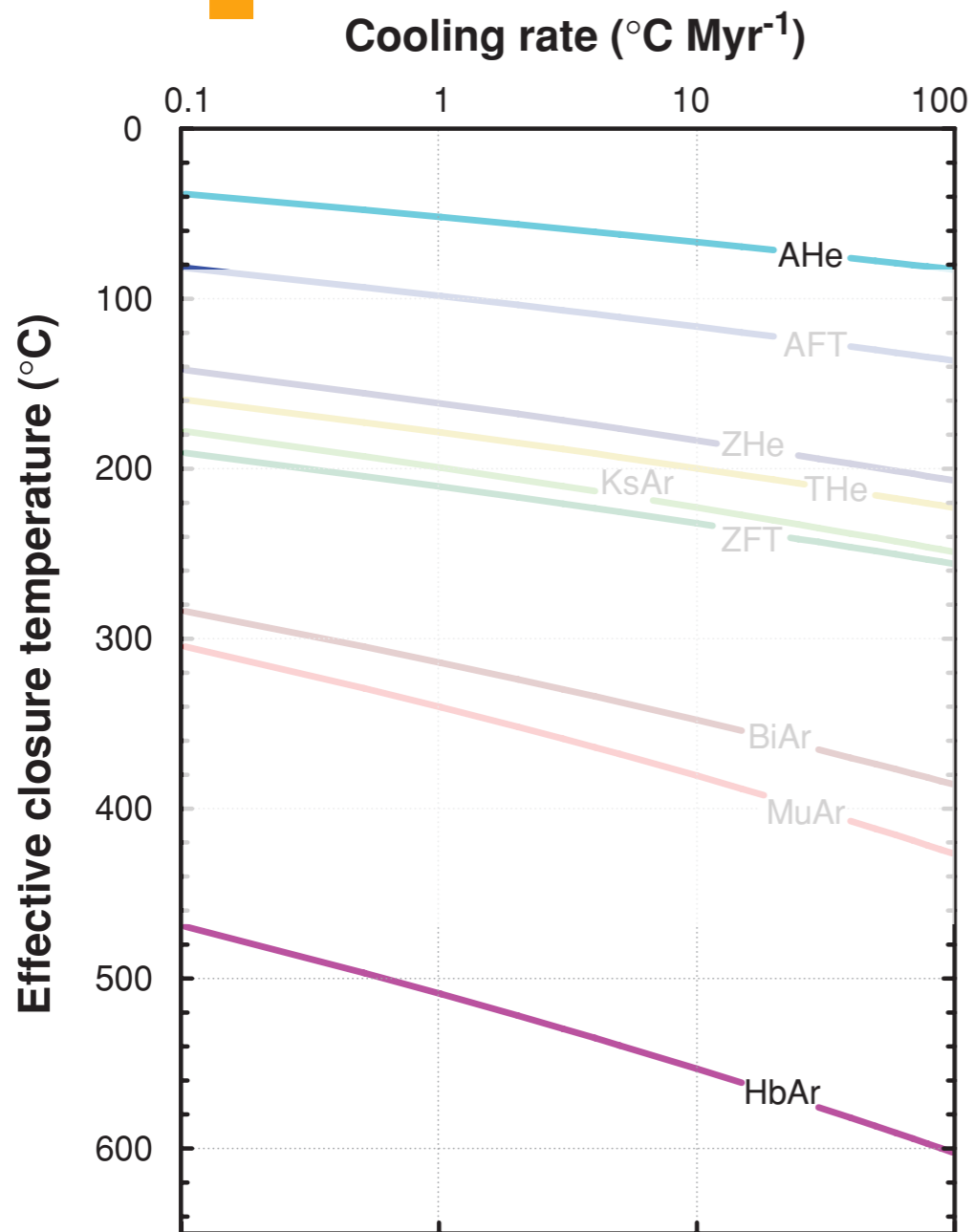


Fig 1.6a, Braun et al., 2006

Influence of cooling rate on effective T_c



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 ⁴He 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 ⁴He in apatite
- ~130°C for ⁴⁰Ar in hornblende

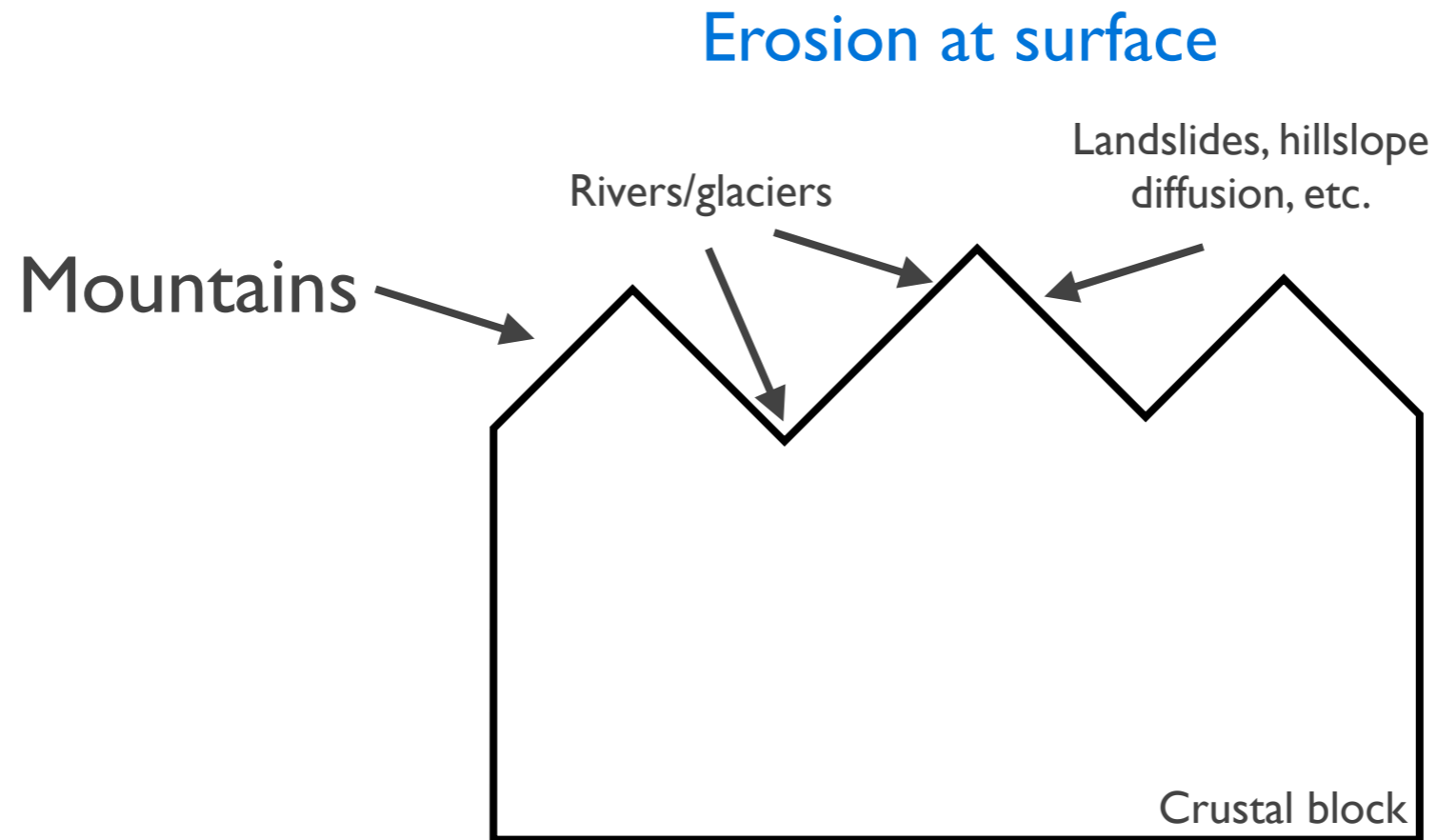


What causes cooling?

- 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?



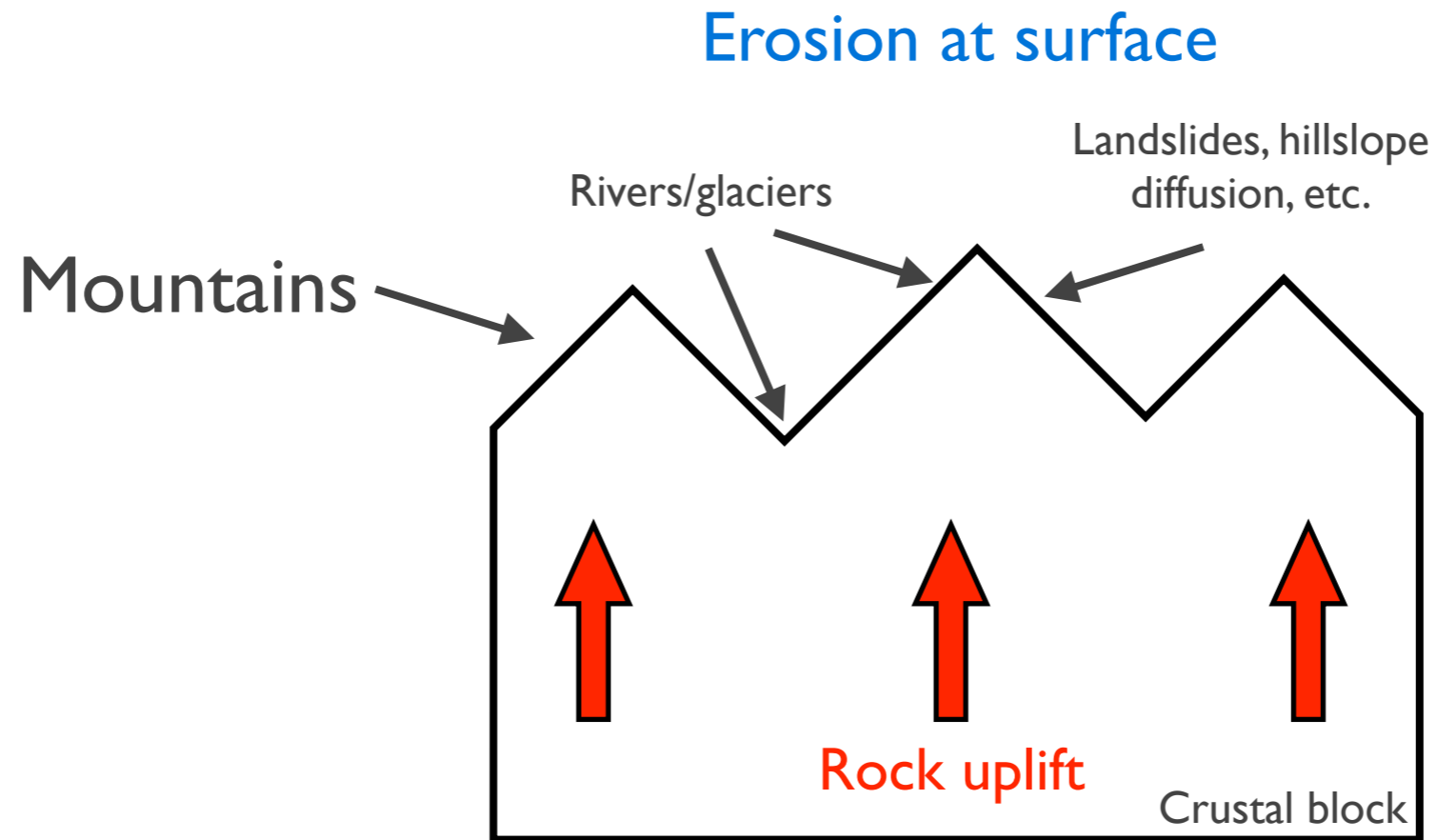
Erosional exhumation



- 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



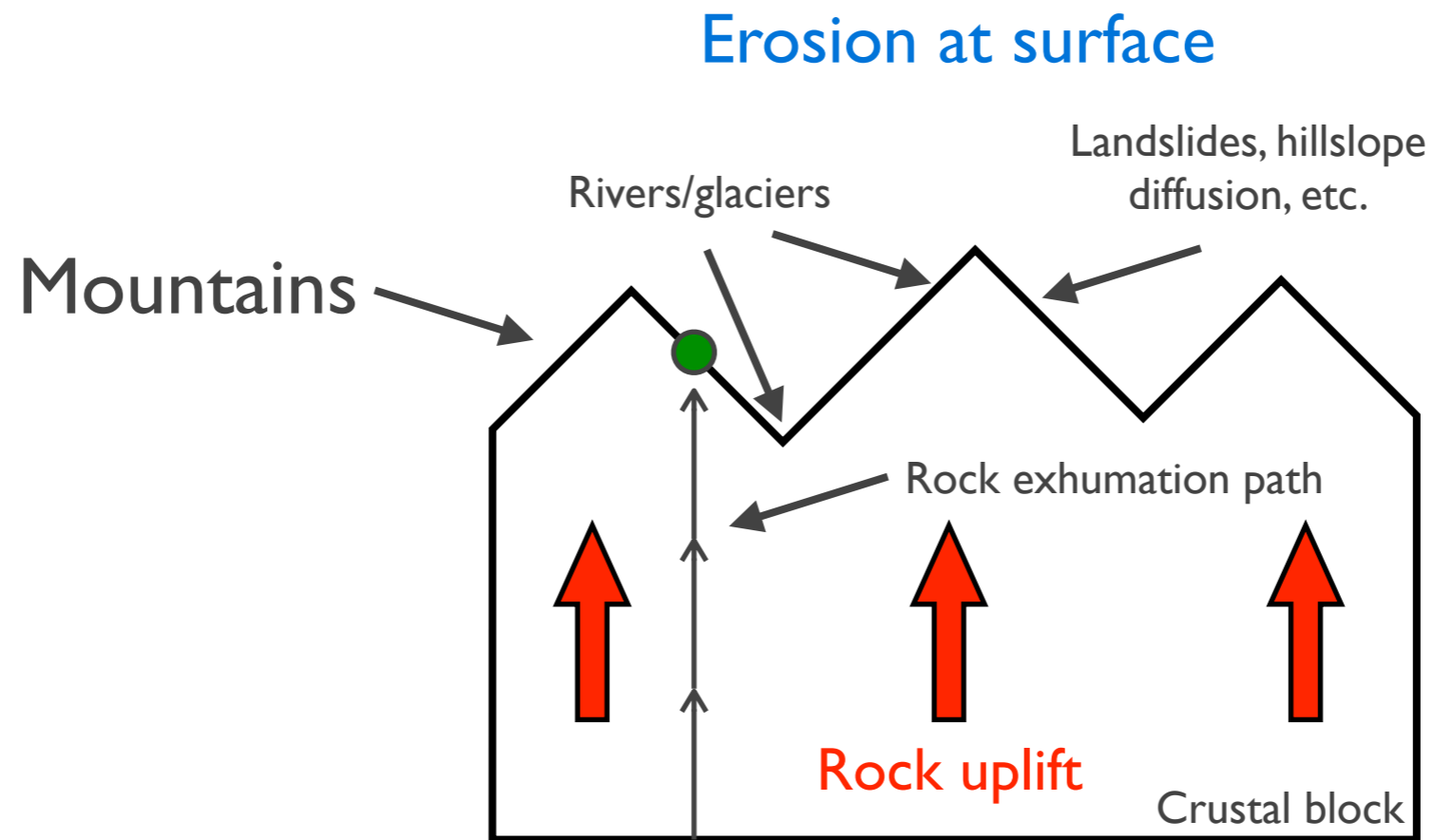
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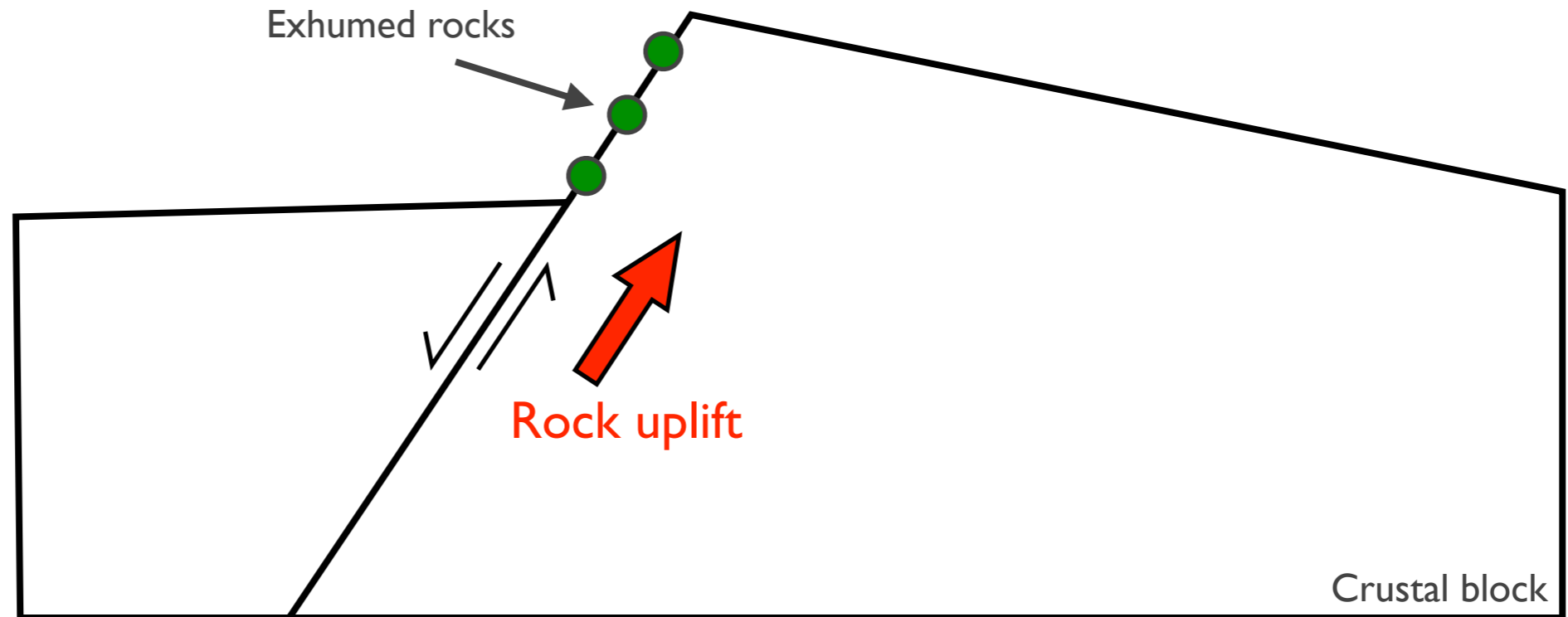
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Tectonic exhumation



- 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

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

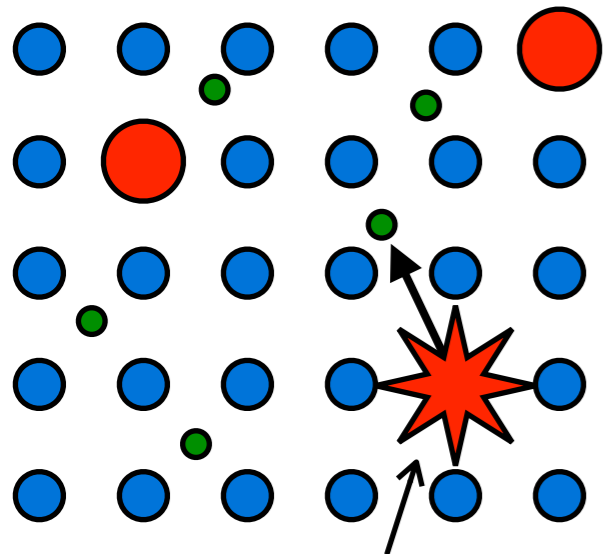
where t is the isotopic age, λ is the radioactive decay constant, N_d is the concentration of the daughter product and N_p is the concentration of the parent isotope

- For thermochronometers, we know that the 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



Alpha decay

- **Parent isotope**
- **“Normal” atom**
- **Daughter isotope**

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

$$\frac{\partial N_d}{\partial t} = D(T) \frac{\partial^2 N_d}{\partial x^2} + P \quad \mathbf{I-D}$$

where $D(T)$ is the temperature dependent diffusivity (see next slide), $\partial^2 N_d / \partial x^2$ 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

$$\frac{D(T)}{a^2} = \frac{D_0}{a^2} e^{-E_a/(RT_K)}$$

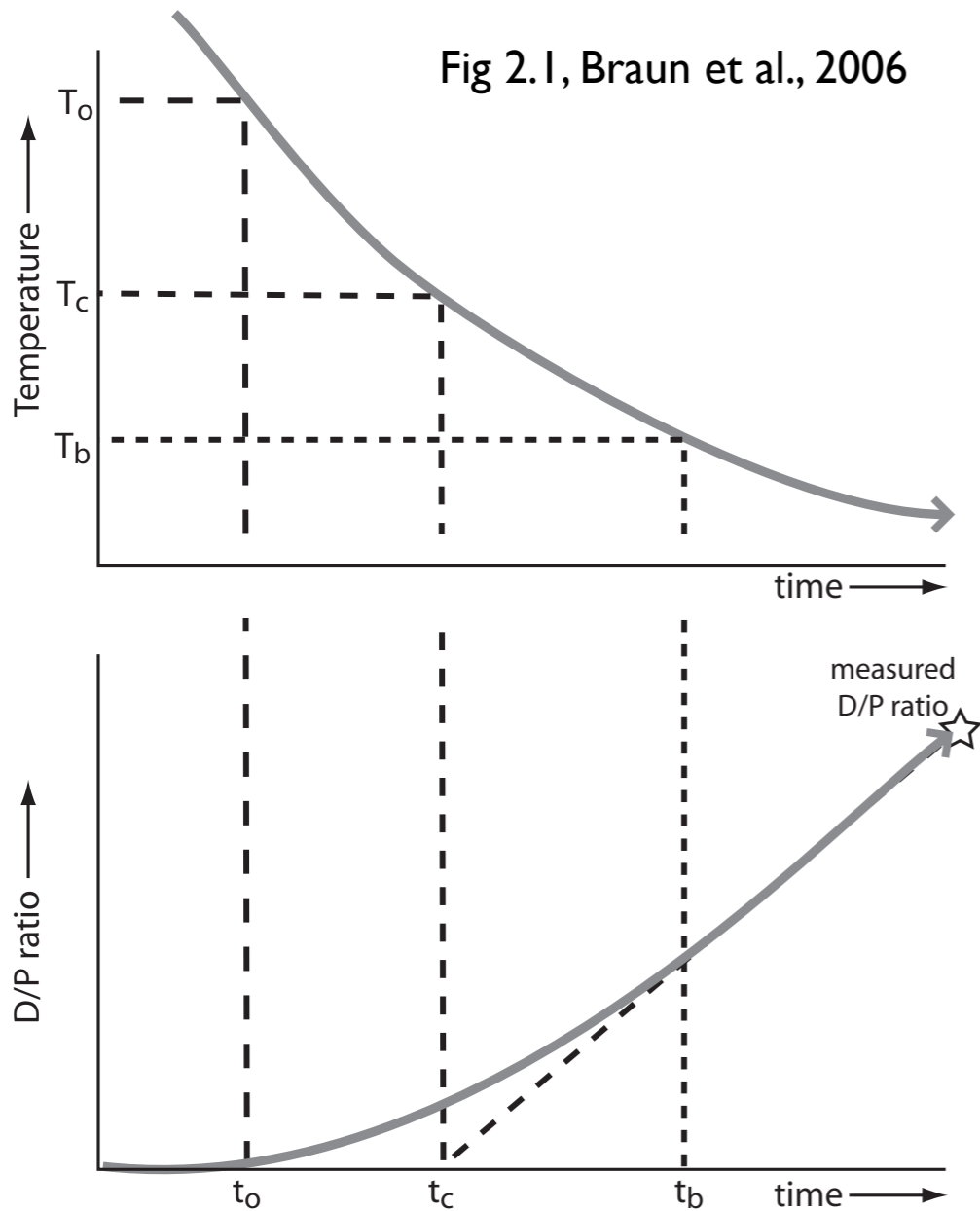
where D_0 is the diffusivity at infinite temperature (diffusion constant), a is the diffusion domain, E_a is the activation energy, R is the gas constant and T_K is temperature in Kelvins

- 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 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
- 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**

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

where τ 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

$$\tau = -\frac{RT^2}{E_a \dot{T}}$$

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

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

$$T_c = \frac{E_a}{R \ln(A\tau D_0/a^2)}$$

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 assuming $T=T_c$ in the equation for τ and iterating



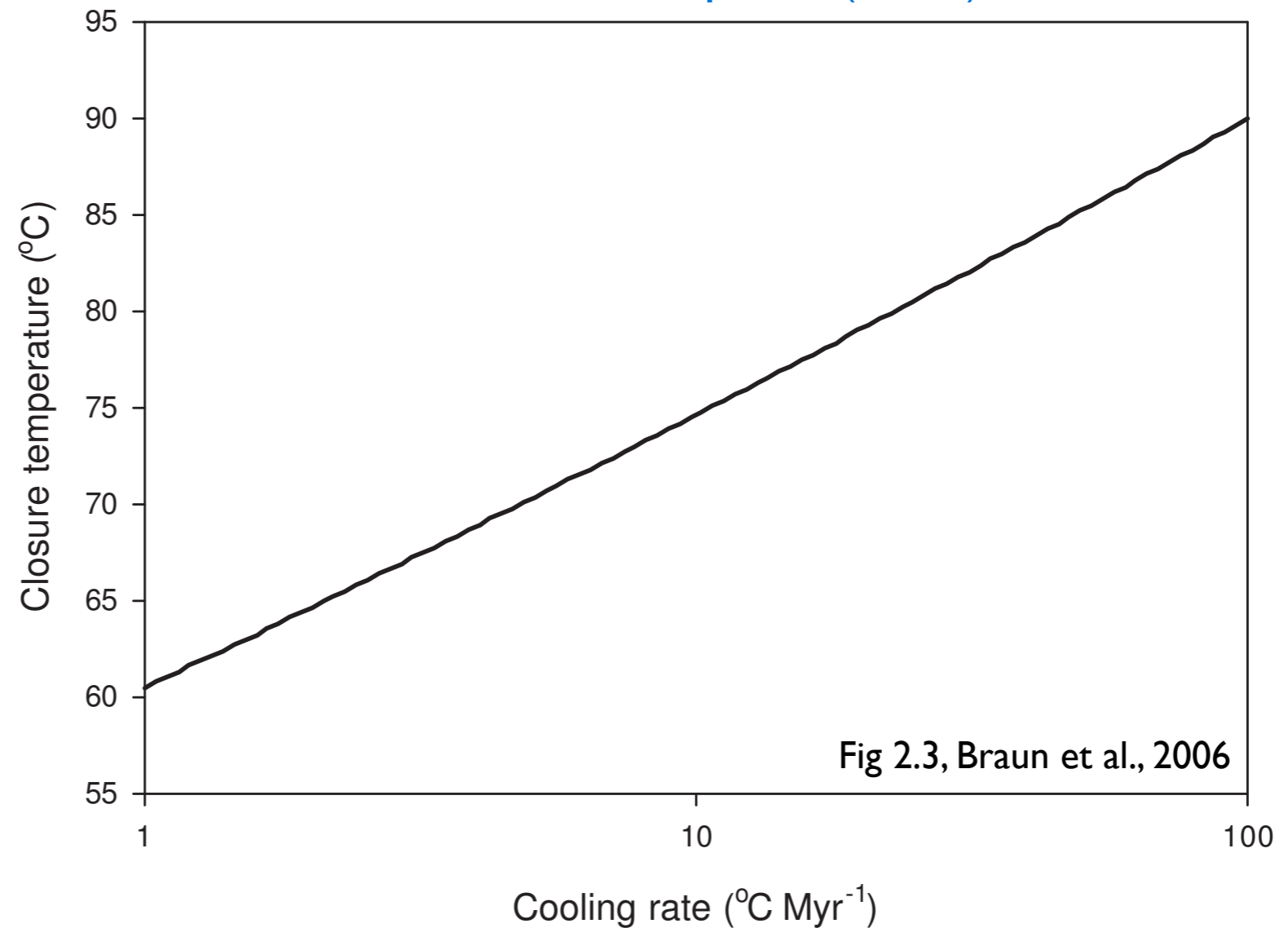
Pseudo-code for solving Dodson's equation

- 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

Estimated T_c for apatite (U-Th)/He



- The effective closure temperature T_c increases significantly at higher cooling rates



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.