Introduction to Quantitative Geology
Lesson 13.2
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 $^{40}\text{Ar}/^{39}\text{Ar}$ method)
What is low-temperature thermochronology?

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

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- **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
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.
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.

**Fig. 1.** Three scenarios in which exhumation rate can be estimated from the slope of an AER. (a) High-$T_c$ thermochronometers, the slope is equal to the exhumation rate. (b) Low-$T_c$ thermochronometers, the slope overestimates the exhumation rate. (c) A decrease in relief leads to a further overestimate of the exhumation rate from the AER. A large decrease in relief can even lead to a negative slope.
Low-temperature = sensitive to topography

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

Change in pathway

EPSL 6231 31-5-02


Braun, 2002
Sensitivity to changing topography

(c) Low $T_c$ thermochronometry + Relief change

- 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)
Sensitivity to changing topography

(c) Low $T_c$ thermochronometry + Relief change

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

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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

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

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)

Ehlers and Farley, 2003
Potential ejection of $^4$He (alpha particles)

- 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 ~20 µm 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) Spontaneous tracks revealed on a polished internal surface of $\sim 27.8$ Ma Fish Canyon Tuff zircon. The crystallographic c-axis lies approximately vertical. (B) Induced tracks implanted on a muscovite detector (Brazilian Ruby clear) that were derived from the region of the photograph (A). (C) Spontaneous tracks on a polished internal surface of $\sim 33$ Ma apatite crystal. The c-axis lies approximately horizontal. (Photos by TT) (C) Spontaneous tracks on a polished internal surface of $\sim 33$ Ma apatite crystal. The c-axis lies approximately horizontal. (Photo by POS) Scale bars are $10 \ \mu\text{m}$.

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 $^{238}U$ decay constant, $\lambda_f$ is the fission decay constant, $N_s$ is the number of spontaneous fission tracks in the sample and $^{238}U$ is the number of $^{238}U$ atoms.

Tagami and O'Sullivan, 2005
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 $t_2$
  (c) 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
**Common thermochronometers**

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Effective closure temperature [°C]
Recap

- **Why is low-temperature thermochronology a particularly interesting tool for those interested in geomorphology or active tectonics?**

- **How is are (U-Th)/He or $^{40}\text{Ar}/^{39}\text{Ar}$ methods different from fission-track dating?**
Recap

- Why is low-temperature thermochronology a particularly interesting tool for those interested in geomorphology or active tectonics?

- How is are (U-Th)/He or $^{40}\text{Ar}/^{39}\text{Ar}$ methods different from fission-track dating?
Lab and final project primer

• 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 6-8 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


