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
Low-temperature thermochronology

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2.12.19
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**
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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.
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.
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
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)

(c) Low $T_c$ thermochronometry + Relief change

Past 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)
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

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Helium dating - (U-Th)/He method

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

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

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 ~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 $\sim 16$ $\mu$m long and $\sim 11$ $\mu$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

\[ t = \frac{1}{\lambda_D} \ln \left( \frac{\lambda_D}{\lambda_f} \frac{N_s}{^{238}\text{U}} + 1 \right) \]

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 - $^{40}$Ar/$^{39}$Ar method

- **Argon dating** is based on the decay of $^{40}$K to radiogenic $^{40}$Ar.

- Potassium is one of the most abundant elements in the crust, making argon dating one of the more common thermochronology methods.

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

- With this, it is possible to see the $^{40}\text{Ar}$ 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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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 $^{40}$Ar/$^{39}$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 $^{40}$Ar/$^{39}$Ar methods different from fission-track dating?
Final project primer

- The final two 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 write/modify a Jupyter notebook 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 exercises 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 is described in detail on the course webpage
References


