Introduction to Quantitative Geology
Lesson 13.1
Basic concepts of thermochronology

Lecturer: David Whipp
david.whipp@helsinki.fi

4.12.17
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)
Why thermochronology?

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

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

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

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
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

- 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

- 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.

Fig 1.1, Braun et al., 2006
The essence of thermochronology

- **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.

Fig 1.3, Braun et al., 2006
The essence of thermochronology

- **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 concept of a closure temperature

- 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 1.3, Braun et al., 2006

Fig 1.6a, Braun et al., 2006
The concept of a closure temperature

- 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)
Influence of cooling rate on effective $T_c$

- 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 $\sim 40^\circ$C at a cooling rate of 0.1 °C/Ma and $\sim 80^\circ$C at a rate of 100°C/Ma.

- The absolute difference in effective closure temperature is also larger for higher temperature thermochronometers.
  - $\sim 40^\circ$C for $^4$He in apatite
  - $\sim 130^\circ$C for $^{40}$Ar in hornblende

Reiners and Brandon, 2006

---

**Figure 2** - Effective closure temperature ($T_c$) as a function of cooling rate for common He, FT, and Ar thermochronometers. Estimates shown here are based on Equation 7 and parameters in Tables 1–2. Results were calculated using the CLOSURE program.

Such cases, the closure temperature concept does not strictly apply, and this could potentially confound attempts to relate thermal and exhumational histories. This underscores the need to consider the conditions of a mineral's formation, as well as its cooling path, in interpreting thermochronologic histories.
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

- 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

- 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
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, \( \lambda \) 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

- 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

\[
\frac{\partial N_d}{\partial t} = D(T) \frac{\partial^2 N_d}{\partial x^2} + P
\]

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

- 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 ($\frac{1}{t}$), 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 $\tau$ 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 $\tau$ 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 $\tau$ and iterating
Pseudo-code for solving Dodson’s equation

- Define constants
- Define initial “guess” for value of $\tau$
- Loop over some range to iterate on values of $\tau$ and $T_c$
  - Calculate new $T_c$ with current value of $\tau$
  - Calculate new value of $\tau$ 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 $T_c$ increases significantly at higher cooling rates

Estimated $T_c$ for apatite (U-Th)/He

Fig 2.3, Braun et al., 2006
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
