An Introduction to the Theory and Methods of (U-Th)/He Thermochronology

2014 Earthscope Institute : Geochronology in the Earth Sciences

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CU TRaIL

http://www.colorado.edu/GeolSci/thermochronology/CU_Thermochronology/Short_Course.html

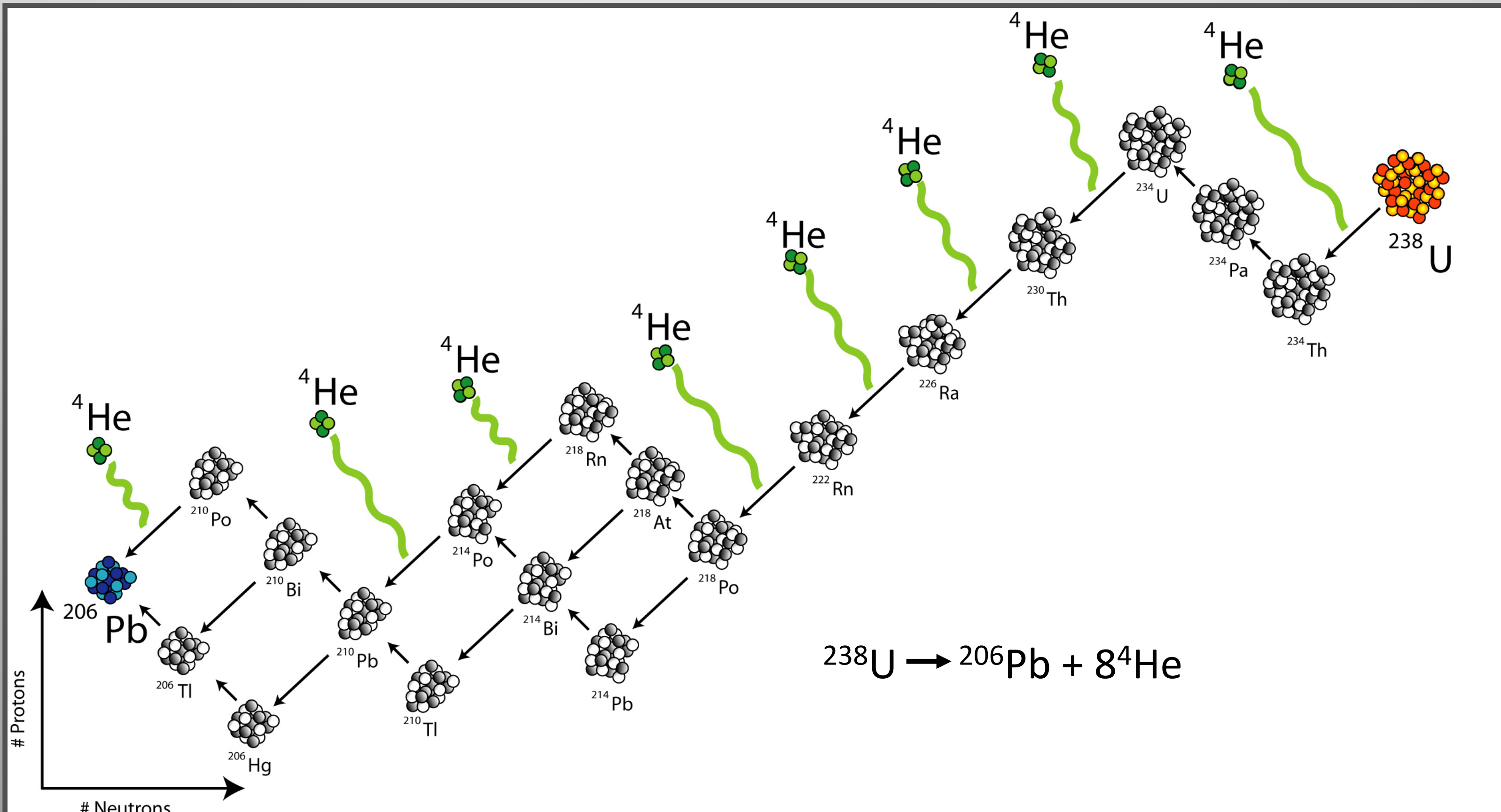
An introduction to thermochronology & fundamentals of the (U-Th)/He method

1) Fundamentals of the (U-Th)/He method
   - ^{4}He production
   - Short history of technique development
   - Analytical methods
   - Special considerations

2) Interpreting He dates

3) Logistics of He dating

^{4}He Production and the Age Equation



$$^{238}U \longrightarrow {}^{206}Pb + 8\,{}^{4}He$$

^{4}He Production and the Age Equation

The vast majority of ^{4}He is produced through the process:

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

Where

λ_{238} = 1.55125 x 10^{-10} a^{-1}

λ_{235} = 9.8485 x 10^{-10} a^{-1}

λ_{232} = 4.9475 x 10^{-11} a^{-1}

History of (U-Th)/He Thermochronometry

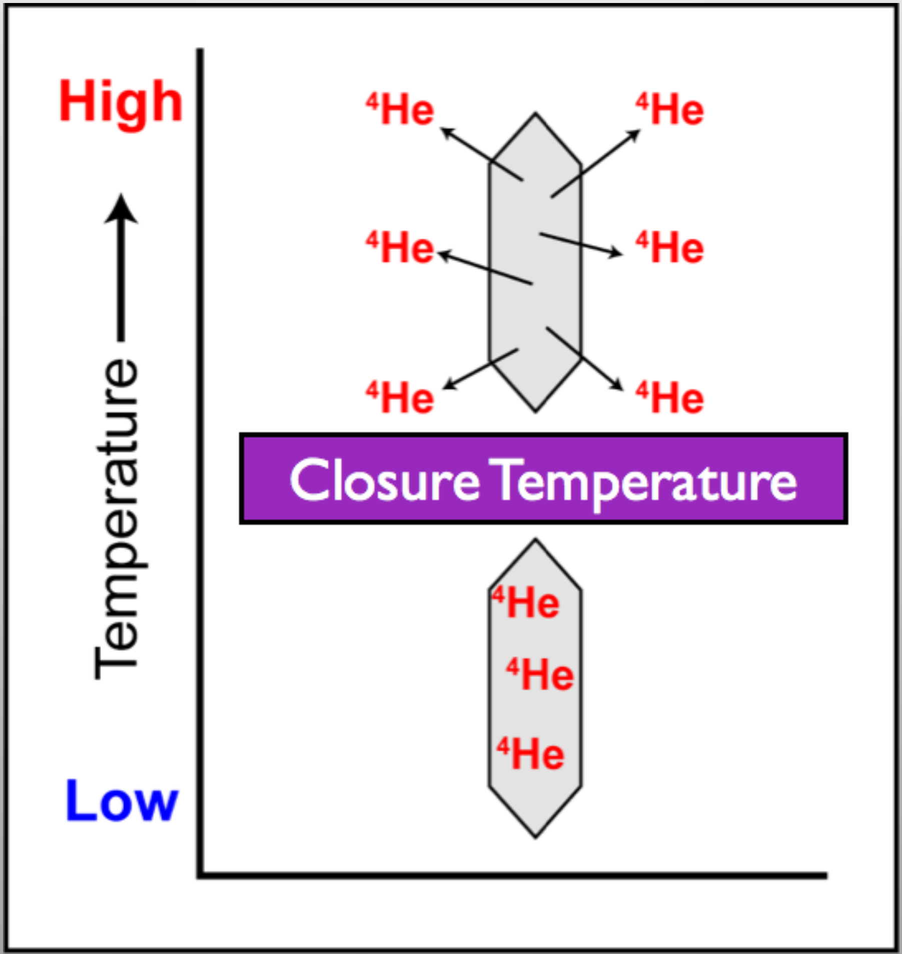
Early days:

1. Rutherford first proposed U-He dating in 1905 (the first geochronometer)
2. RJ Strutt published He dates, acknowledged that they were minimum ages due to “He leakage.”
3. Hurley, 1954 tried applying the technique to date geologic materials - System yielded results that were unreasonably young

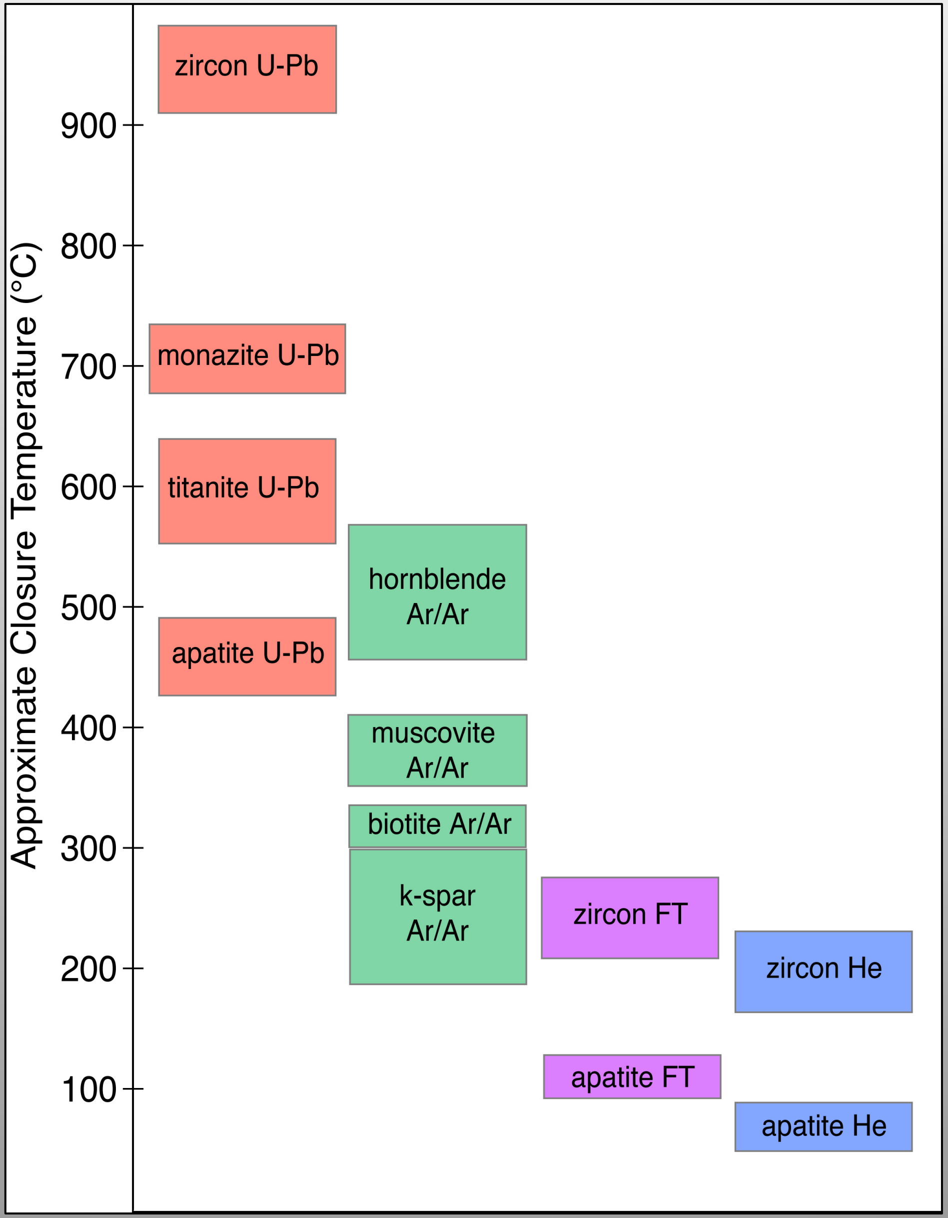
Revival:

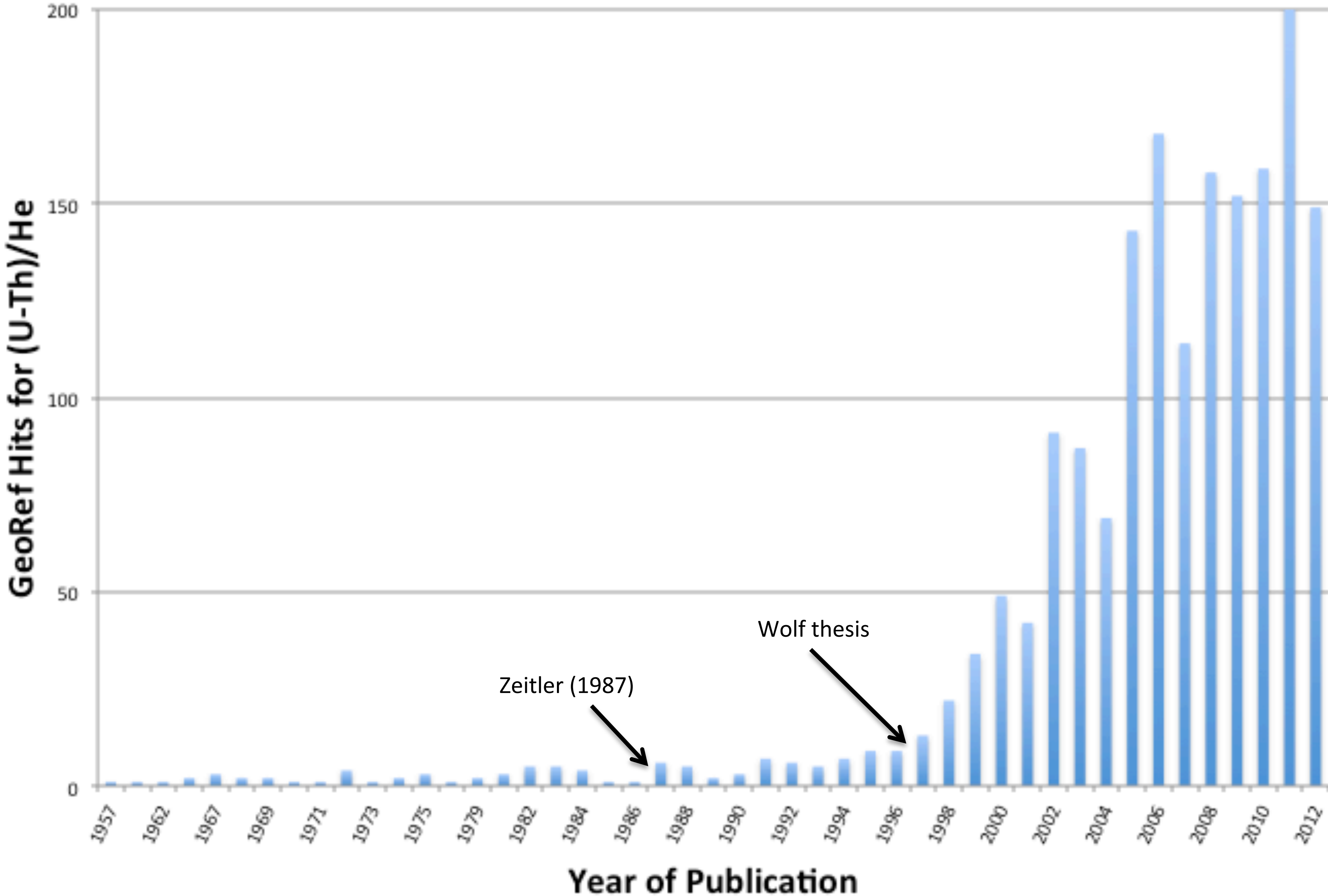
1. Zeitler et al., 1987 proposed use of (U-Th)/He in apatite as a “thermochronometer”
2. Farley and w/ dealt with alpha particle emission from grain edges and carried out diffusion experiments to characterize apatite He diffusivity
3. Wolf (1996) determined the basic properties of the thermochronometer

Interpreting He dates



(U-Th)/He Thermochronology





GeoRef Hits for (U-Th)/He
200
150
100
50
0
1957
1962
1967
1969
1971
1973
1975
1979
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year of Publication
Zeitler (1987)
Wolf thesis

History of (U-Th)/He Thermochronometry

Minerals used for (U-Th)/He thermochronometry

Most applications thus far have focused on apatite and zircon.

However, any U-Th bearing mineral can be dated.

Other possibilities on which some work has been or is being carried out include titanite, monazite, xenotime, rutile, magnetite, goethite, epidote, calcite, garnet, baddeleyite, and conodonts.

Mineral	Approximate Tc (°C)
Apatite	60-100
Zircon	~180
Titanite	~200
Monazite	~200
Goethite	N/A
Fluorite	60-100
Hematite	100-180

Diversity of Applications

- Uplift and exhumation
- Landscape formation
- Eruption and mineralization ages
- Detrital thermochronology
- Reheating and basin thermal histories
- Protracted thermal histories
- Meteorite thermochronology
- Weathering chronology
- Wildfire chronology
- Dating thermal resetting events like basalt flows, impacts, and pseudotachylyte formation

The Nuts and Bolts of Measuring Ages

Unlike some other chronometers, multiple instruments must be used to measure the parents and daughters.

1. Select and Characterize the Grain.
2. Measure the daughter (He).
3. Measure the parents (U, Th, and Sm).

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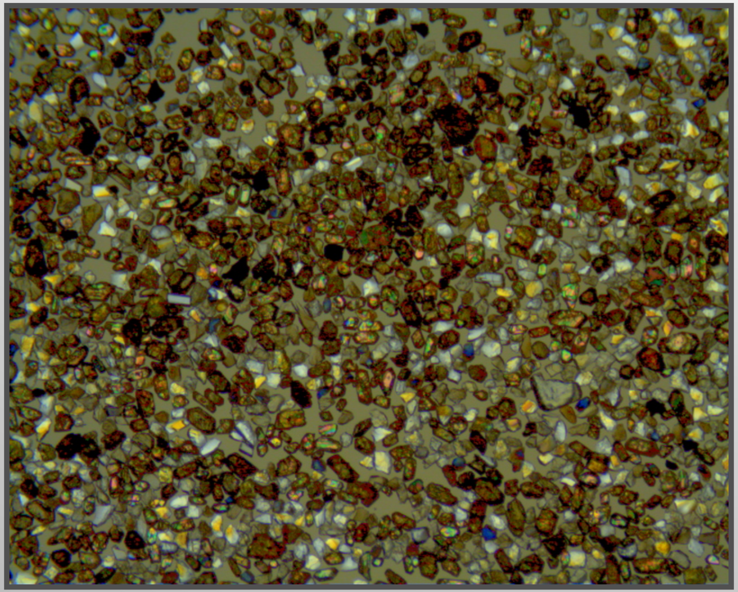
I'll describe "standard" (U-Th)/He dating, but other methods (e.g. *in situ* dating) are also possible.

Selecting Grains to Analyze



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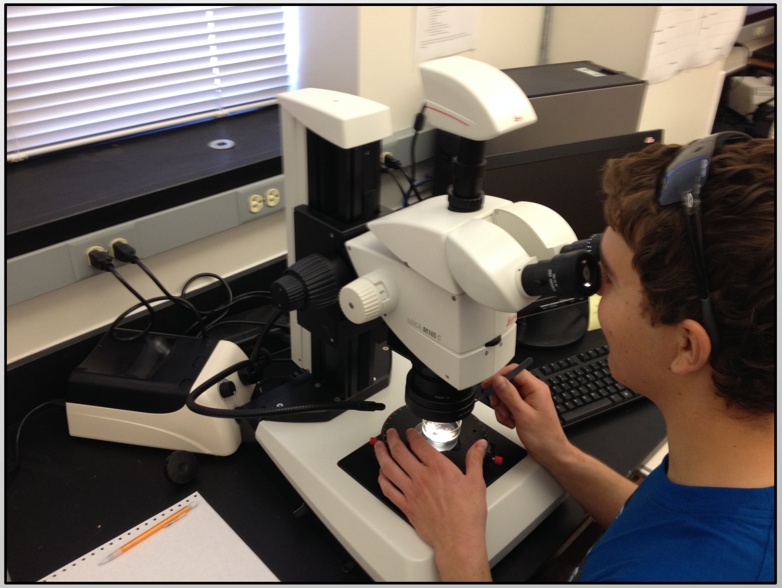

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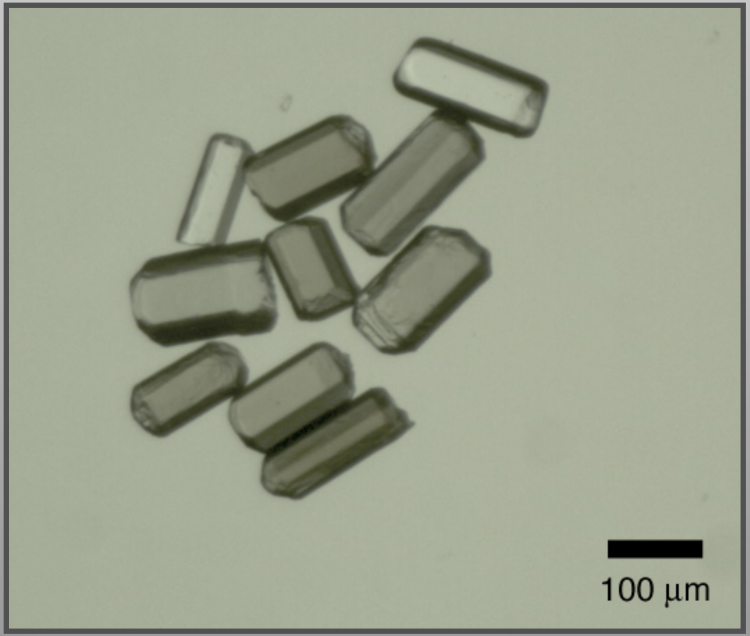
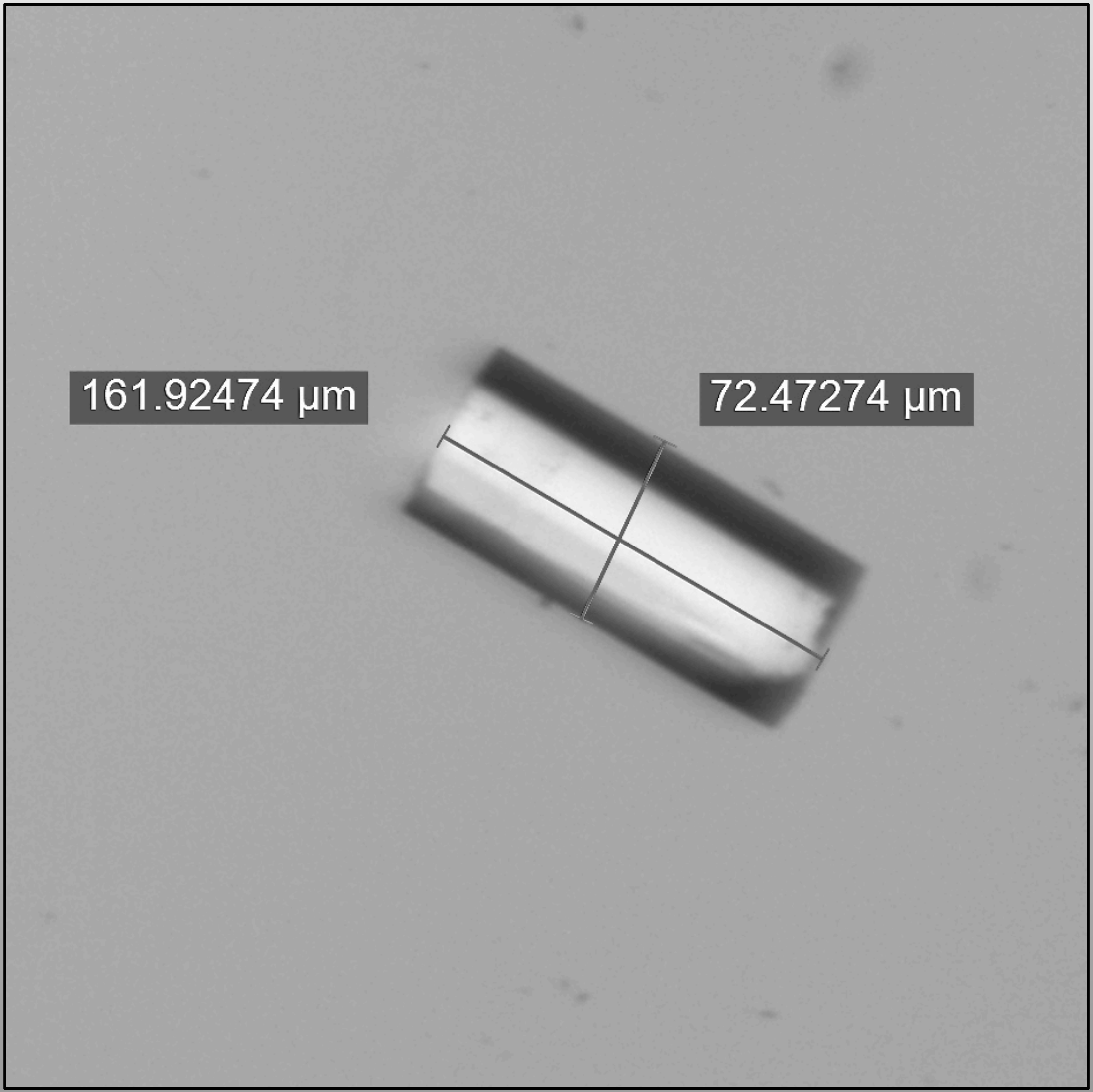
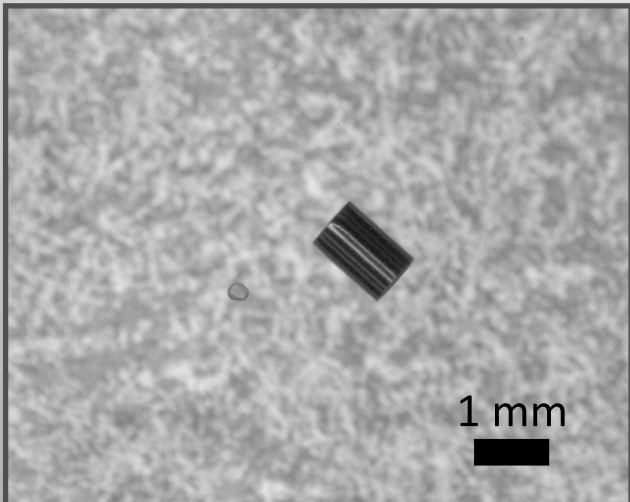
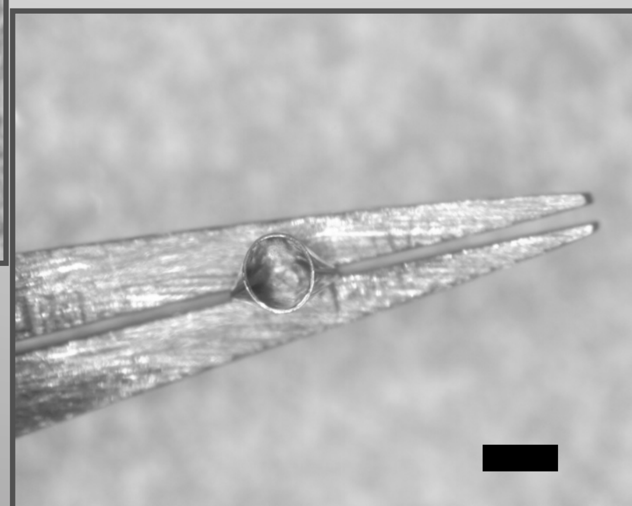


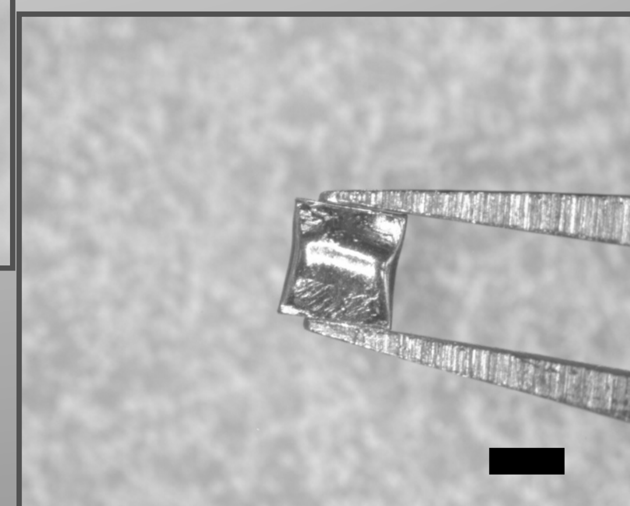
Characterize grains



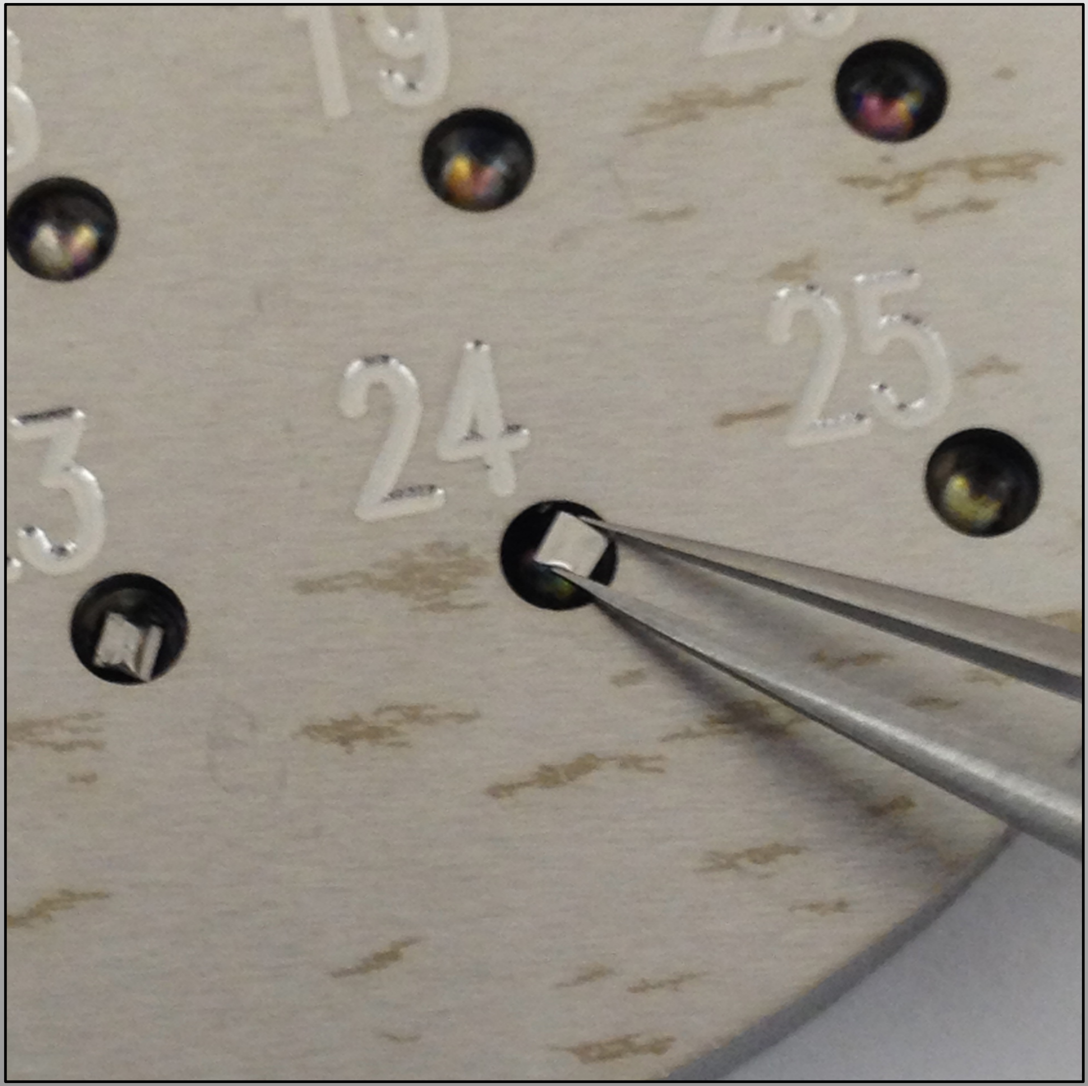
Pack crystals into Pt/Nb packets







Load samples into He extraction line

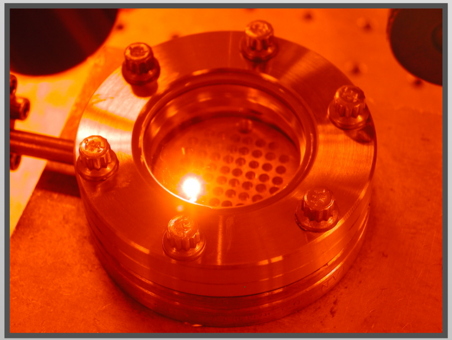


He Extraction Line

Dissolve and spike samples

Calculating a Date

He



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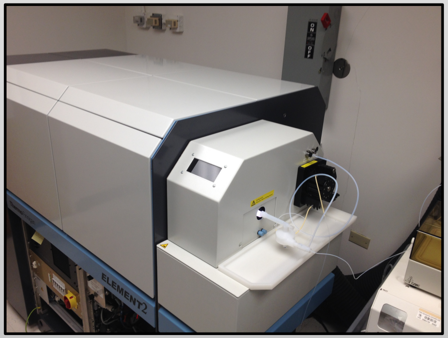
U, Th, Sm



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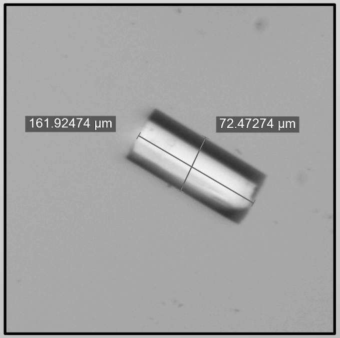
F_T



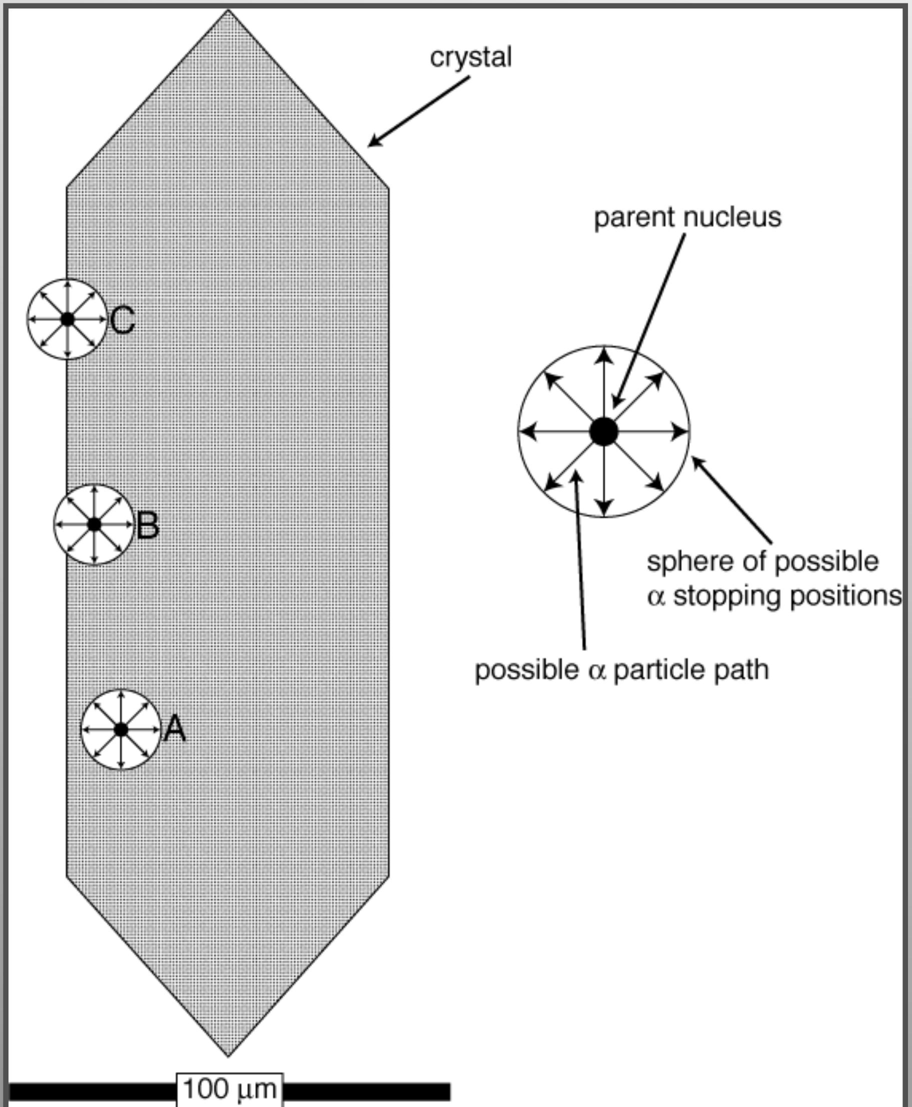
= (U-Th-Sm)/He date

(U-Th)/He Thermochronology

Special considerations

1. Alpha-ejection correction
2. Inclusions
3. Radiation damage
4. Other issues

1. α−ejection



10-30% of α-particles are ejected

For apatite, geometric corrections work well

Measure each individual crystal, assume a homogenous distribution of U and Th.

Calculate F_T, the alpha-ejection correction.

After Farley et al. (1996)

2. Inclusions

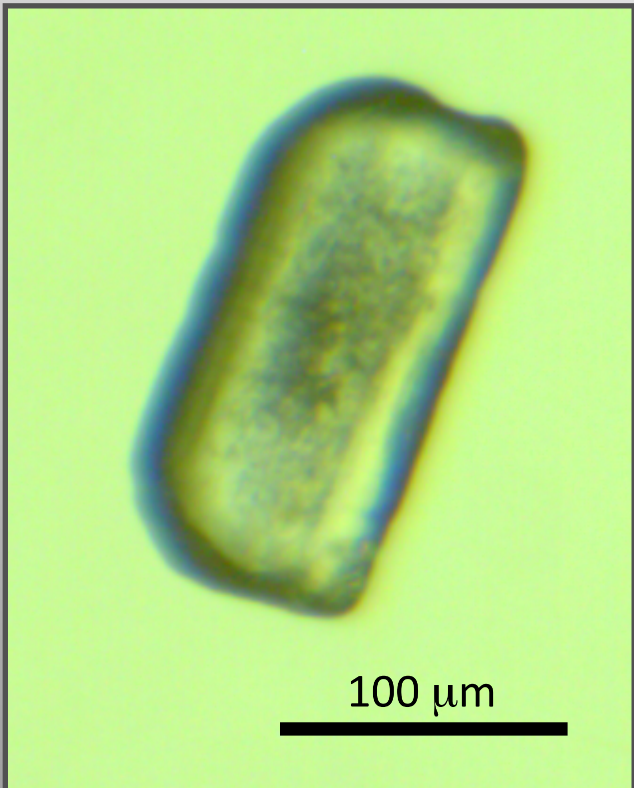
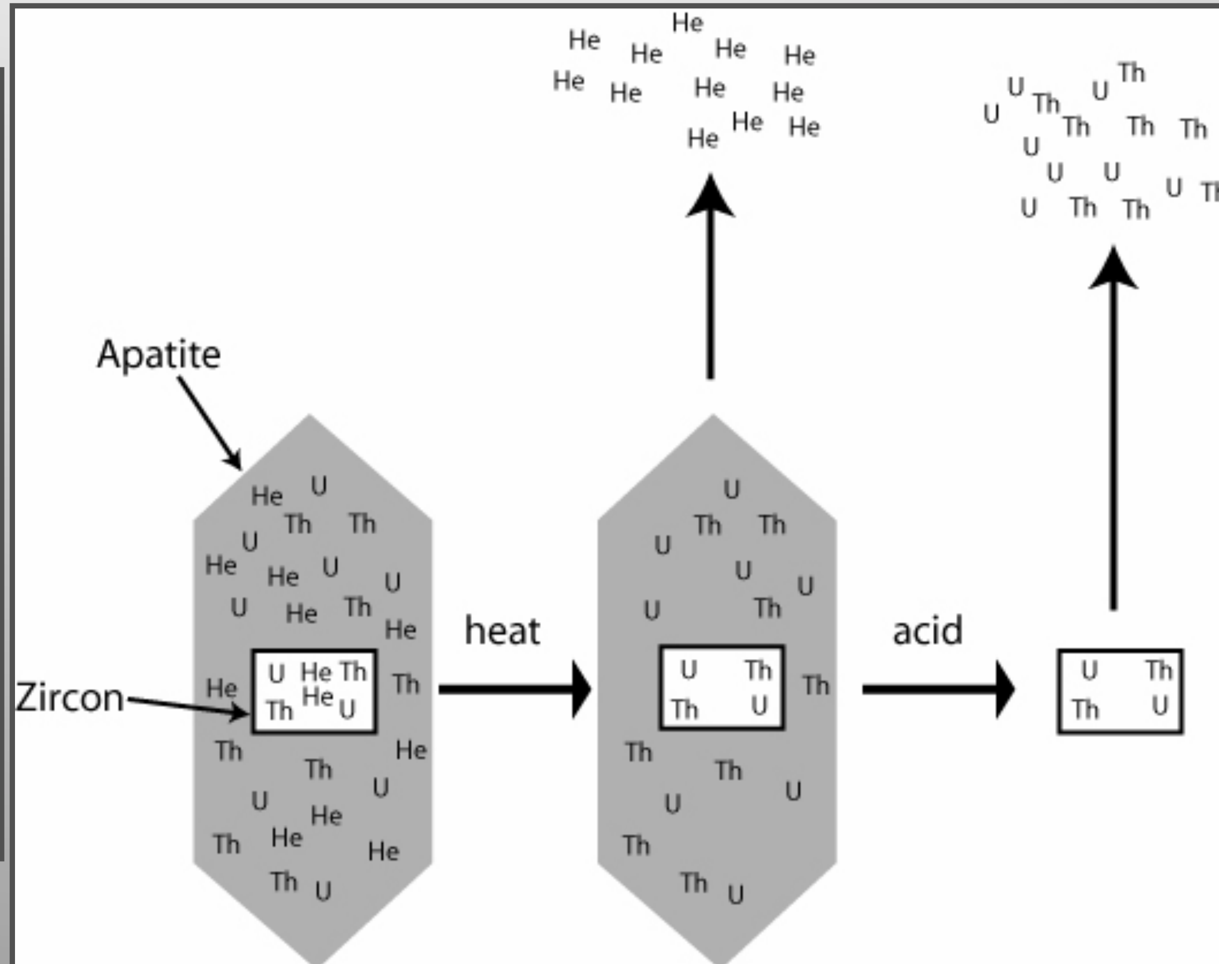


Photo courtesy J. Fosdick



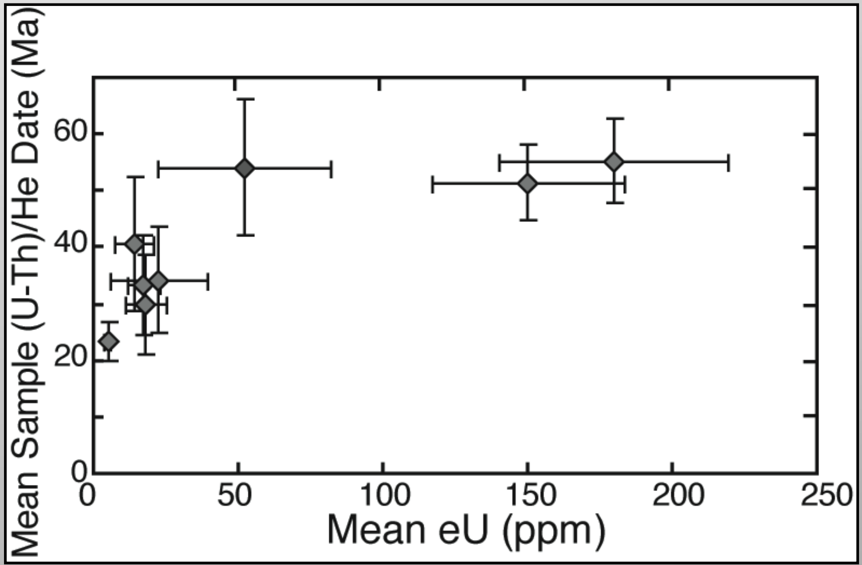
3. Radiation Damage Controls on He Diffusion Kinetics

The He retentivity of a grain is a function of how much radiation damage the crystalline structure has accumulated.

In apatite, radiation damage makes the closure temperature **higher**. So higher eU grains may be **older** than low eU grains.

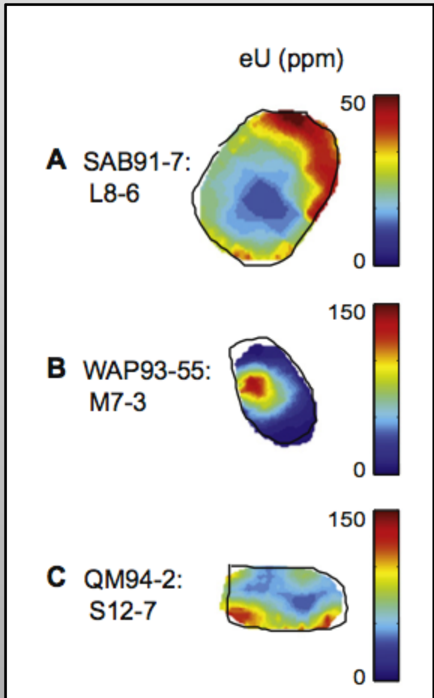
Dispersion in some (U-Th)/He datasets is geologically meaningful

Possible to extract additional information about details of t-T path because of this effect

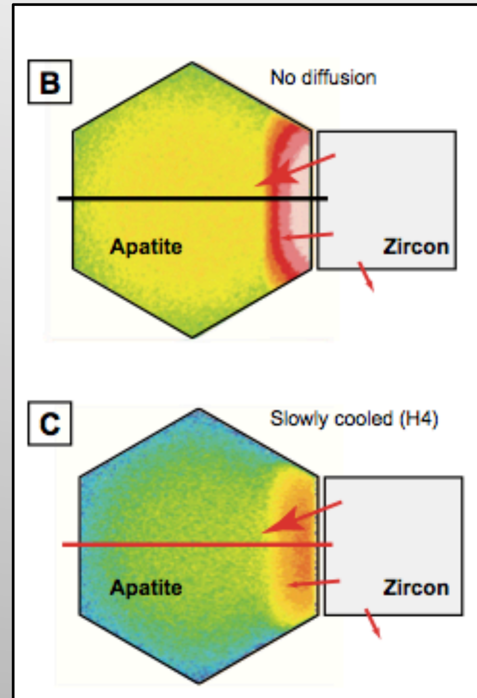


After Flowers, R.M., and Farley, K.A., 2012, Apatite 4He/3He and (U-Th)/He Evidence for an Ancient Grand Canyon: Science, v. 338, no. 6114, p. 1616–1619.

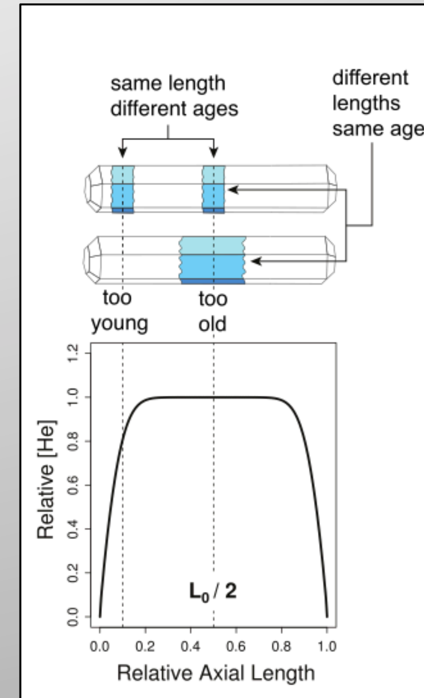
4. Other Factors



U,Th Zonation



“Bad Neighbors”



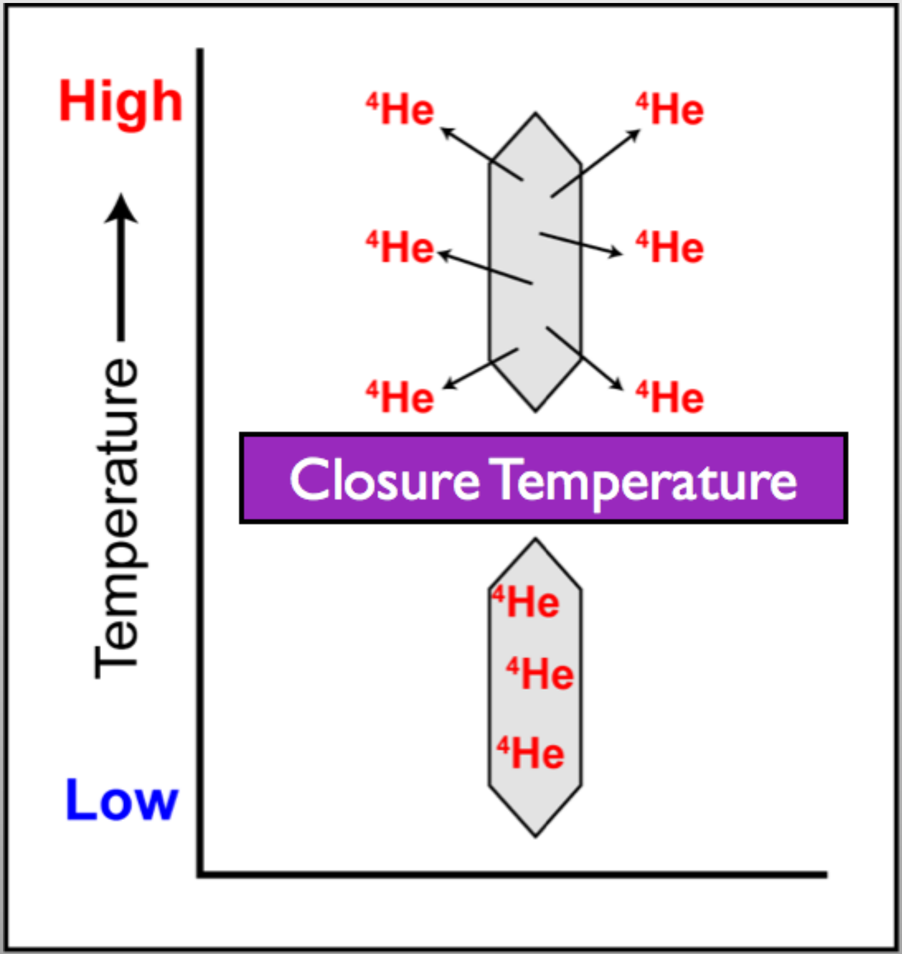
Grain Shape Alteration

Ault, A. K., & Flowers, R. M. (2012). Is apatite U-Th zonation information necessary for accurate interpretation of apatite (U-Th)/He thermochronometry data? *Geochmica et Cosmochimica Acta*, *79*(C), 60–78.

Gautheron, C., Tassan-Got, L., Ketcham, R. A., & Dobson, K. J. (2012). Accounting for long alpha-particle stopping distances in (U–Th–Sm)/He geochronology: 3D modeling of diffusion, zoning, implantation, and abrasion. *Geochmica et Cosmochimica Acta*, *96*, 44–56.

Brown, R.W., Beucher, R., Roper, S., Persano, C., Stuart, F., and Fitzgerald, P.G., 2013, Natural age dispersion arising from the analysis of broken crystals. Part I: Theoretical basis and implications forthe apatite (U–Th)/He thermochronometer: Geochmica et Cosmochimica Acta, v. 122, no. C, p. 478–497

Interpreting He dates



Interpreting He dates

To non-experts, why do He data often seem more difficult to understand than other geochronologic data?

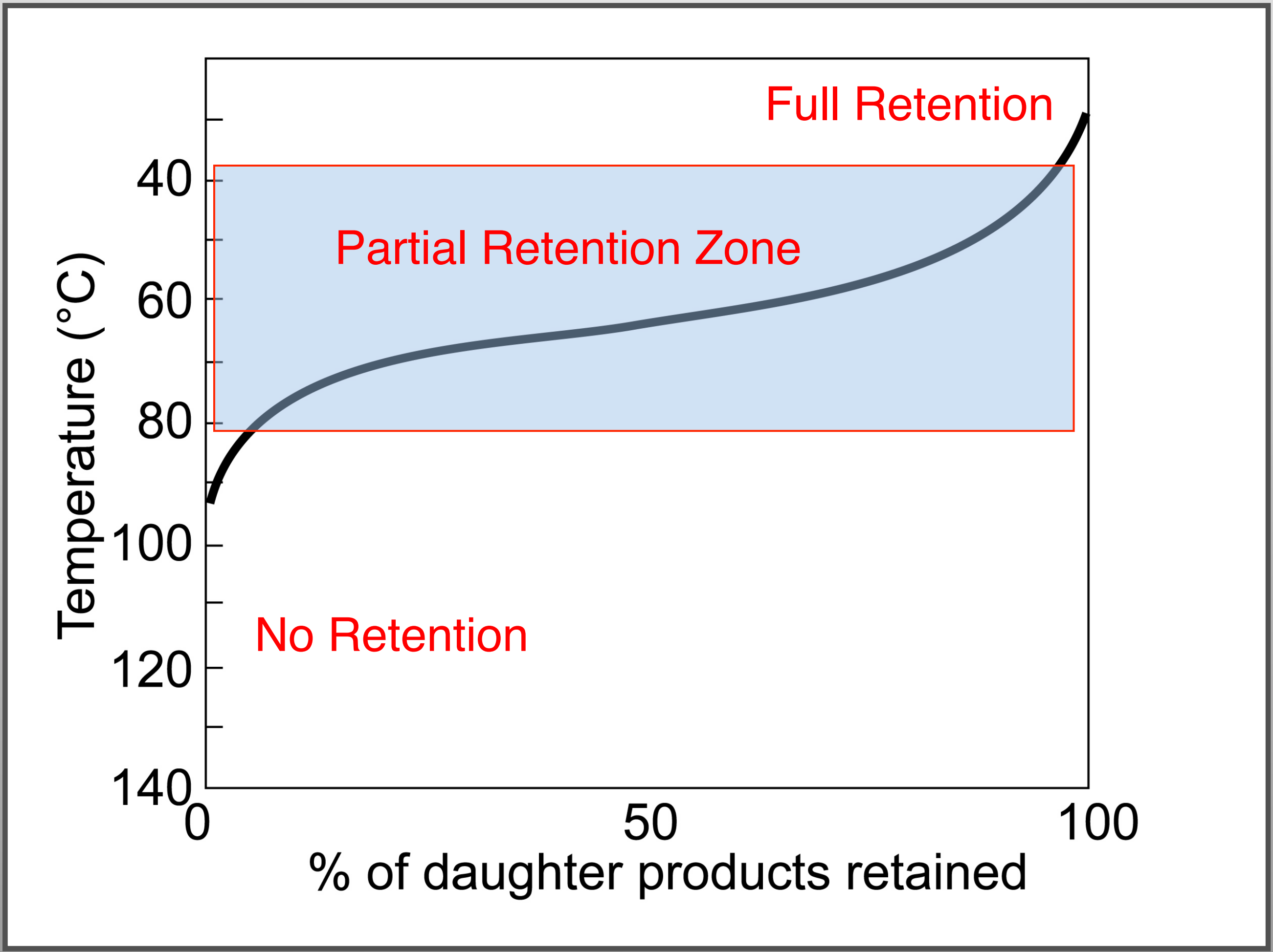
A thermochronologic date need not and usually does not date an event, or even the time at which the closure isotherm was crossed.

1. Notion of He partial retention zone (HePRZ)

2. How to better understand your thermal history
   - Geologic constraints
   - Vertical profiles
   - Thermal Modeling

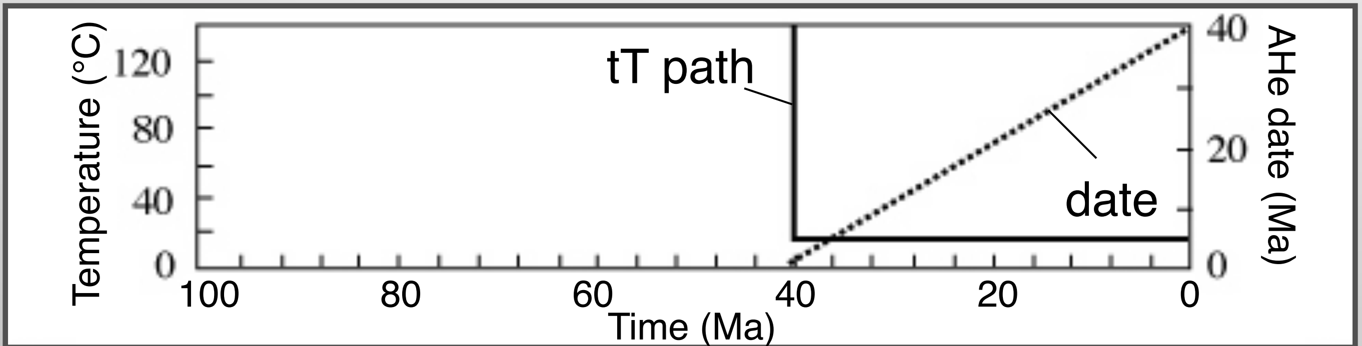
Notion of the Apatite HePRZ

Temperature range over which He is partially retained in and partially lost from the apatite crystal.



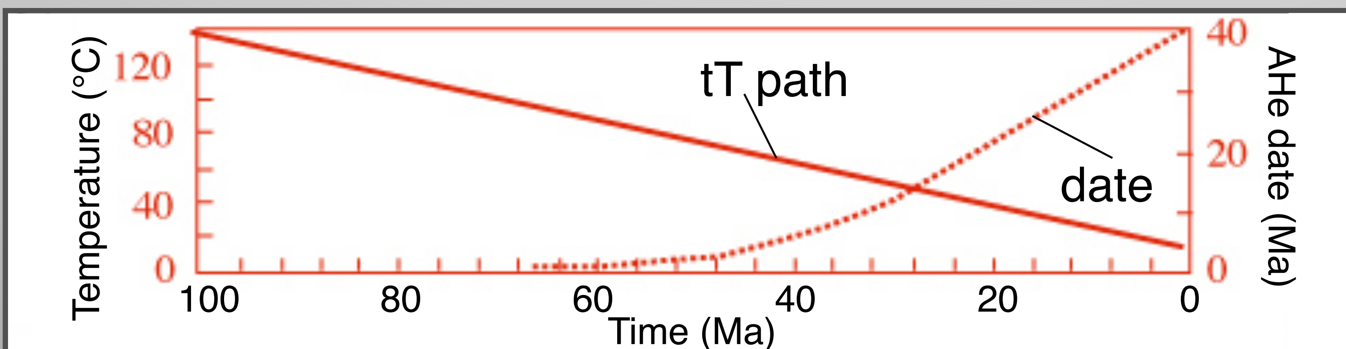
After Wolf et al., (1996)

These thermal histories yield AHe dates of 40 Ma



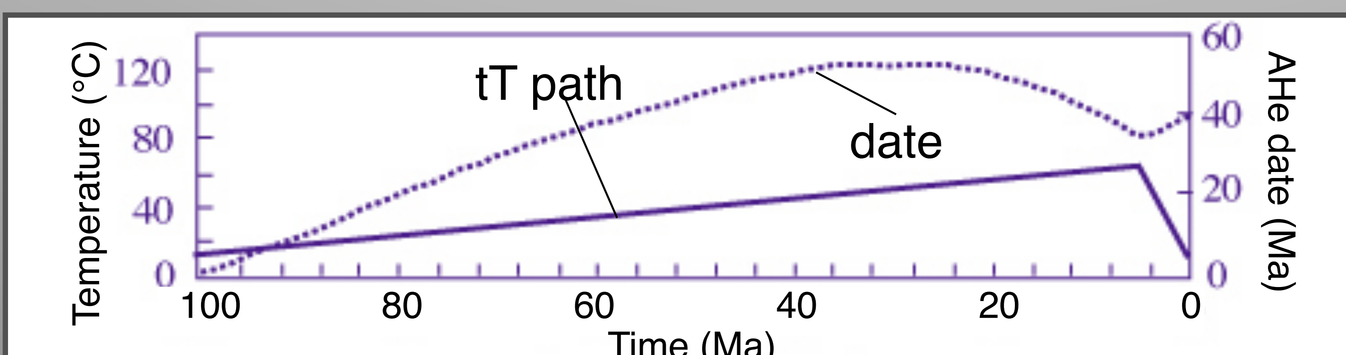
<u>Rapid Cooling</u>

Rapidly exhumed fault block



<u>Slow Cooling</u>

Erosional exhumation

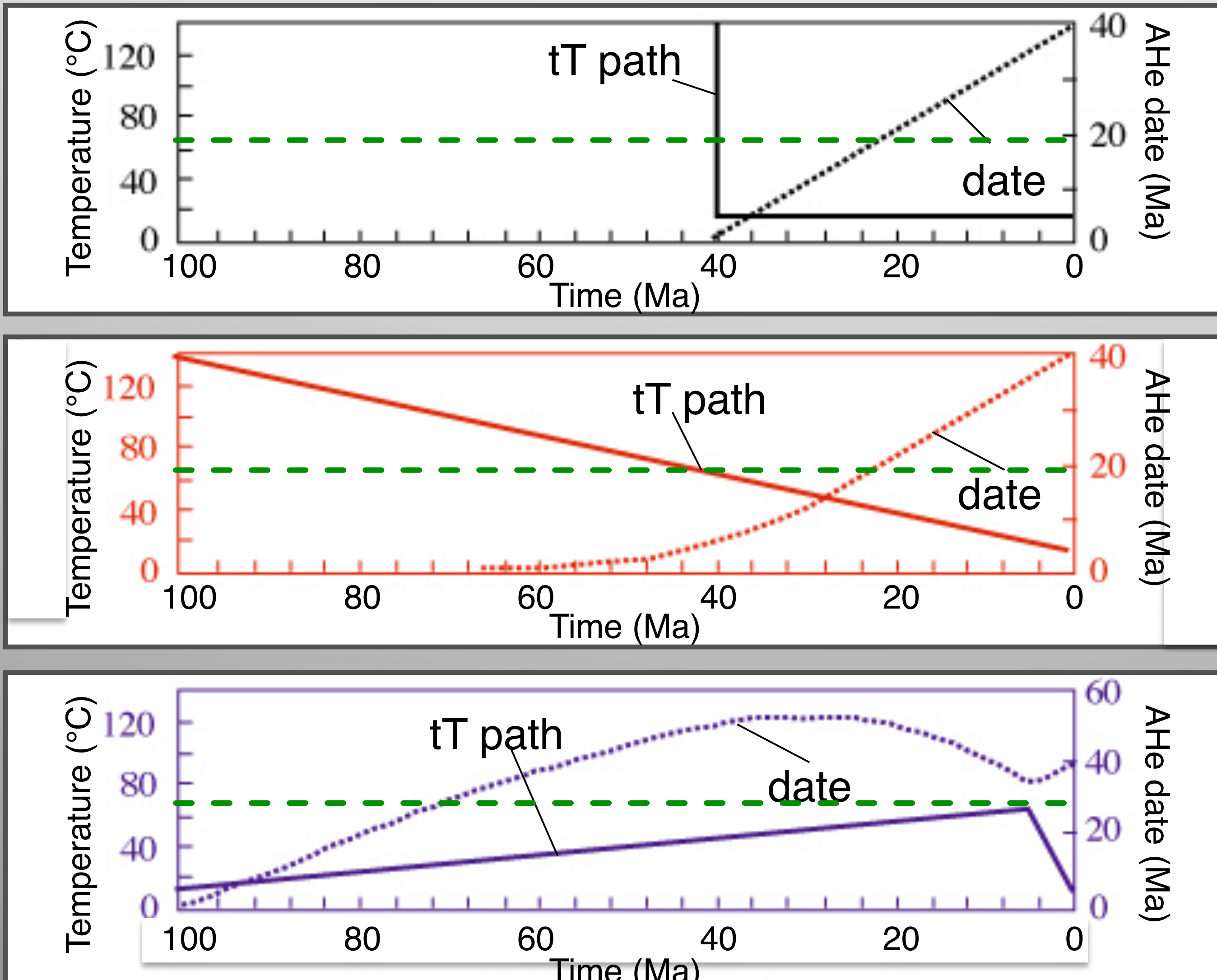


<u>Reheating</u>

Sedimentary basin

After Wolf et al., (1998)

Some key points:

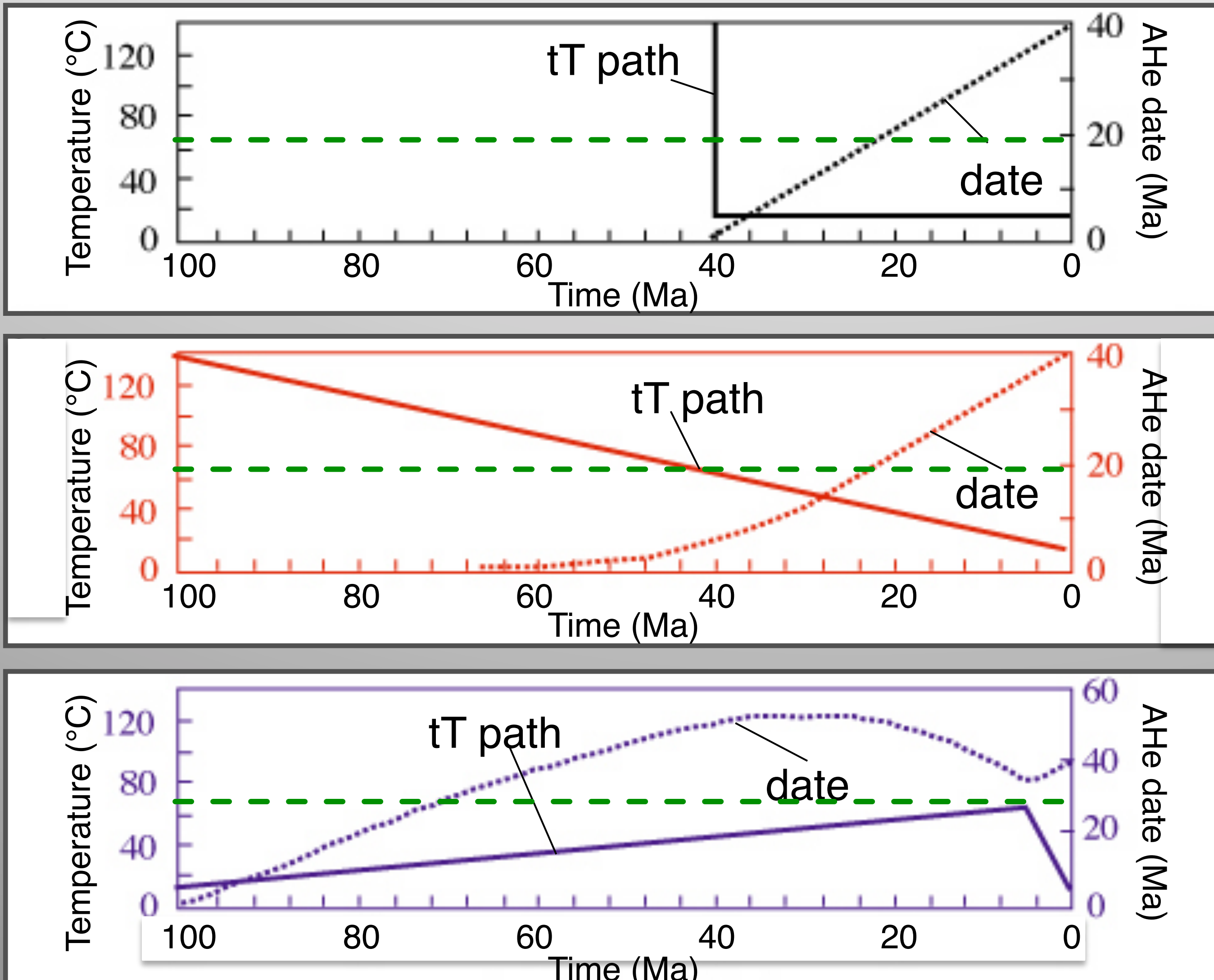


Closure temperature of 70°C is an oversimplification because of the temperature range over which He is partially retained in apatite

An AHe date represents the apatite's integrated thermal history since the onset of radiation damage accumulation and He retention

After Wolf et al., (1998)

Method 1 – Additional Geologic Constraints



For example:

An offset unit like a basalt flow that poses a maximum timing constraint on the onset of faulting

Or

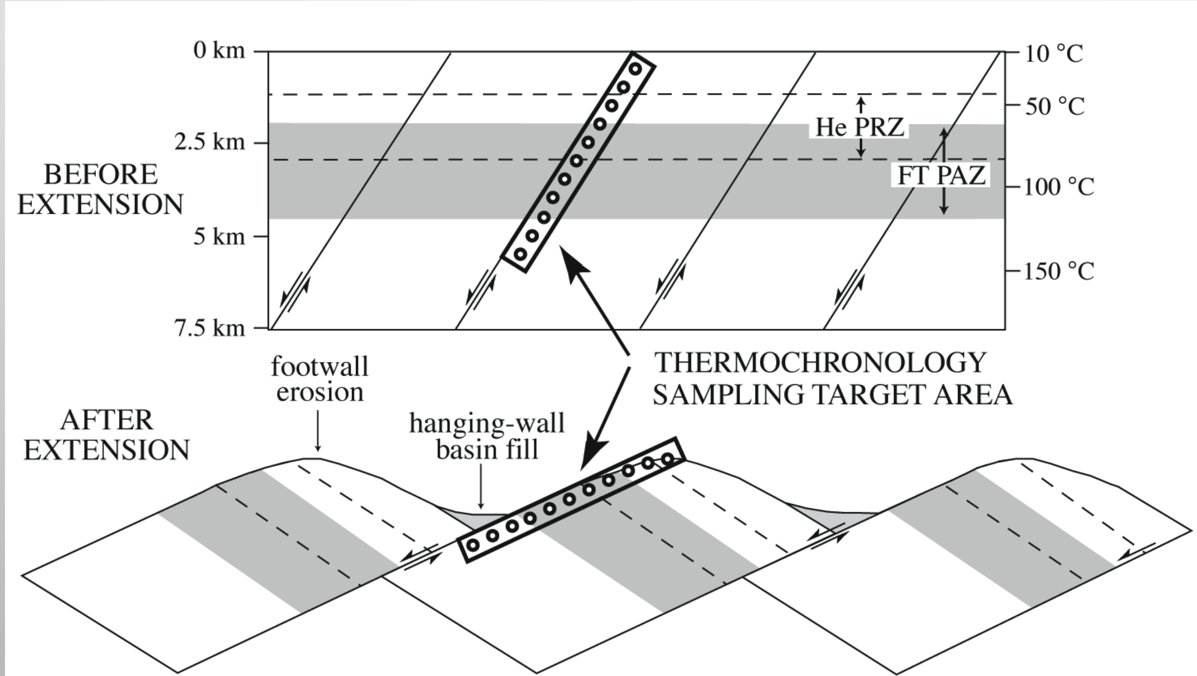
Unconformable relationship that constrains the onset of burial or when the rocks reached the surface

After Wolf et al., (1998)

Method 2 – Vertical Sampling Profile

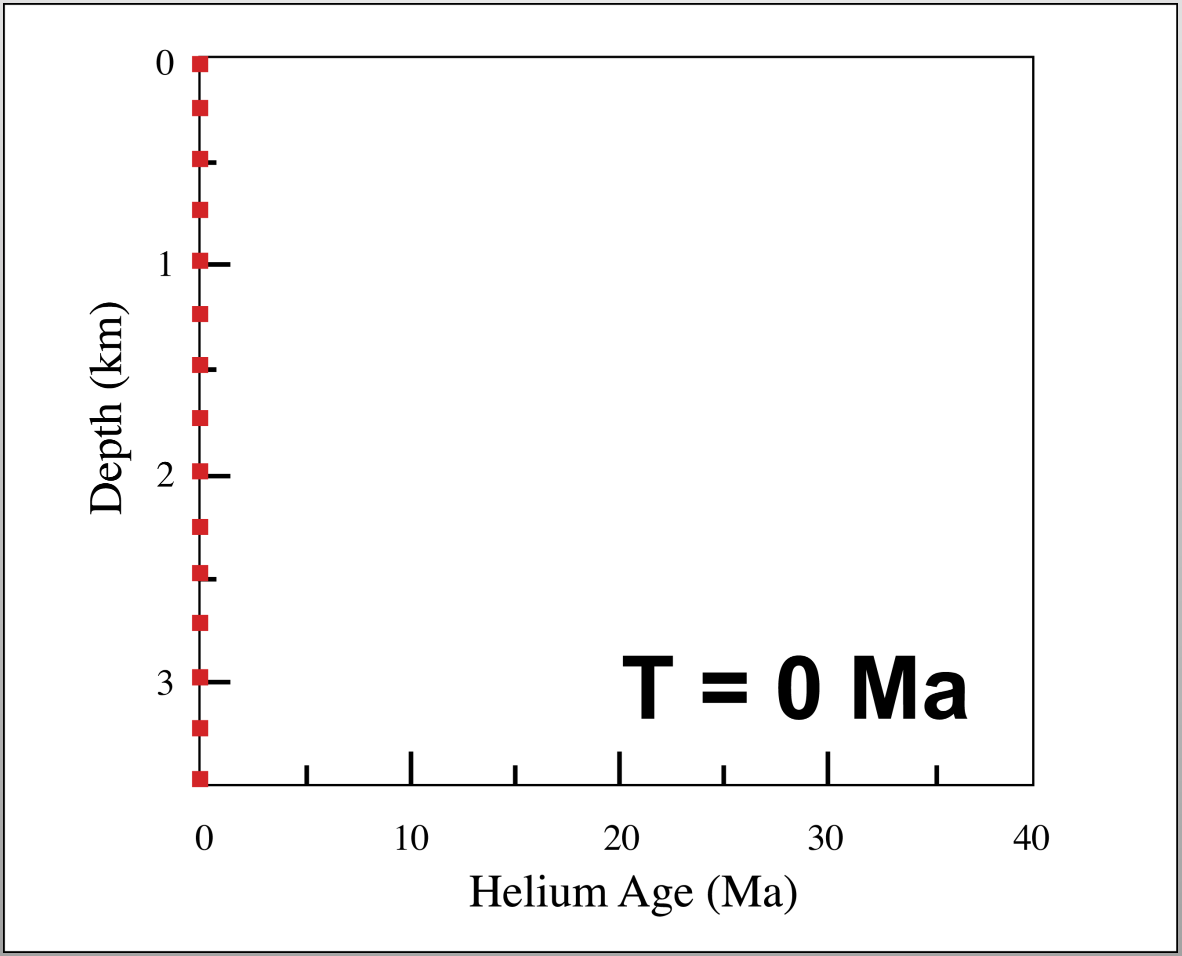
Some styles of faulting move rocks relative to isotherms

Vertical sampling profile: He date vs. elevation



Stockli, D., Farley, K.A., and Dumitru, T., 2000, Calibration of the apatite (U-Th)/He thermochronometer on an exhumed fault block, White Mountains, California: Geology, v. 28, no. 11, p. 983.

PRZ and Vertical Profiles



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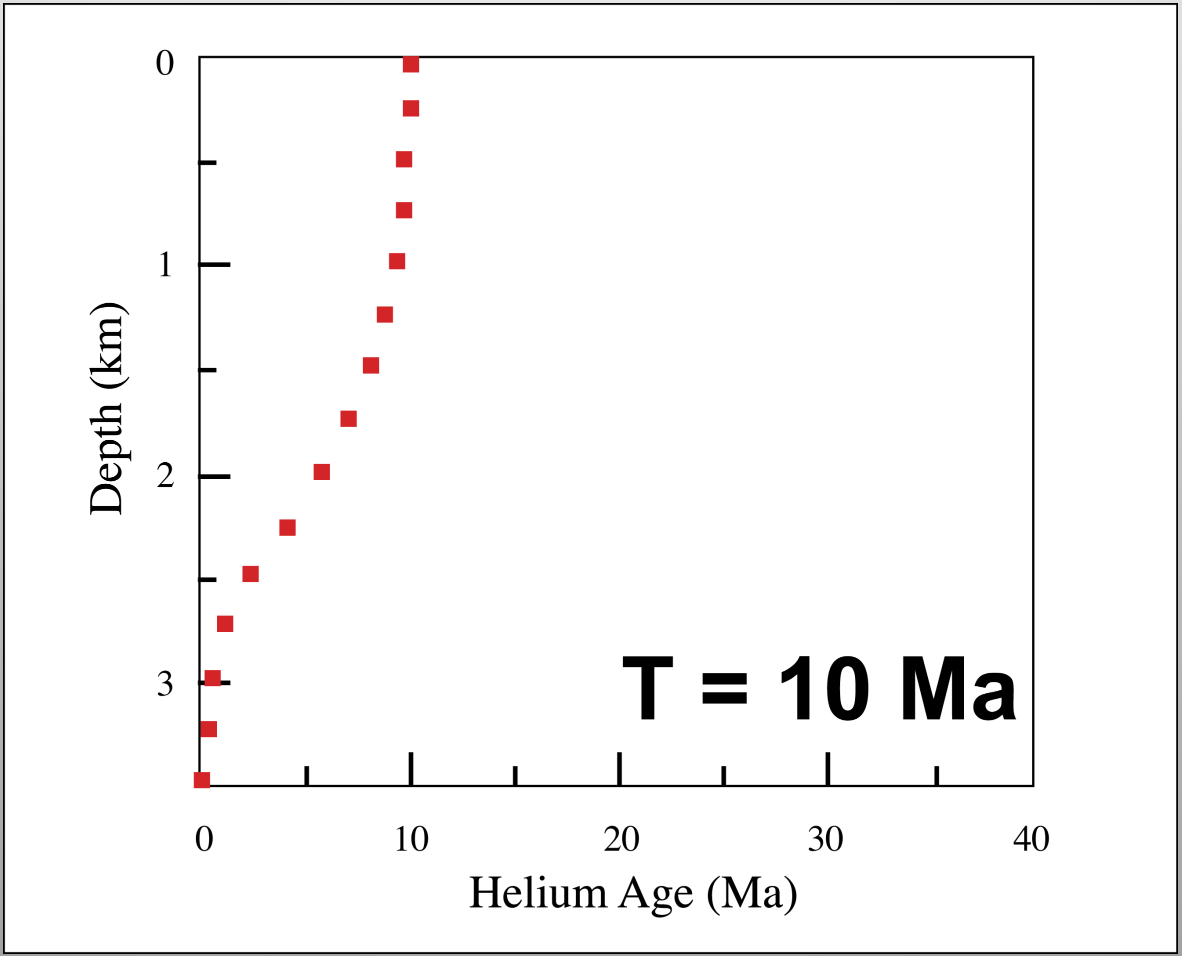

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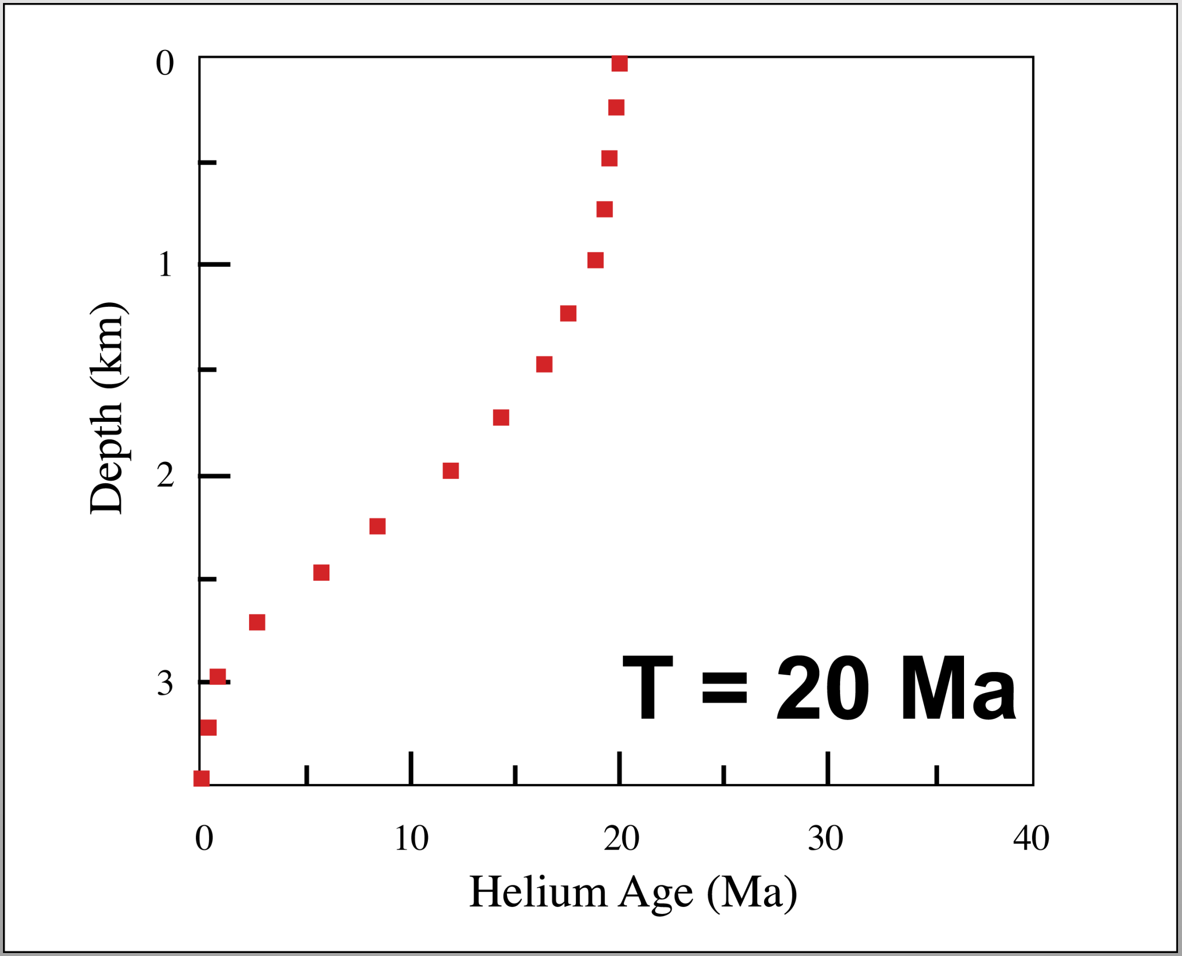

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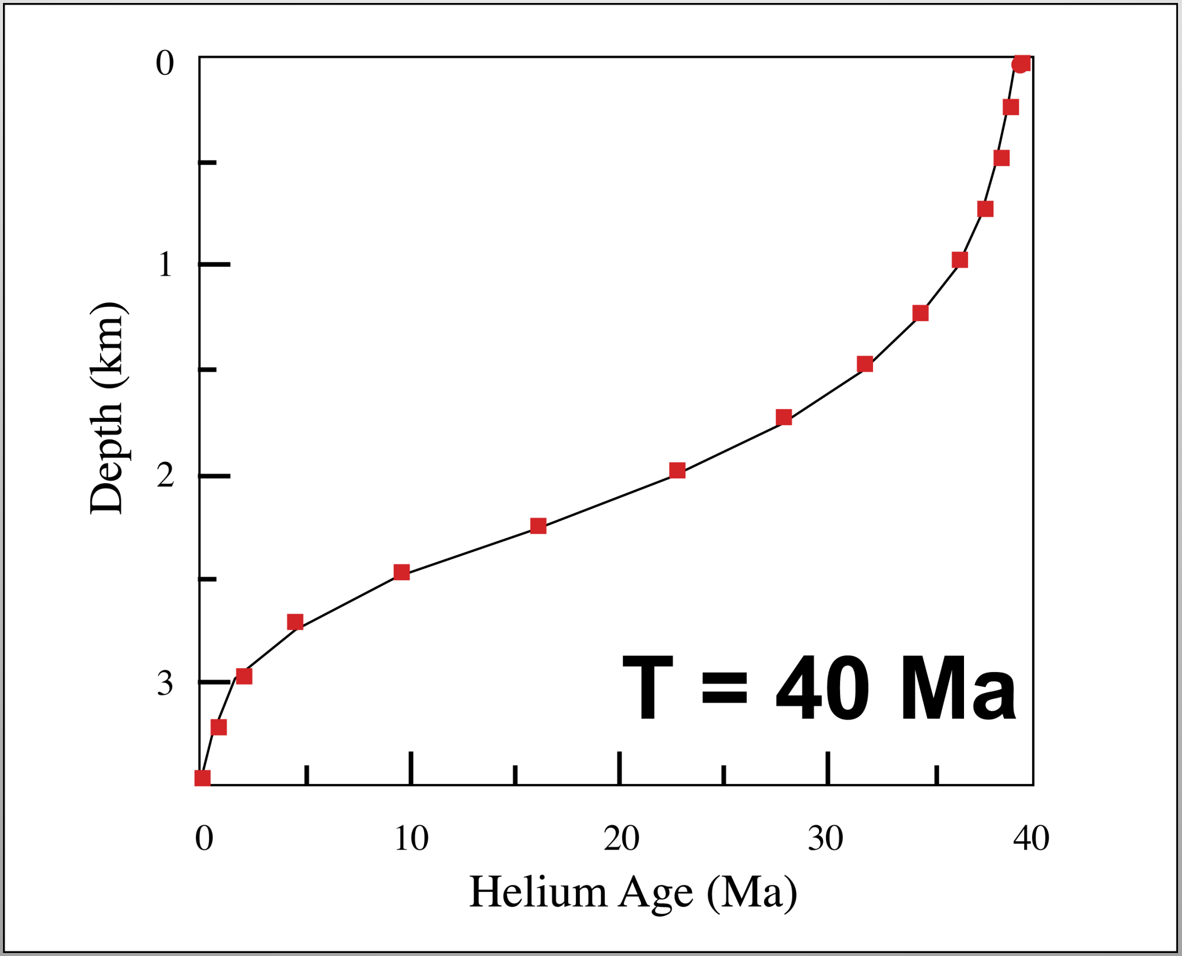
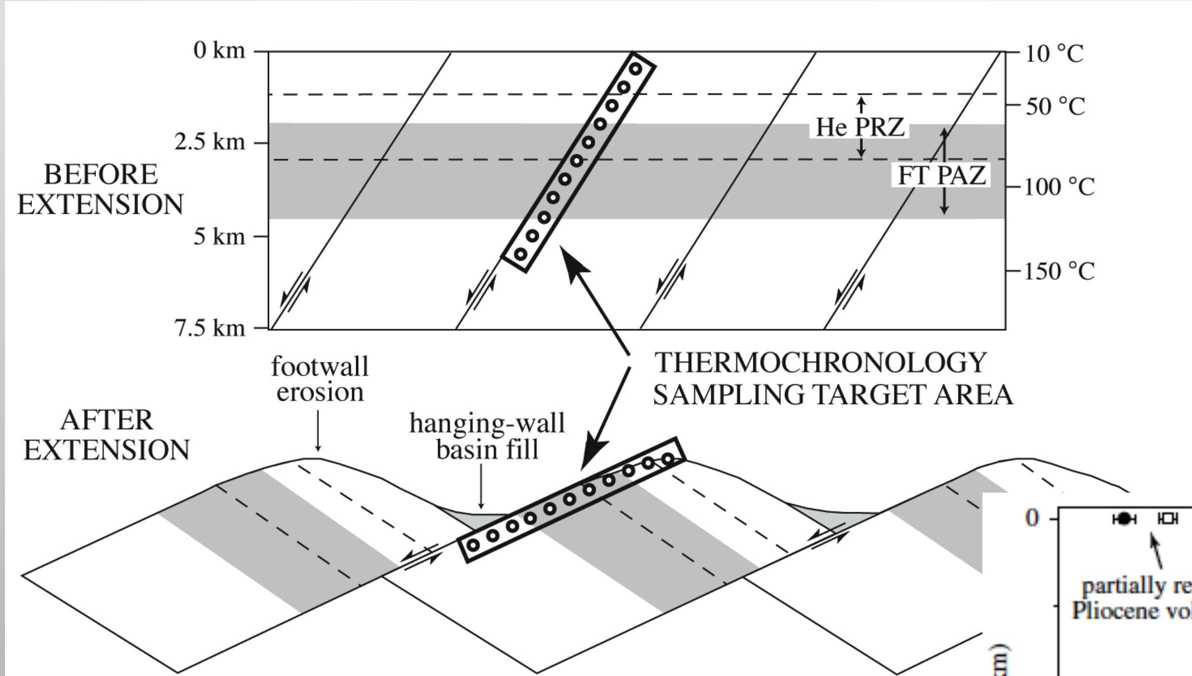


Vertical sampling profile: He date vs. elevation



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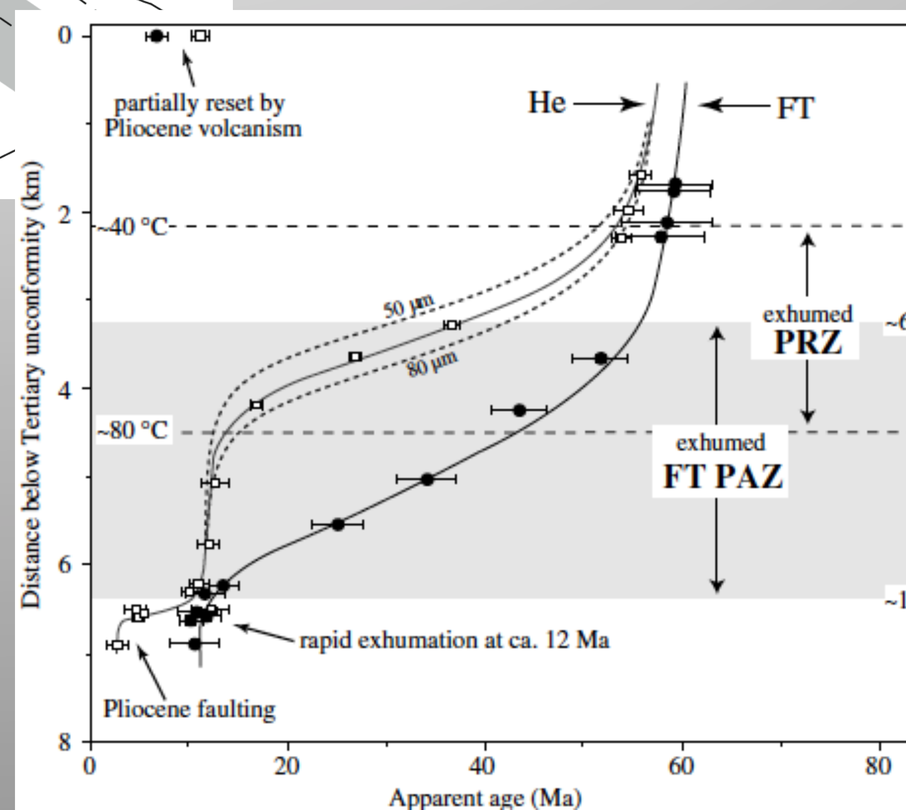
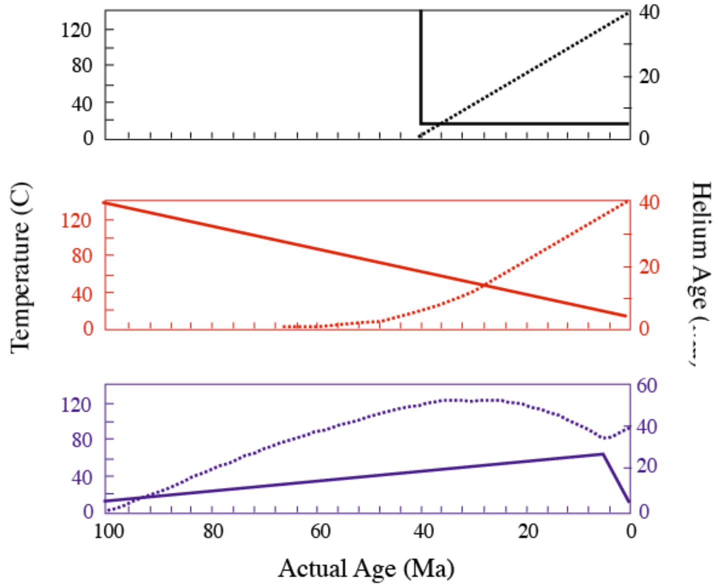
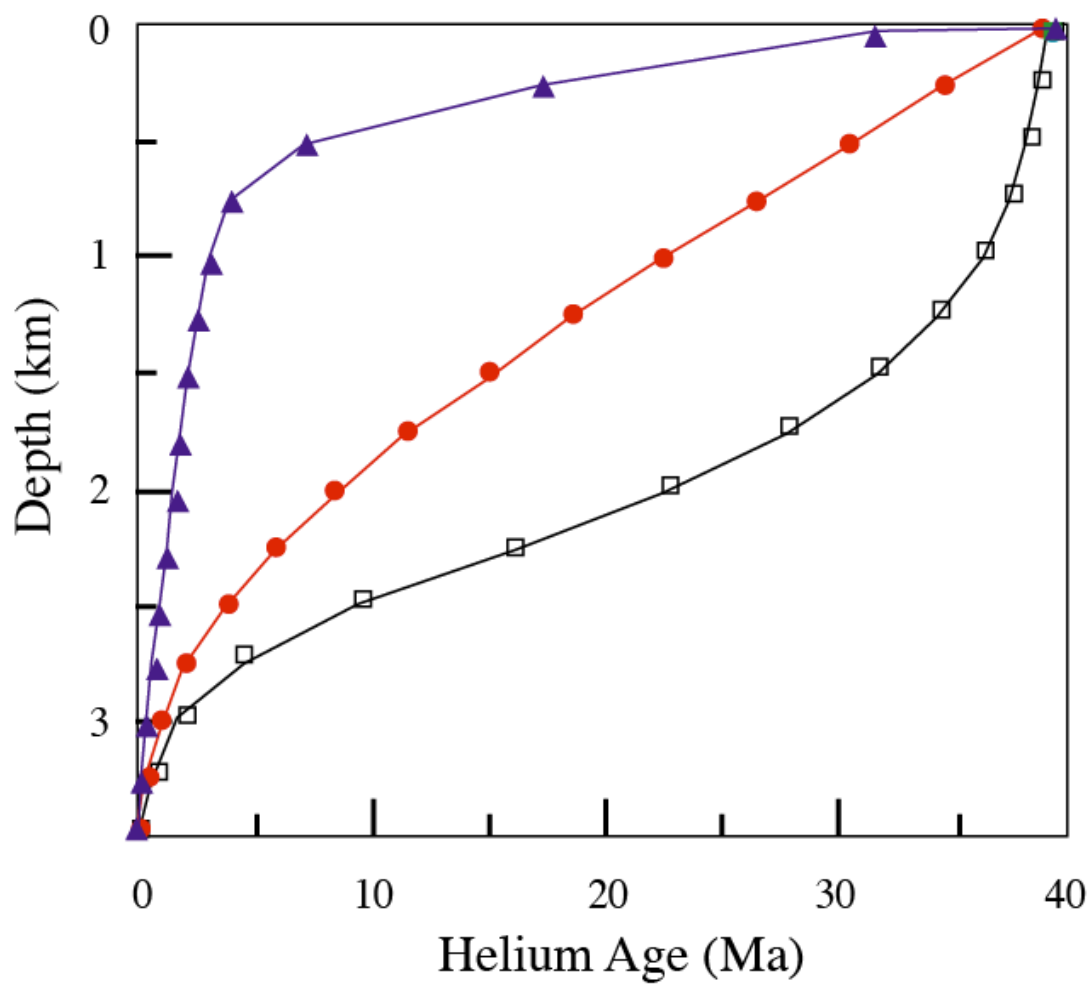
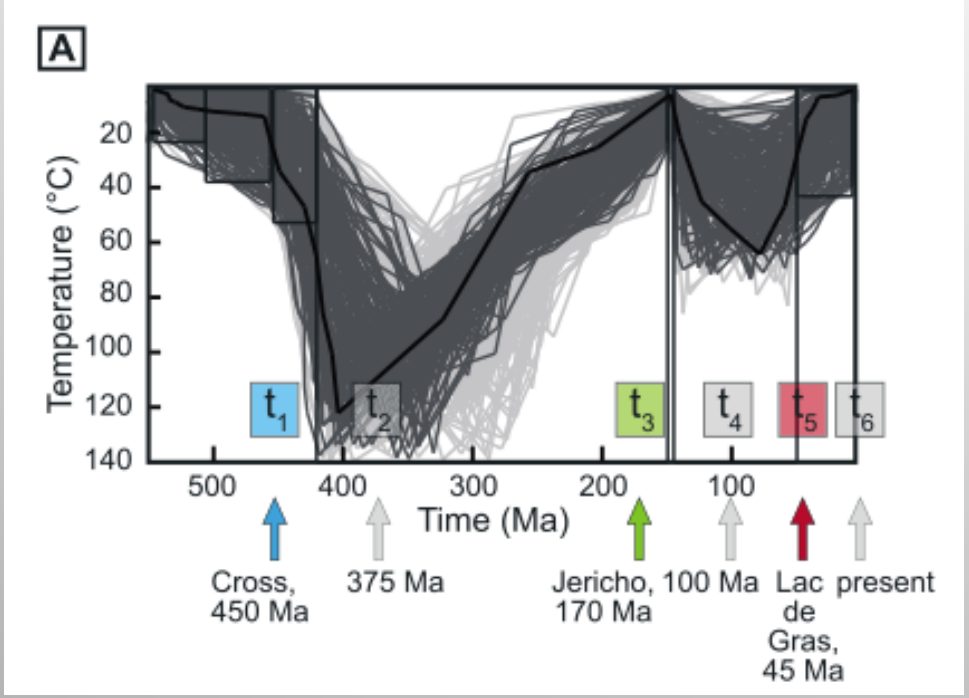


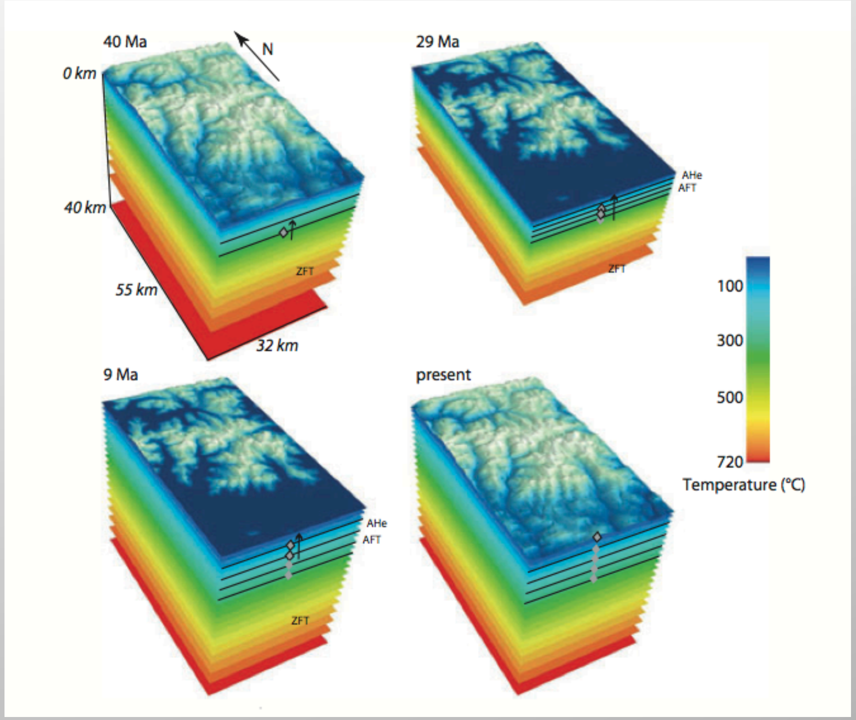




After Wolf et al., (1998)

Method 3 – Thermal Modeling





Ault, A.K., Flowers, R.M., and Bowring, S.A., 2013, Phanerozoic surface history of the Slave craton: Tectonics, v. 32, no. 5, p. 1066–1083, doi: 10.1002/tect.20069.

Fillon, C., and van der Beek, P., 2012, Post-orogenic evolution of the southern Pyrenees: constraints from inverse thermo-kinematic modelling of low-temperature thermochronology data: Basin Research, v. 24, p. n/a–n/a, doi: 10.1111/j.1365-2117.2011.00533.x.

Logistics of He dating (at CU TRaIL)

What you need:

1. Strategic and planned sample suite
2. Typical studies use 10 or more samples
3. Arrive with pure mineral separates

What you do:

1. Select, characterize, and pack grains. 1-2 samples per day is a typical speed
2. We measure the He, U, Th, and Sm and calculate a date
3. We collaborate on data interpretation