Introduction to Quantitative Geology
Lecture 12
Low-temperature thermochronology

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Goals of this lecture

• Define low-temperature thermochronology

• Introduce three common types of low-temperature thermochronometers
  • Helium dating (The (U-Th)/He method)
  • Fission-track dating (The FT method)
  • Argon dating (The $^{40}$Ar/$^{39}$Ar method)
What is low-temperature thermochronology?

- **Low-T thermochronology** uses thermochronometers with effective closure temperatures **below ~300°C**
What is low-temperature thermochronology?

- **Low-T thermochronology** uses thermochronometers with effective closure temperatures below ~300°C
Why is thermochronology useful?

- Thermochronometer ages provide a constraint on the **time-temperature history** of a rock sample.
- In many cases, the age is the time since the sample cooled below the system-specific effective closure temperature.
Why is thermochronology useful?

- Because the temperatures to which thermochronometers are sensitive generally occur at depths of 1 to >15 km and ages are typically 1 to 100’s of Ma, they record long-term cooling through the upper part of the crust and can be used to calculate long-term average rates of tectonics and erosion.
Why is low-\(T\) thermochronology useful?

- **Low-temperature thermochronometers** are unique because of their increased sensitivity to topography, erosional and tectonic processes.
High temperature = no topography sensitivity

(a) High $T_c$ thermochronometers

- For thermochronometers with a high effective closure temperature, the closure temperature isotherm will not be influenced by surface topography.
- Note that age will increase with elevation as a result of the topography.

Braun, 2002
Low-temperature = sensitive to topography

- The effective closure temperature isotherm for low-temperature thermochronometers will generally be “bent” by the surface topography, changing the age-elevation trend

- The lower the value of $T_c$, the more its geometry will resemble the surface topography
Sensitivity to changing topography

- Because $T_c$ is sensitive to topography for low-temperature thermochronometers, it is possible to record changes in topography in the past (!)

- Here, topographic relief decreases and the age-elevation trend gets inverted (older at low elevation)
Common thermochronometers

**Ar-based systems**
- Hornblende (500±50°C)
- Muscovite (350±50°C)
- Biotite (300±50°C)
- K-Feldspar (150-350°C)

**(U-Th)/He systems**
- Zircon (200-230°C)
- Titanite (150-200°C)
- Apatite (75±5°C)

**Fission-track systems**
- Titanite (265-310°C)
- Zircon (240±20°C)
- Apatite (110±10°C)
Helium dating - (U-Th)/He method

- **(U-Th)/He thermochronology** is based on the production and accumulation of $^4\text{He}$ from parent isotopes $^{238}\text{U}$, $^{235}\text{U}$, $^{232}\text{Th}$ and $^{147}\text{Sm}$

- $^4\text{He}$ ($\alpha$ particles) produced during decay chains
  - $^{238}\text{U}$ - 8 $\alpha$ decays
  - $^{235}\text{U}$ - 7 $\alpha$ decays
  - $^{232}\text{Th}$ - 6 $\alpha$ decays
  - $^{147}\text{Sm}$ - 1 $\alpha$ decay

Fig. 3.3, Braun et al., 2006
Helium dating - (U-Th)/He method

Production of alpha particles by decay

- Ignoring the contribution of $^{147}$Sm, we can say that the production of $^4$He is

$$^4\text{He} = 8 \times 238\text{U}(e^{\lambda_{238}t} - 1) + 7 \times \frac{238\text{U}}{137.88}(e^{\lambda_{235}t} - 1) + 6 \times 232\text{Th}(e^{\lambda_{232}t} - 1)$$

where $^4$He, $^{238}$U and $^{232}$Th are the present-day abundances of those isotopes, $t$ is the He age and the $\lambda$ values are the decay constants.
Helium dating - (U-Th)/He method

Ages are calculated by measuring the $^4$He concentration by heating and degassing the mineral sample, then separately measuring the U and Th concentrations, for example by using an inductively coupled plasma mass spectrometer (ICP-MS).

Nice, datable apatites

Not-so-nice apatites

Ehlers and Farley, 2003
Helium dating - (U-Th)/He method

- Selected mineral grains for dating should be high-quality, euhedral minerals free of mineral inclusions with a prismatic crystal form.
- Why does the crystal form matter? Alpha particles travel \(\sim 20 \mu m\) when created and may be ejected from or injected to the sample crystal.
- We can correct for this!

Fig. 3.4, Braun et al., 2006
Fission-track dating - FT method

- **Fission-track dating** is based on measuring the accumulation of damage trails in a host crystal as the result of spontaneous fission of $^{238}\text{U}$

- Fission splits the $^{238}\text{U}$ atom into two fragments that repel and damage the crystal lattice over the distance they travel

- In apatite, fresh fission tracks are $\sim 16 \, \mu\text{m}$ long and $\sim 11 \, \mu\text{m}$ long in zircon

- Similar to diffusive loss of $^4\text{He}$, these damage trails will be repaired, or anneal, at temperatures above $T_c$

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Etched fission tracks in apatite

(A) (B) (C)

Tagami and O'Sullivan, 2005
Fission-track dating - FT method

- To be visible under a microscope, tracks must be chemically etched and enlarged
- At this point, tracks can be manually (or automatically) counted to determine the track density
- The FT age can be calculated as
  \[ t = \frac{1}{\lambda_D} \ln \left( \frac{\lambda_D}{\lambda_f} \frac{N_s}{^{238}U} + 1 \right) \]
  where \( \lambda_D \) is the \(^{238}\text{U} \) decay constant, \( \lambda_f \) is the fission decay constant, \( N_s \) is the number of spontaneous fission tracks in the sample and \(^{238}\text{U} \) is the number of \(^{238}\text{U} \) atoms
Argon dating - $^{40}\text{Ar}/^{39}\text{Ar}$ method

- **Argon dating** is based on the decay of $^{40}\text{K}$ to radiogenic $^{40}\text{Ar}$
- Potassium is one of the most abundant elements in the crust, making argon dating one of the more common thermochronology methods
- $^{40}\text{Ar}/^{39}\text{Ar}$ dating is used on white micas, biotite, K-feldspar and amphiboles
Argon dating - $^{40}\text{Ar}/^{39}\text{Ar}$ method

- $^{40}\text{Ar}/^{39}\text{Ar}$ ages are found by irradiating a sample (and standard) with fast neutrons, producing $^{39}\text{Ar}$ from $^{39}\text{K}$ in the sample.

- The $^{40}\text{Ar}/^{39}\text{Ar}$ ratio is then measured as samples are either degassed entirely or step heated (next slide).

- The $^{40}\text{Ar}/^{39}\text{Ar}$ age can be calculated as

$$ t = \frac{1}{\lambda} \ln \left( 1 + J \frac{^{40}\text{Ar}}{^{39}\text{Ar}} \right) $$

where $\lambda$ is the decay constant of $^{40}\text{K}$, $^{40}\text{Ar}/^{39}\text{Ar}$ is the measured sample $^{40}\text{Ar}/^{39}\text{Ar}$ ratio and $J$ is the irradiation factor

$$ J = \frac{e^{\lambda t} - 1}{^{40}\text{Ar}/^{39}\text{Ar}} $$

where $t$ is a known age for a standard and $^{40}\text{Ar}/^{39}\text{Ar}$ is its measured $^{40}\text{Ar}/^{39}\text{Ar}$ ratio.
Argon dating - Step heating

- **Step heating** of $^{40}$Ar/$^{39}$Ar samples involves stepwise heating of samples to gradually release Ar as the sample temperature increases.

- With this, it is possible to see the $^{40}$Ar distribution in the sample, which is a function of the sample cooling history.

Harrison and Zeitler, 2005
Argon dating - Step heating

- As we have seen on the previous slide,
  (a) flat age spectra indicate rapid cooling of a rock sample (at time $t_1$, here)
  (b) spectra with lower concentrations initially either indicate partial reheating of the sample at time $t_2$ or slow cooling from $t_1$ to $t_2$
- In (c), there is an unexpected behavior with higher Ar concentrations initially (i.e., near the rim of the grain)
  - This “excess” Ar may have been taken up from surrounding minerals

Fig. 3.1, Braun et al., 2006
Common thermochronometers

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Recap

- **Low-temperature thermochronology** refers to the application of thermochronometers with effective closure temperatures below ~300°C.

- The most commonly applied low-T thermochronometers are
  - **Helium dating** (The (U-Th)/He method)
  - **Fission-track dating** (The FT method)
  - **Argon dating** (The $^{40}\text{Ar}/^{39}\text{Ar}$ method)
The final two laboratory exercises will be based on thermochronology.

The exercises will be divided into two parts, with the second exercise building on what you will have done the previous week.

As usual, you will modify a Python code to produce some plots and provide short answers to some related questions.

The questions you will answer for the write-ups for these two labs will be relatively simple, only to let me know that you were able to do the requested tasks, because…
Lab and final project primer

- …you will expand on the work you do in the final two labs in a formal written report
- The report will be no longer than 6 typed pages (single spaced) including figures and references
- The idea is to describe some background on the data you will work with, the concept for its interpretation and your results/conclusions
- The structure for the report will be described in detail on the final laboratory exercise handout
References


