Low-Temperature Thermochronology Course

Fission Track Dating

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ESD EARTH SYSTEM DYNAMICS RESEARCH GROUP

Motivation

Timing of events:

- when was this fault active
- when did exhumation start/end – start of collision
- forming topography, plateaus, changing atmospheric pattern etc.
- magmatism, volcanism, contact metamorphism
- metamorphic events (PtT conditions)

Rate of a process:

- erosion rates (local/regional/orogen)
- exhumation rates (tectonic and/or erosion)
- river incision
- fault activity (how long and how much displacement)

Temperature-time history:

- burial depths (oil exploration)
- metamorphic paths

Goals

During this class we will learn:

1. Understand fission track dating
2. Count fission tracks
3. Using fission track lengths
4. Forward/Inverse modeling of t-T-histories

Road Map

1) Historical background
2) Fission track formation
3) Fission track dating methods
4) Preparation of samples/grains
5) Age equations
6) Fission track annealing
7) Fission track length
8) Annealing kinetics
9) Modeling of t-T-histories

Historic Background

- Price and Walker (1962) found spontaneous tracks in natural micas and induced fission tracks by fission of Uranium > they proposed that counting both yield the age of the mineral

- Fleischer and Price (1963) applied the method to a variety of minerals incl. apatite and zircon

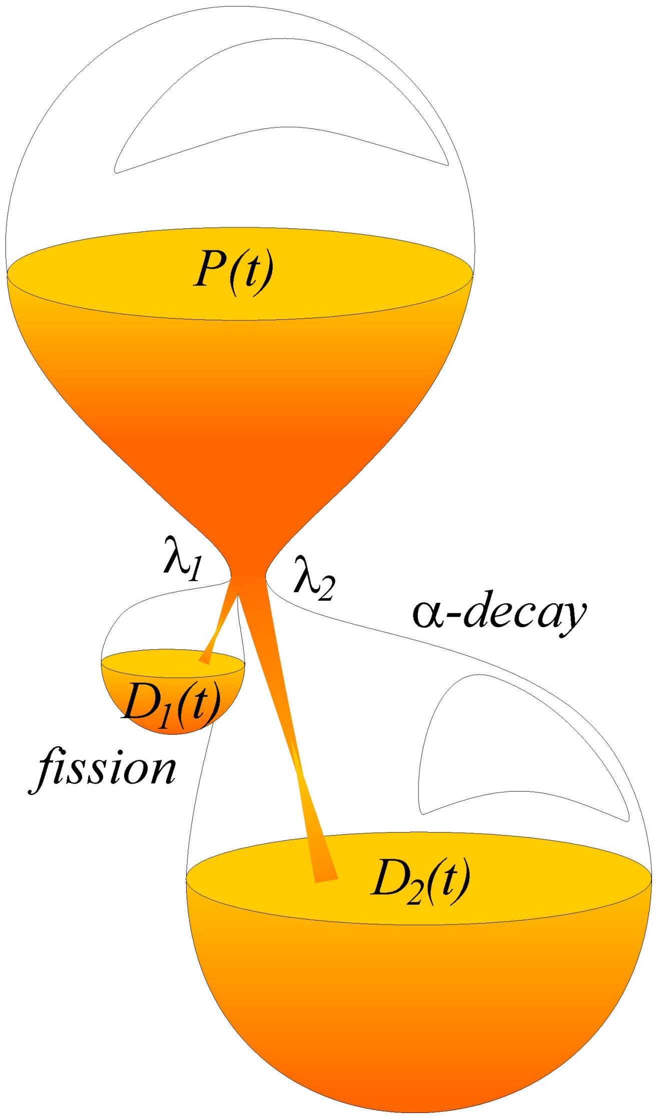
- Reproducibility of FT ages between labs, users, and irradiations was bad

- To overcome these methodological problems Hurford and Green (1982) suggested to relate the FT age to reference ages of age standards

- 90'ies FT annealing studies and the development of temperature-time path modeling based on FT measurements

- currently two methods are used the external detector method (Hurford and Green 1972) and the laser-based fission track method (Hasebe et al. 2004)

Uranium Decay

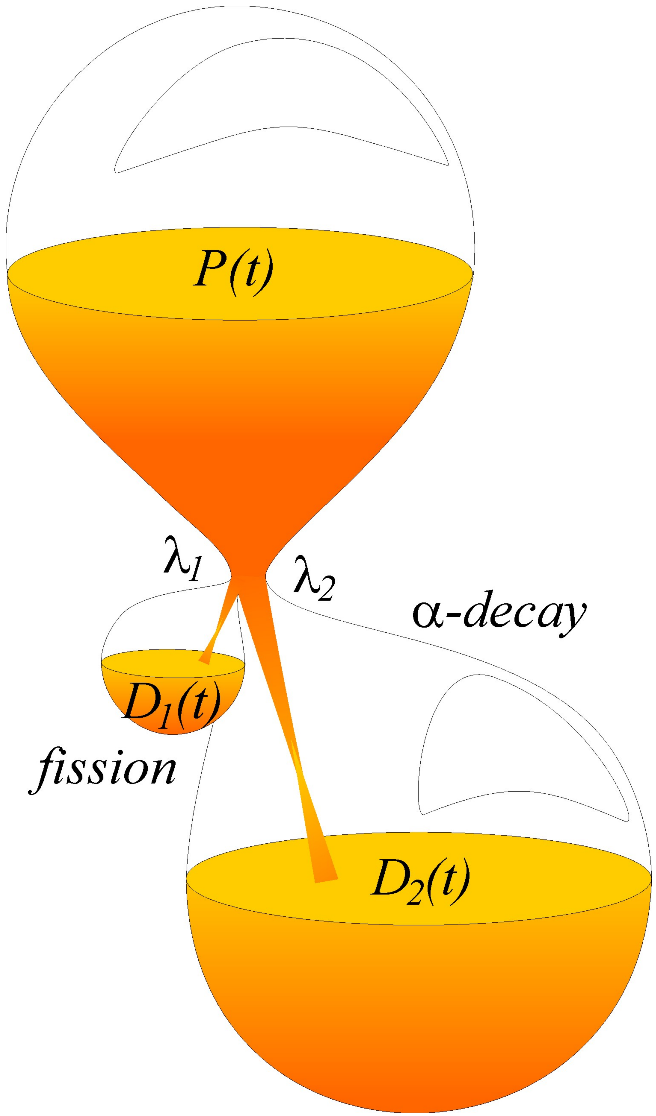


^{238}U is unstable in nature

Decays in 2 different ways:

1. Alpha (α) ejection
   [?] spalls off a ^{4}He particle
   ($T_{1/2}$ is ~4.5 x10^{9} yrs)

Uranium Decay



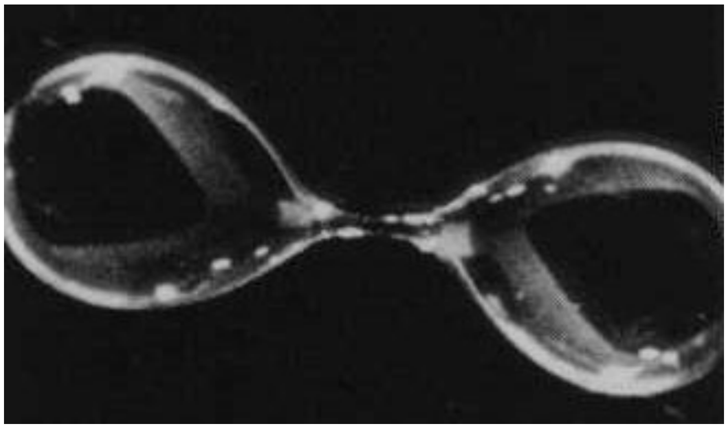
^{238}U is unstable in nature

Decays in 2 different ways:

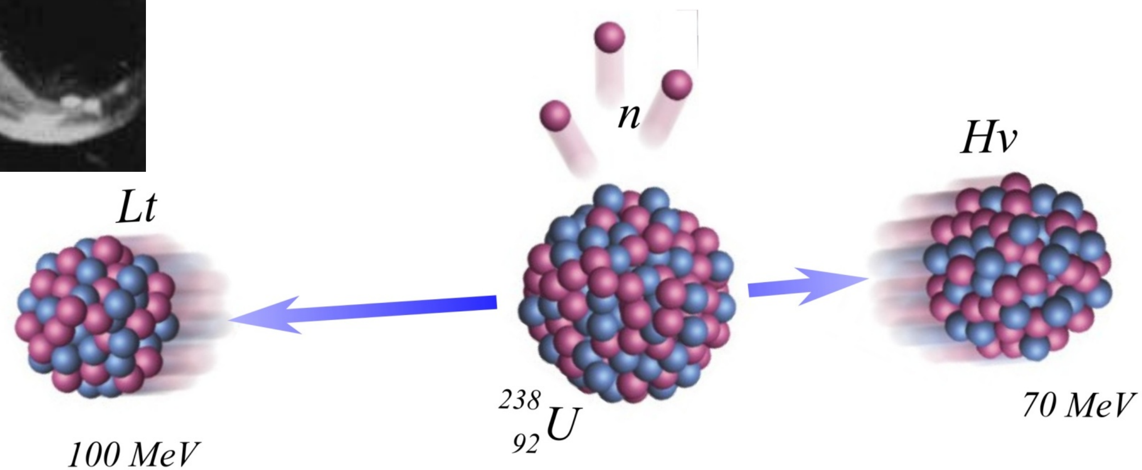
1. Alpha (α) ejection
   [?] spalls off a ^{4}He particle
   ($T_{1/2}$ is ~4.5×10^{9} yrs)

2. Fission (1 in every ~2,000,000 decays)
   [?] nuclei splits & leaves damage trail*
   (^{238}U fission $T_{1/2}$ is ~1.3×10^{16} yrs)
   *length of track formed is constant

Spontaneous Fission of ^{238}U



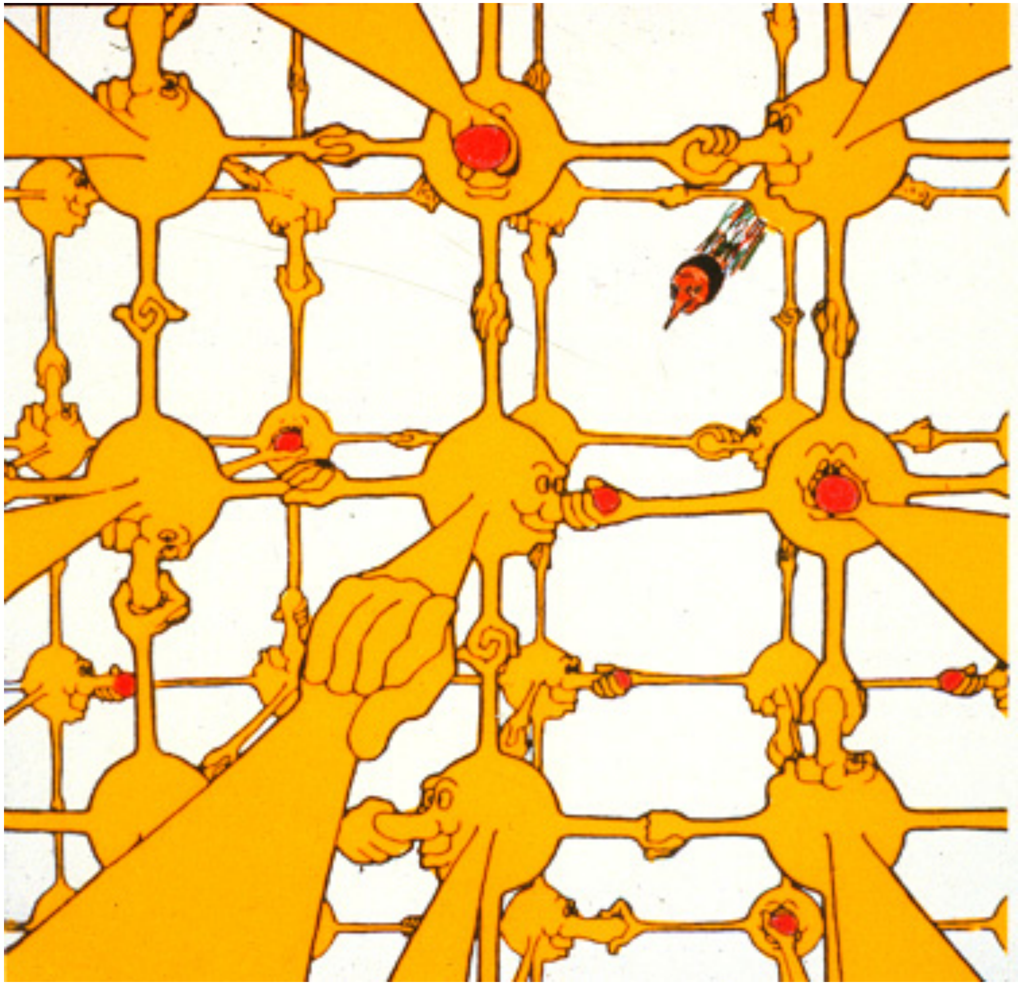
spontaneous fission of ^{238}U



- Fission releases 210 MeV of which 170 MeV are kinetic energy
- Fission track = linear damage of the mineral lattice along the trajectories of the fission fragments

Track Formation

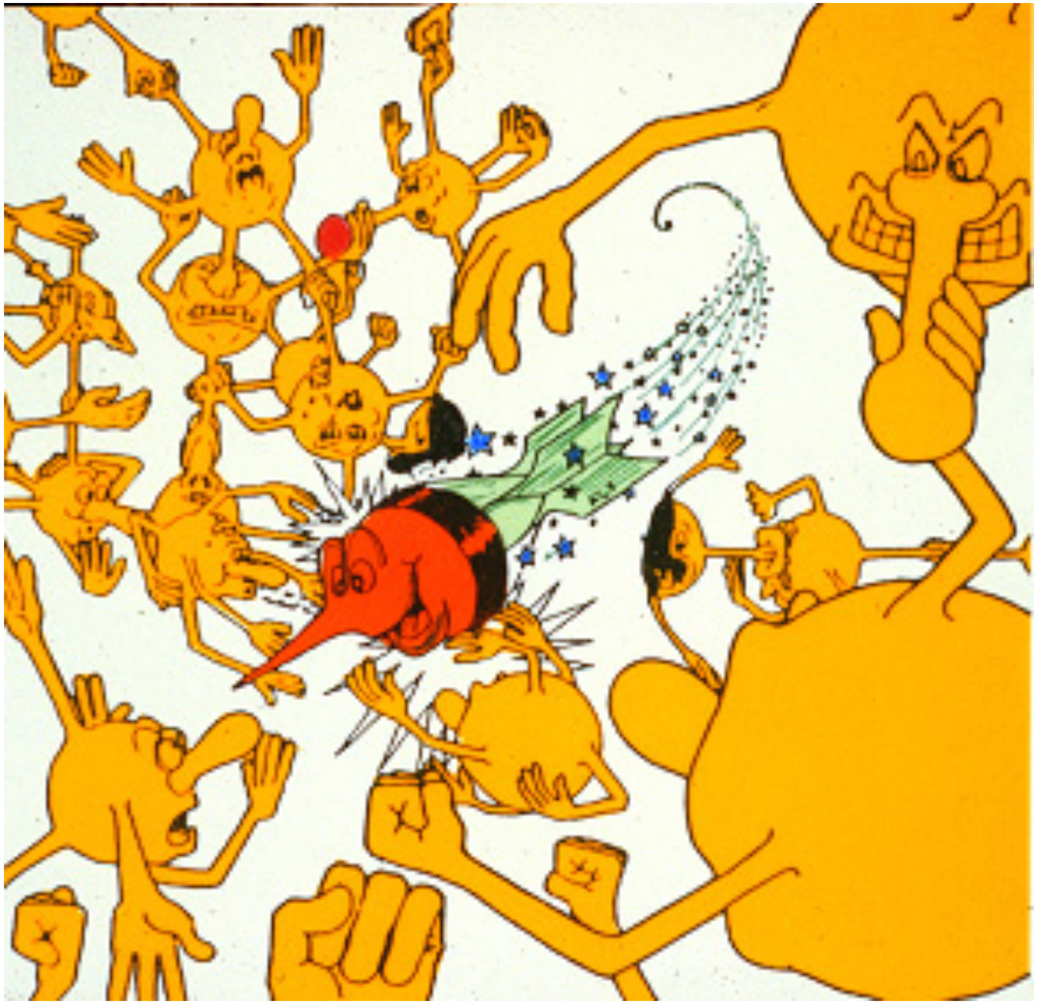
Our level of understanding…



according to Richard Ketcham

Track Formation

Our level of understanding…



according to Richard Ketcham

Track Formation

After ion explosion spike model

(Fleischer et al. 1965a):

(A) Rapid massively positively-charged particle strips lattice electrons along its trajectory, leaving an array of positively-ionized lattice atoms

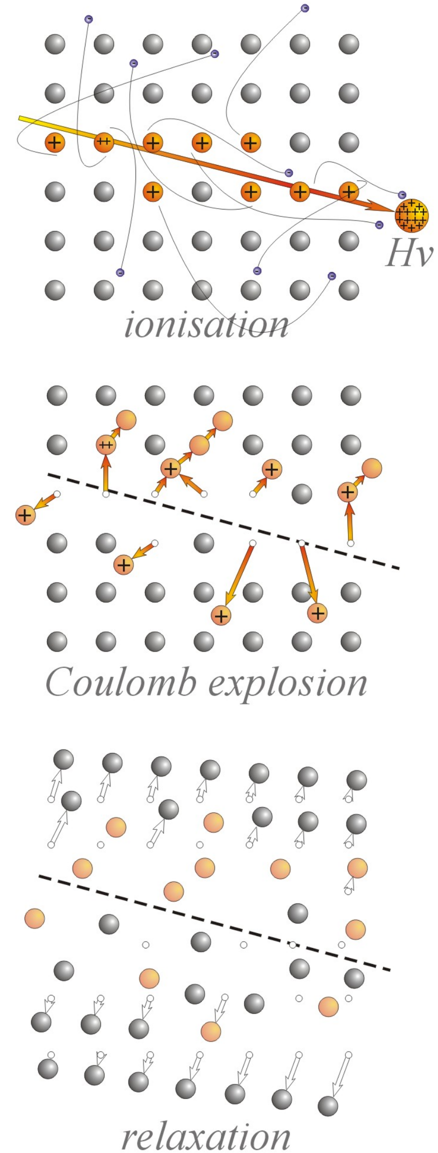
(B) Resulting positive ions displaced due to like-charge repulsion, creates vacancies

(C) Stressed region relaxes elastically, straining surrounding undamaged lattice.

A

B

C



Tagami & O'Sullivan, 2005, MSA volume

Track Formation

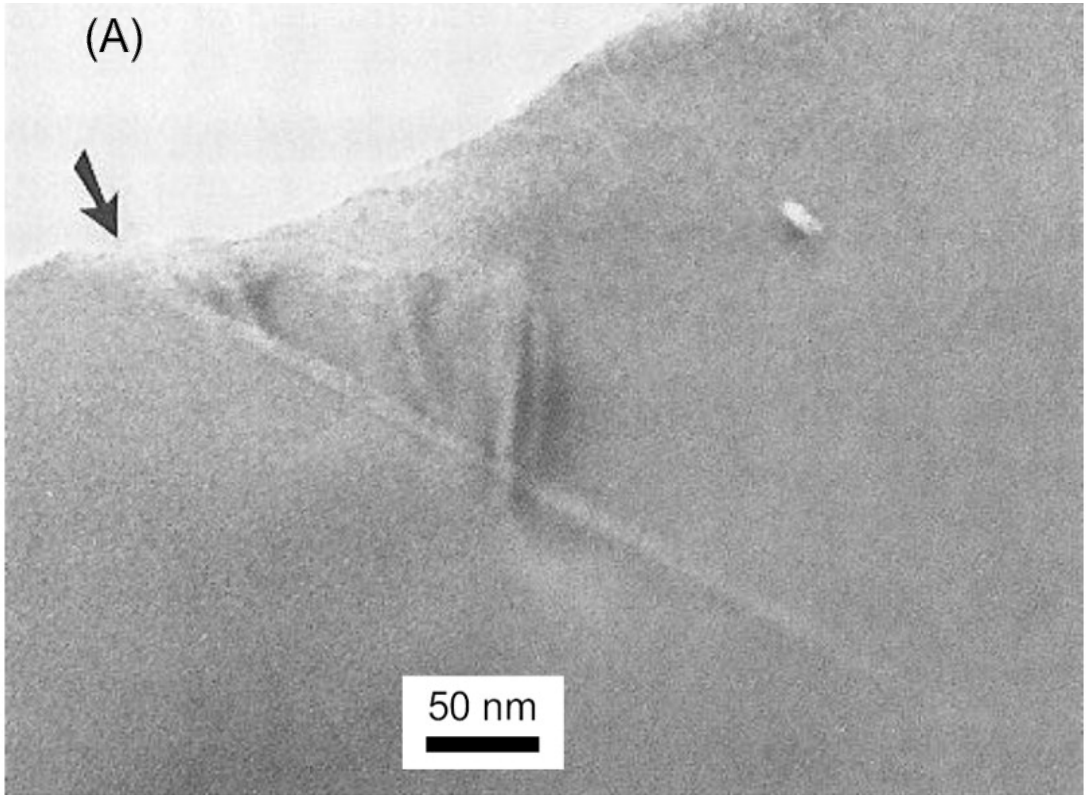


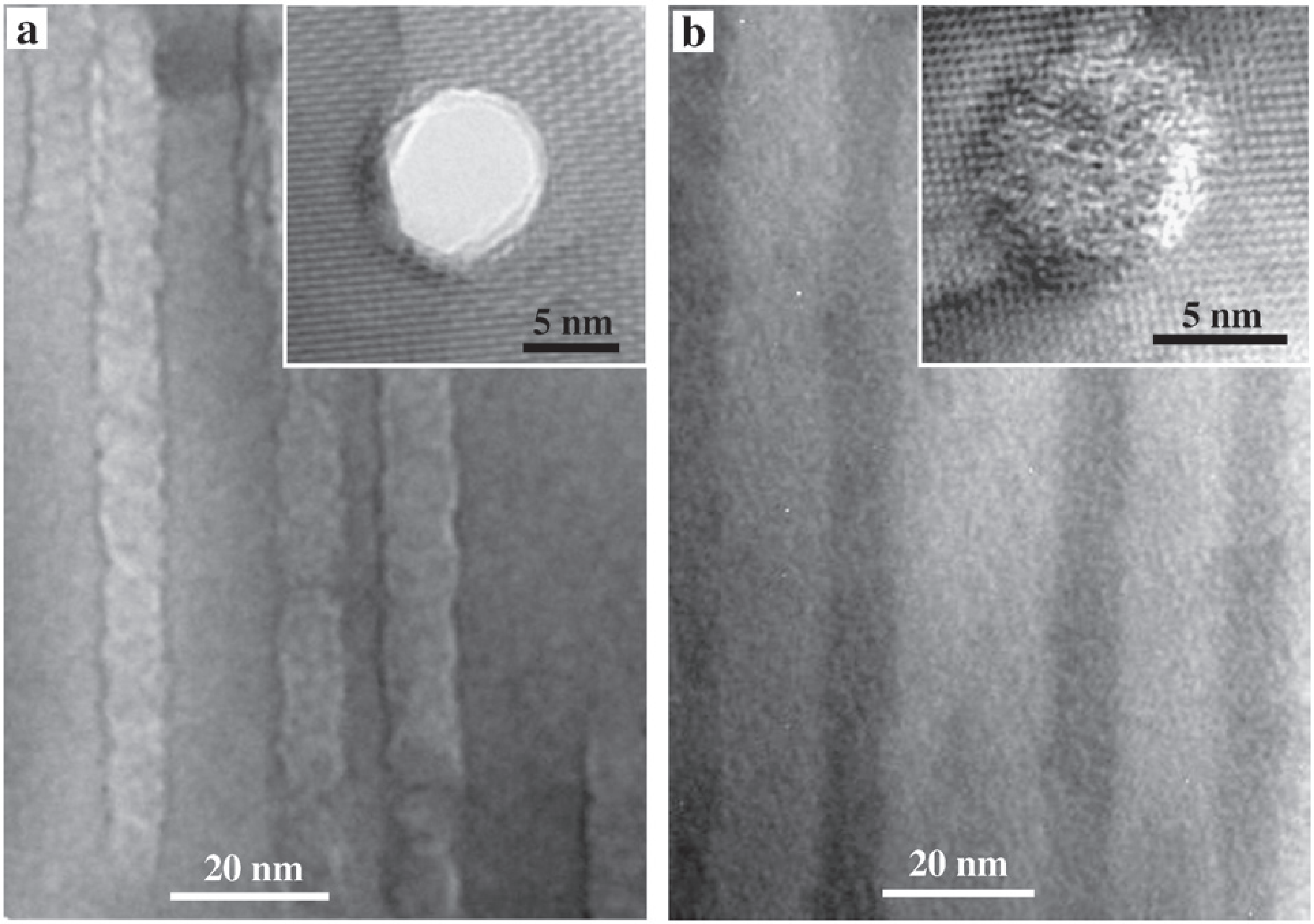
Figure 2. Atomic-scale images of latent (unetched) tracks: (A) an induced track in Durango fluorapatite observed subparallel to its length by transmission electron microscopy (Paul and Fitzgerald 1992).

Track Formation

TEM images of latent induced tracks parallel and perpendicular to view

Apatite

Zircon

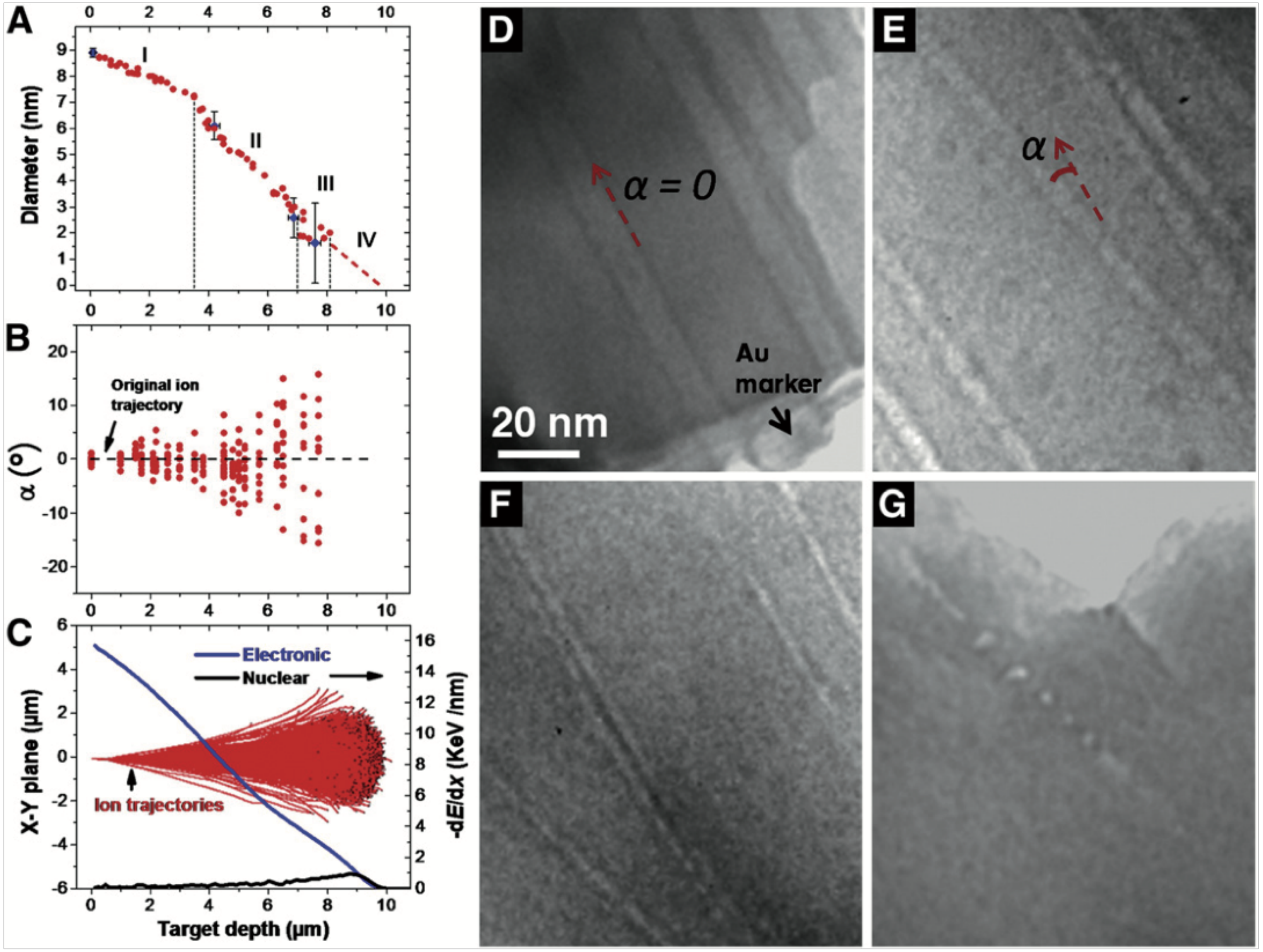


Li et al. (2011)

Track Formation

Apatite

- Track diameter reduction along the track can be subdivided in four sections
- Tracks may be segmented in section IV (G)
- As the particle lose kinetic energy nuclear collisions increases and deflect the particle from its straight path (B), deflection fits with modeled paths (C)

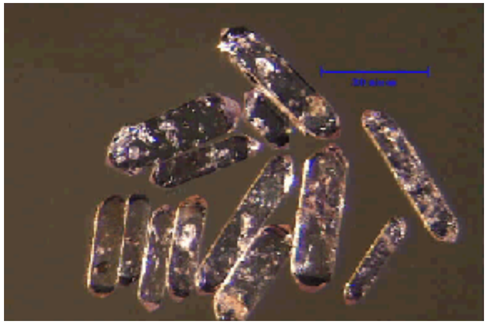


Li et al. (2012)

Commonly used Mineral Phases

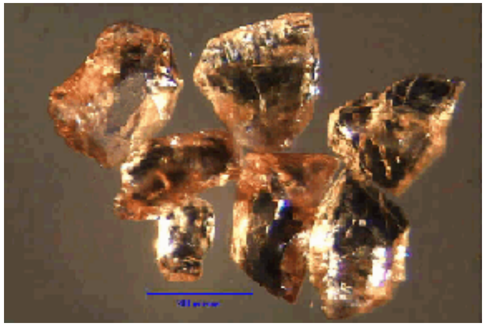
Apatite
$Ca_5(PO_4)_3(F,Cl,OH)$

T_c = 100 – 110° C
U,Th 5–50 ppm



Zircon
$ZrSiO_4$

T_c = 210 – 290° C
U,Th 100s–1000s ppm

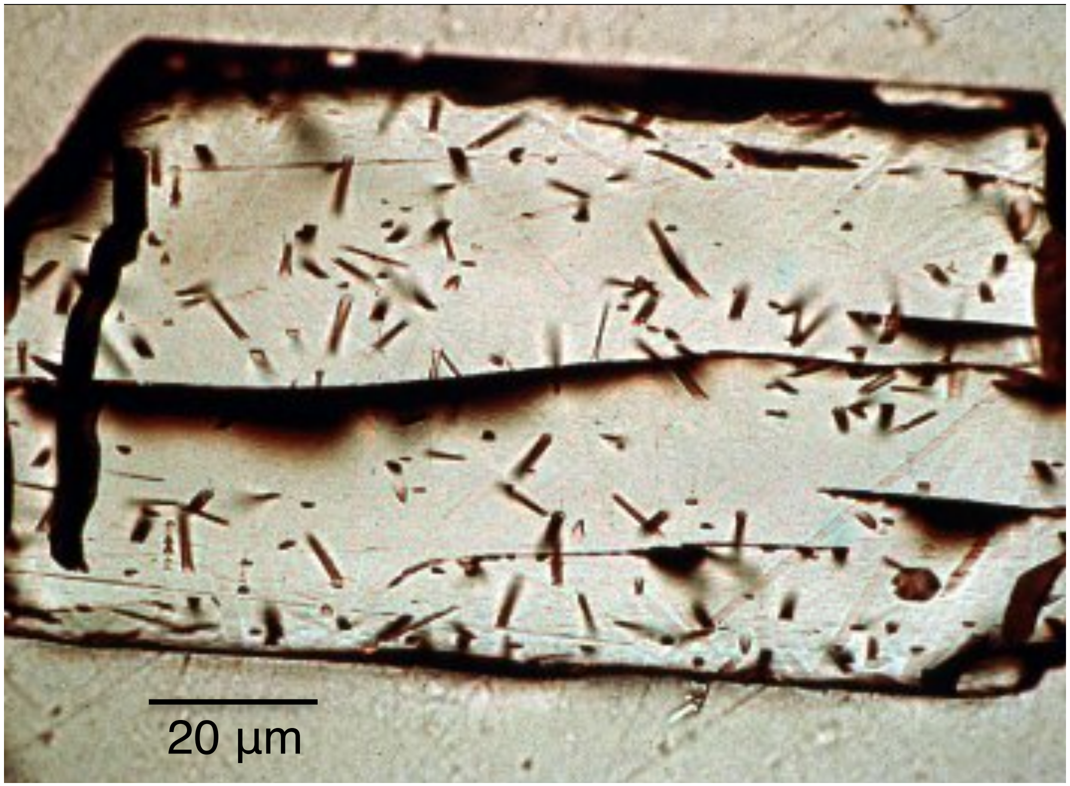


Titanite
$CaTiSiO_5$

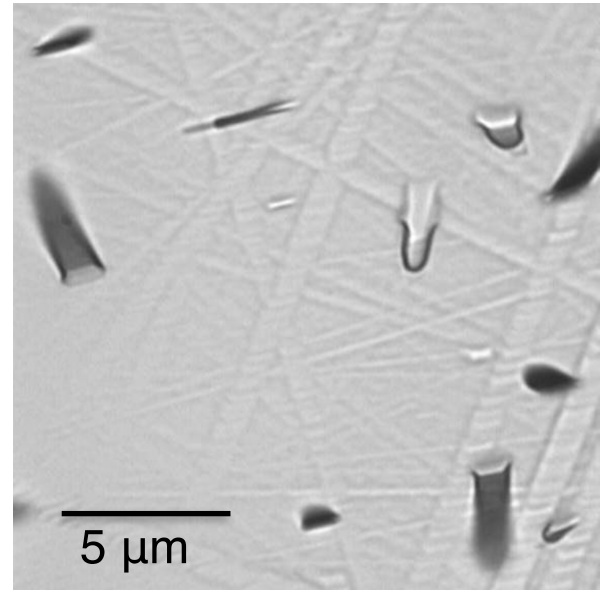
T_c = ~240° C
U,Th 10s–100s ppm

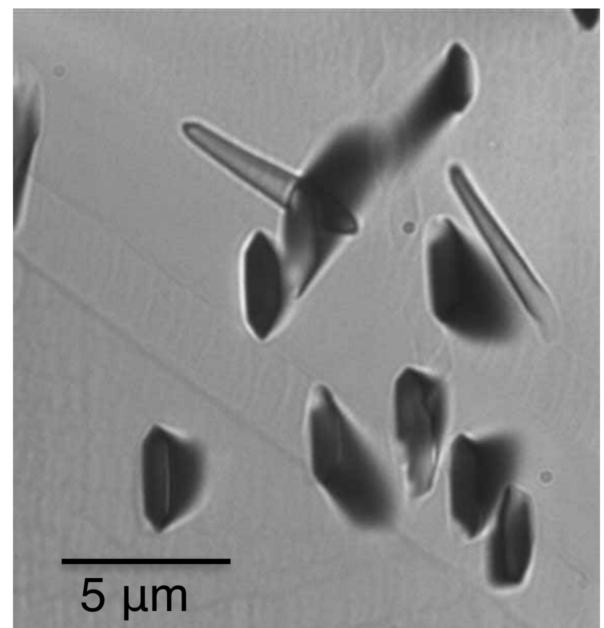
100 µm

Etched Tracks in Apatite

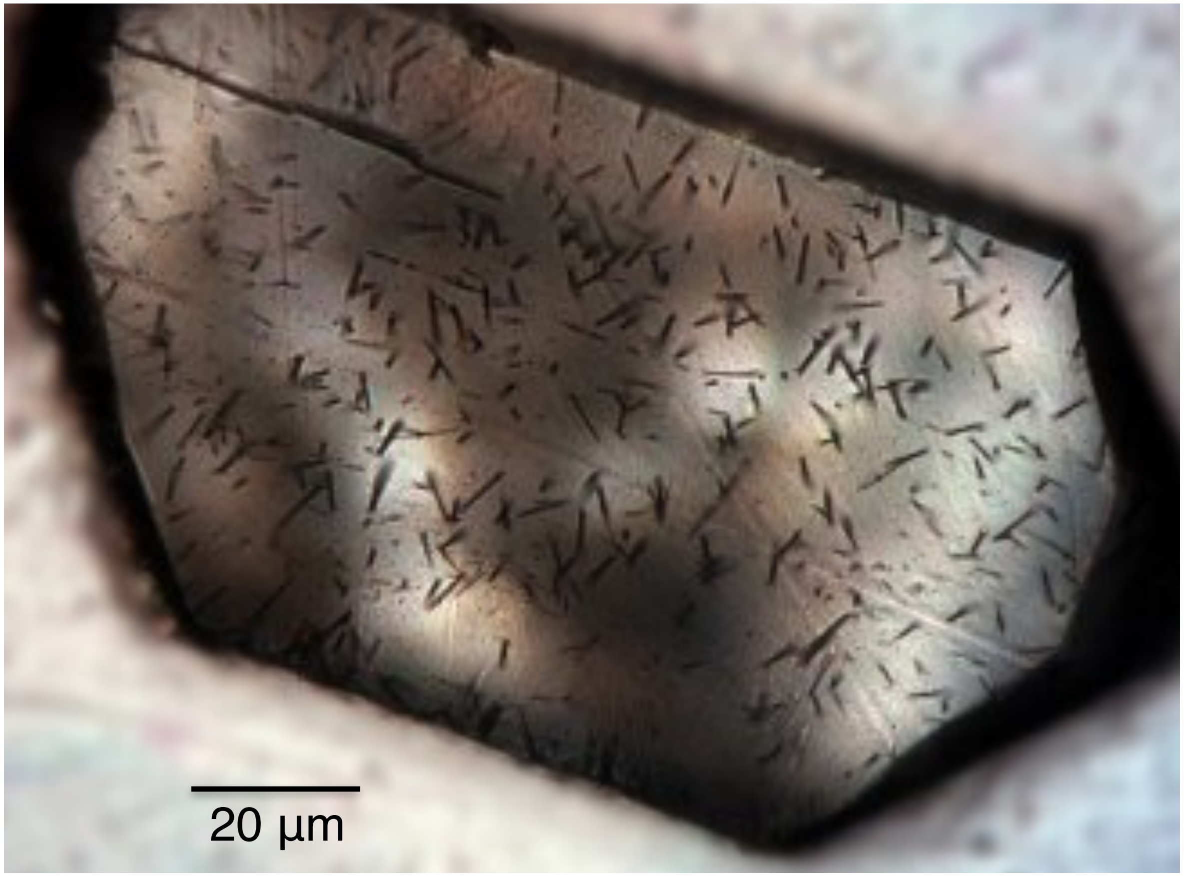


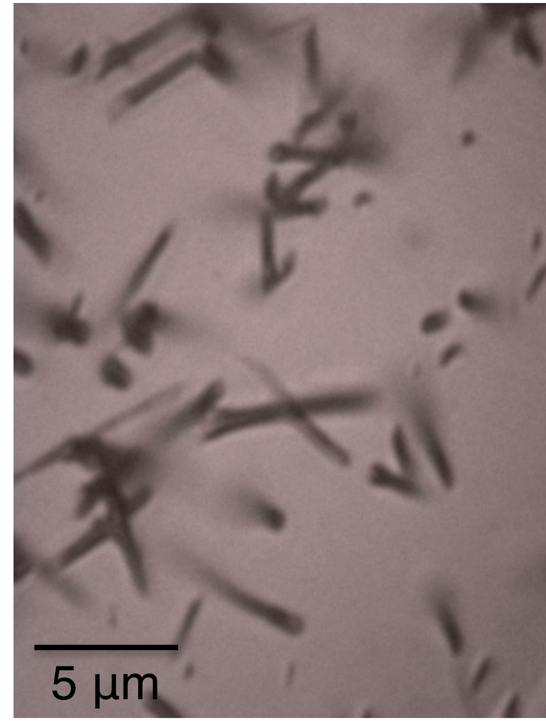
in apatite: ~16 µm length, 1-6 µm width

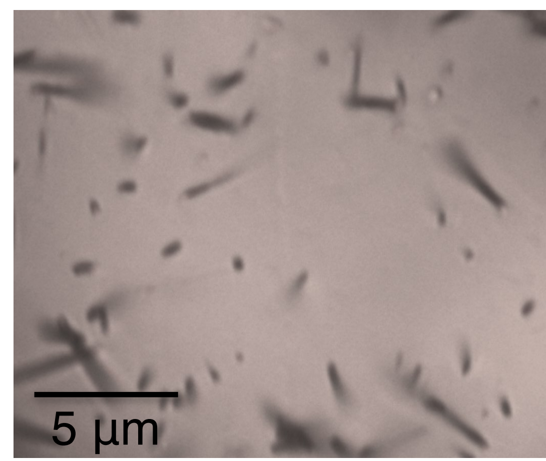




Etched Tracks in Zircon







in zircon: ~12 µm length, ~1 µm width

Fission Track Dating

Difference to other radiometric dating methods:

- Daughter product is a physical damage of the crystals lattice

Which factors control the amount of fission tracks in a mineral?

Number of fission tracks is increasing with time

Number of fission tracks is proportional to the uranium concentration

But: Fission tracks can anneal and number of fission tracks decrease with annealing!

Reason: Fission track annealing can lead to complete healing of the crystal defects. The healing is mainly depending on temperature T (and the annealing kinetics of individual grains).

Fission Track Dating Protocol

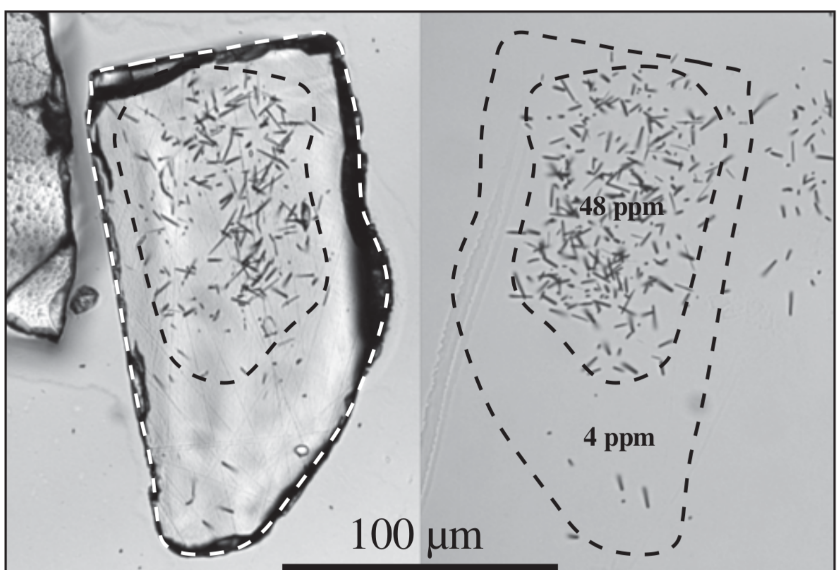
Two principle dating protocols:

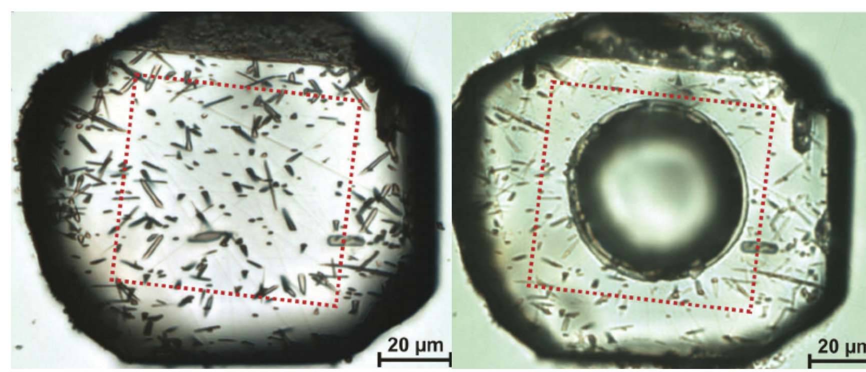
External Detector Method (EDM)

Determination of uranium concentration - irradiation with thermal neutrons and inducing inducing fission of ^{235}U and counting on an external detector

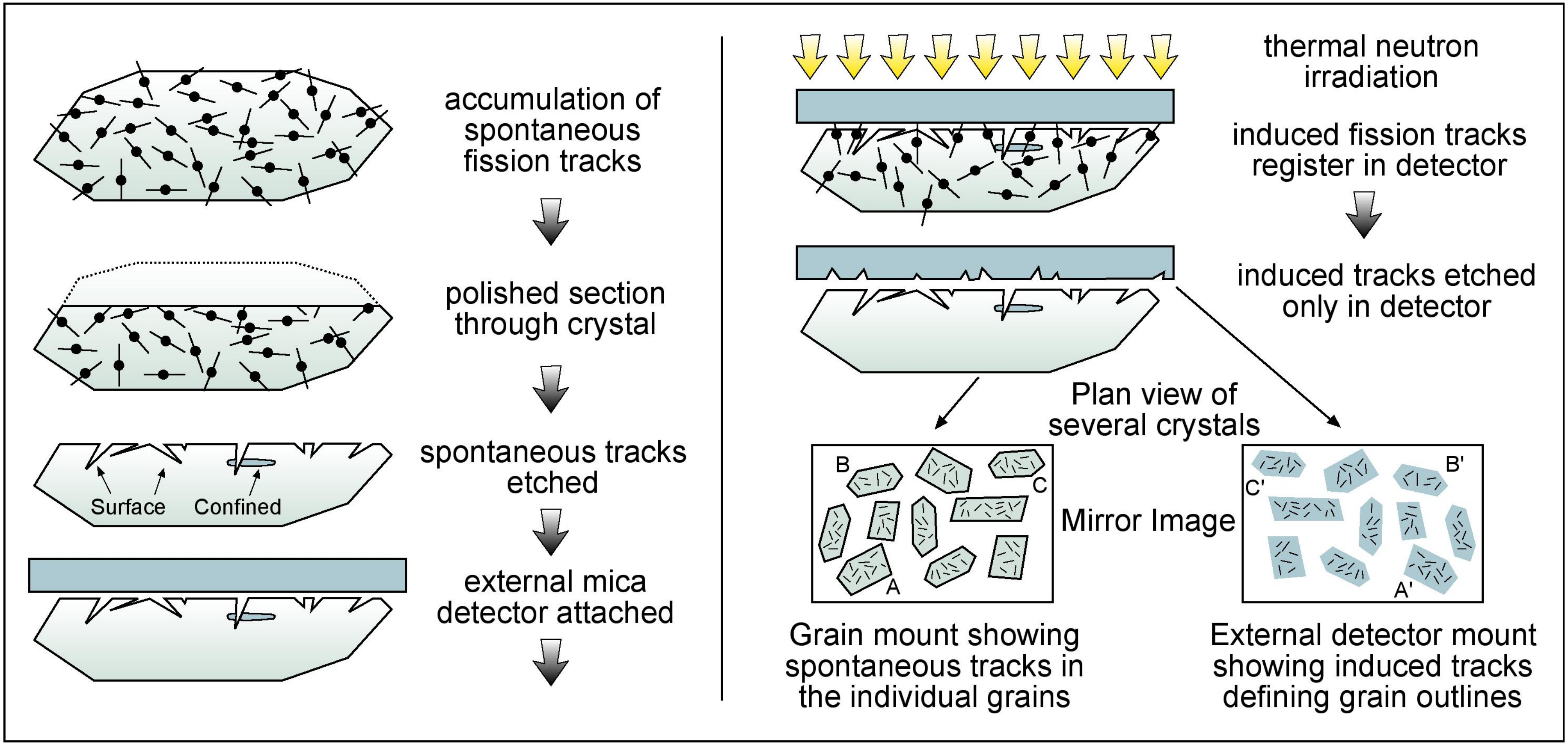
Laser-Based Fission Track Method (LAFT)

Determination of uranium with a Laser Ablation – Inductively Coupled Plasma – Mass Spectrometry (LA-ICP-MS)

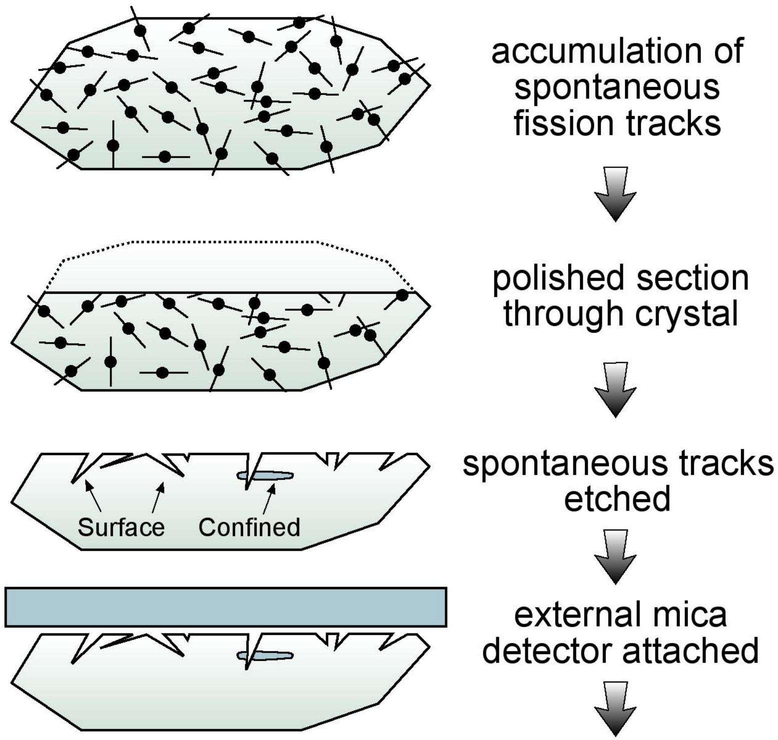




External Detector Method



External Detector Method

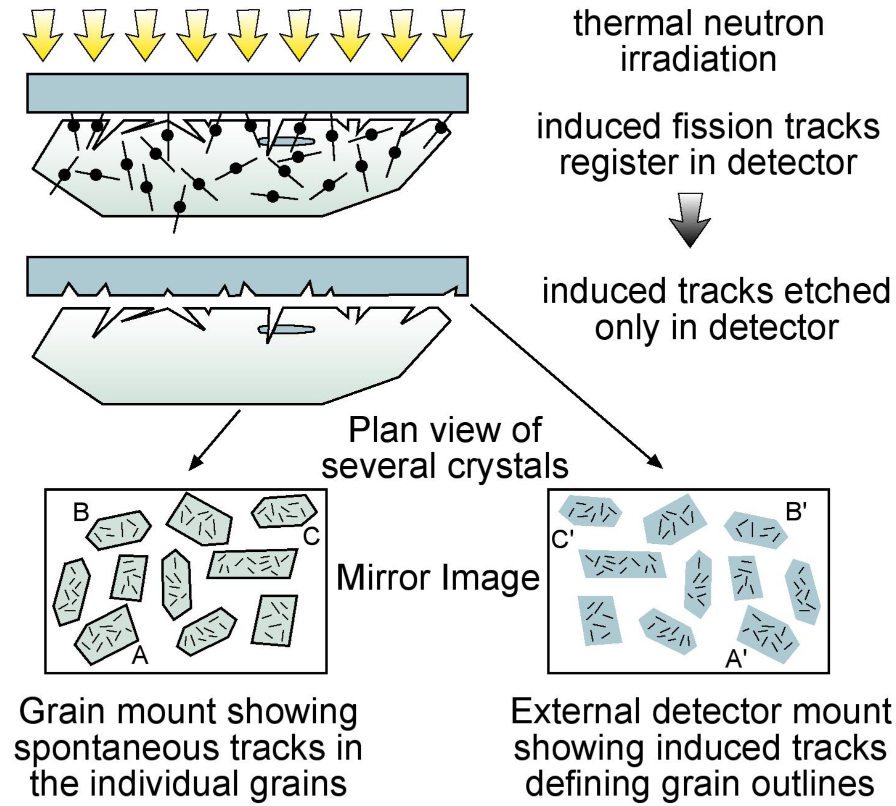


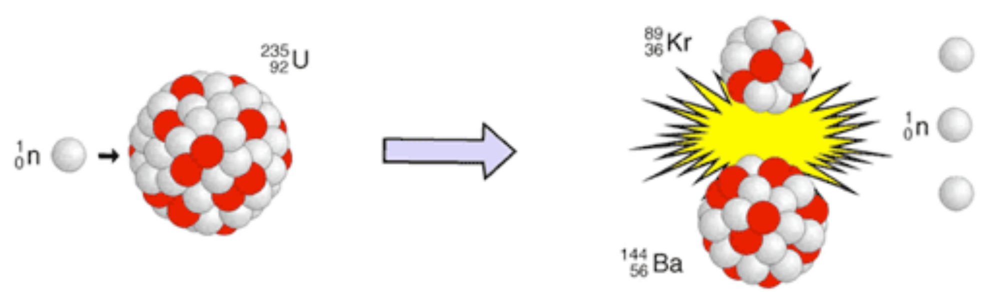
External detector:

- Natural muscovite mica free of uranium and impurities
- Thickness of 0.1 mm

External Detector Method

- Quantifying the number of parent isotopes (^{238}U) by counting tracks induced by fission of ^{235}U by thermal neutrons during irradiation in a nuclear reactor
- Thermal neutrons may be captured by ^{235}U, it get instabil and fission into two fragments
- A large fraction of the released energy is kinetic energy and an induced fission track is formed in the grain and on the external detector
- Number of induced tracks is depending on ^{235}U, and $^{235}U/^{238}U$ ratio is constant in nature (1/137.9)
- Determine irradiation flux by counting induced tracks in a dosimeter glass with known uranium concentration

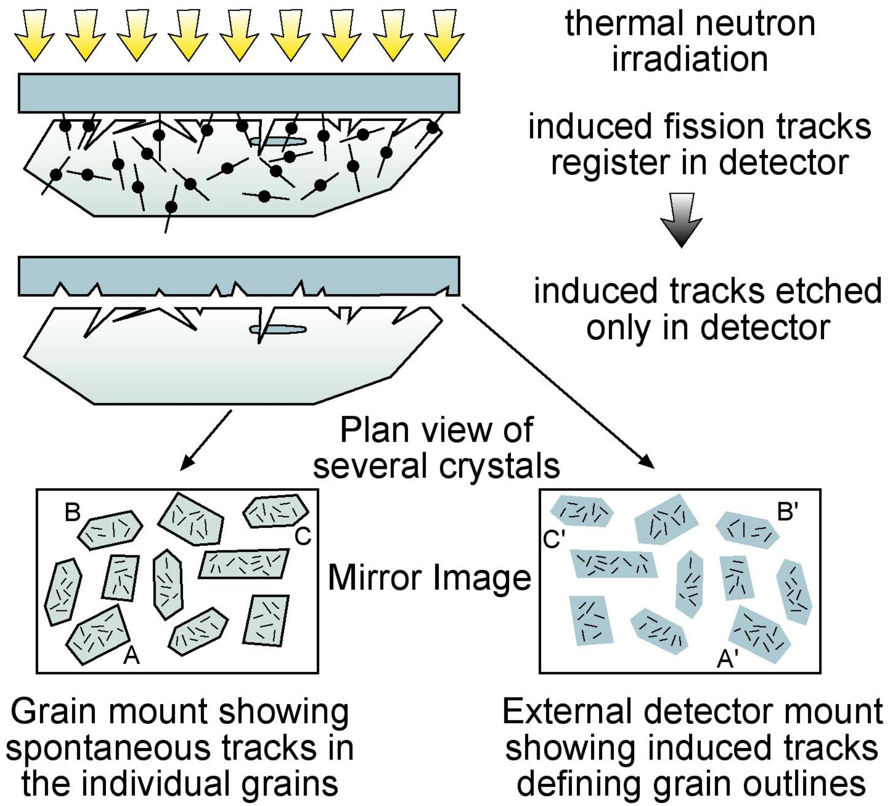




$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{89}_{36}Kr + ^{144}_{56}Ba + 3^{1}_{0}n + 210\ MeV$$

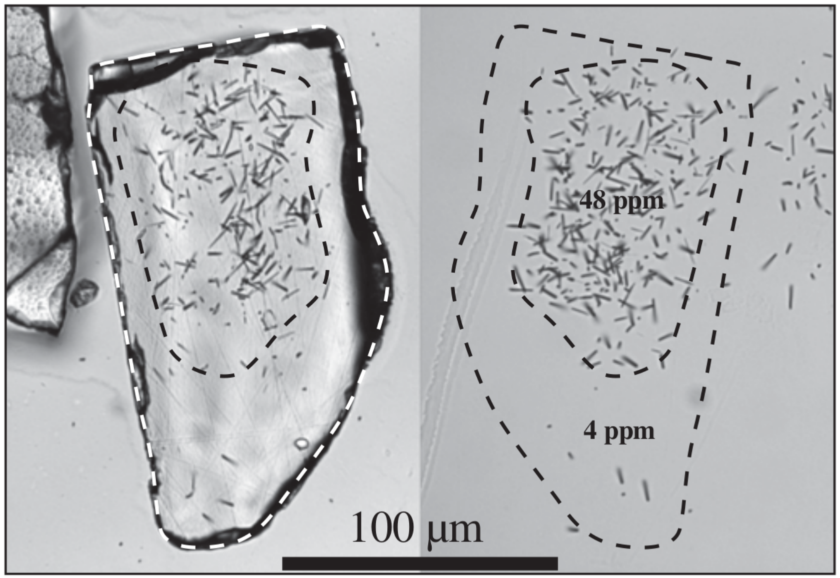
External Detector Method

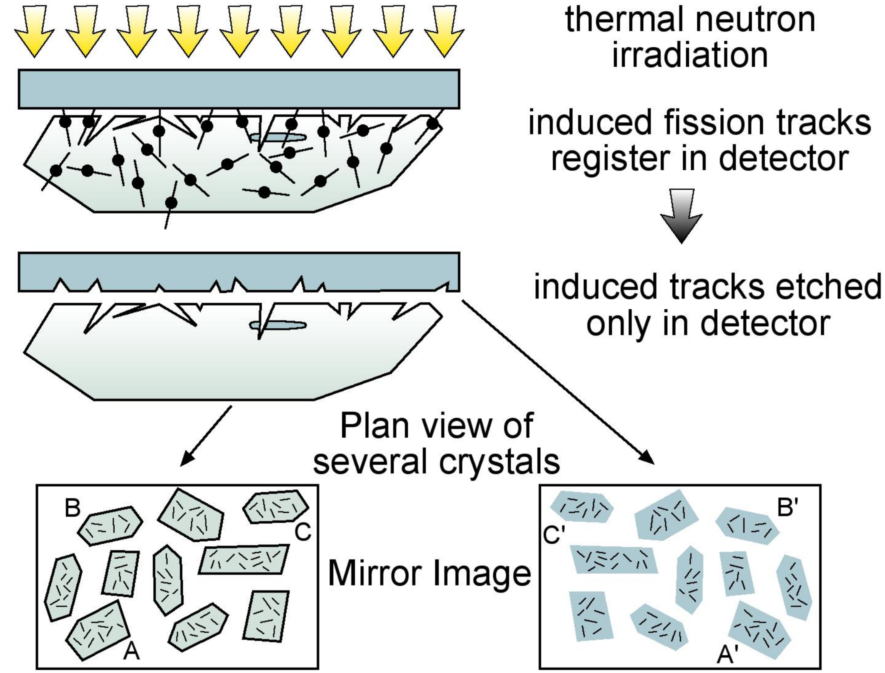
- Samples are irradiated together with a dosimeter glass with known uranium concentration to determine the irradiation flux by counting induced tracks and age standards to determine personal zeta calibration factor
- Irradiation process takes ~1 month, mainly depending on the fading of Induced short-lived radio-isotopes
- Handling of radioactive material!
- Induced fission tracks recorded on the external detector are etched 30 min with 40% HF



External Detector Method

- Sample mount and mica detector are aligned on a glass slide (mirror-inverted)





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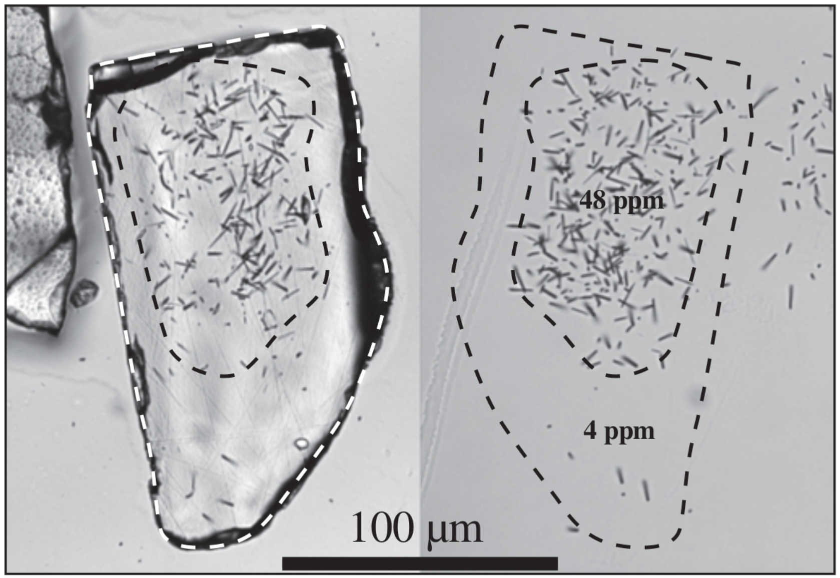

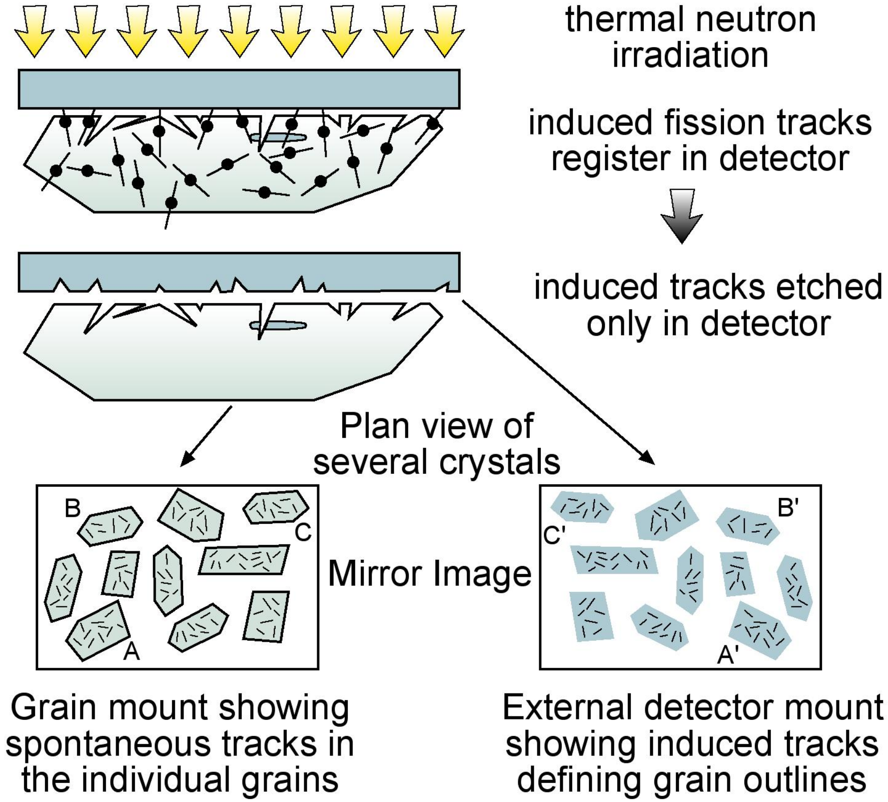

induced track density

$\rho_i \sim {}^{235}U \;\; \phi \;\; \sigma$

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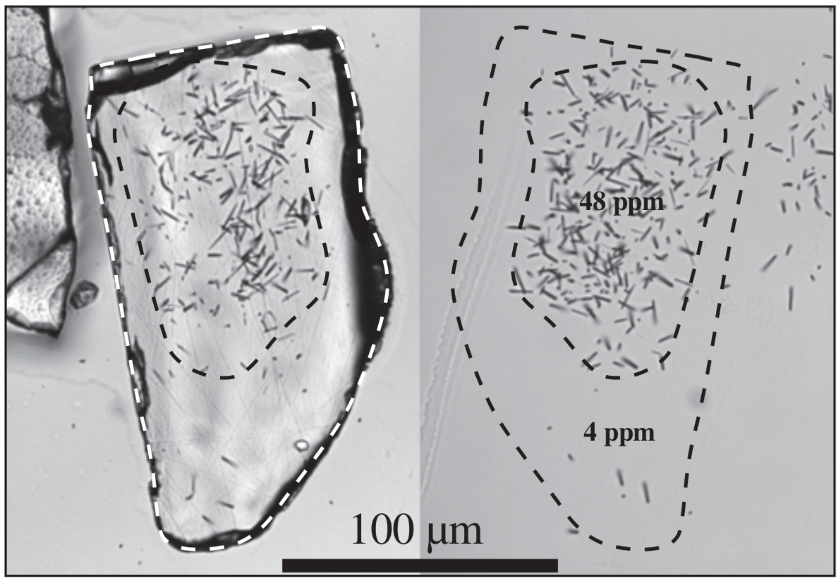
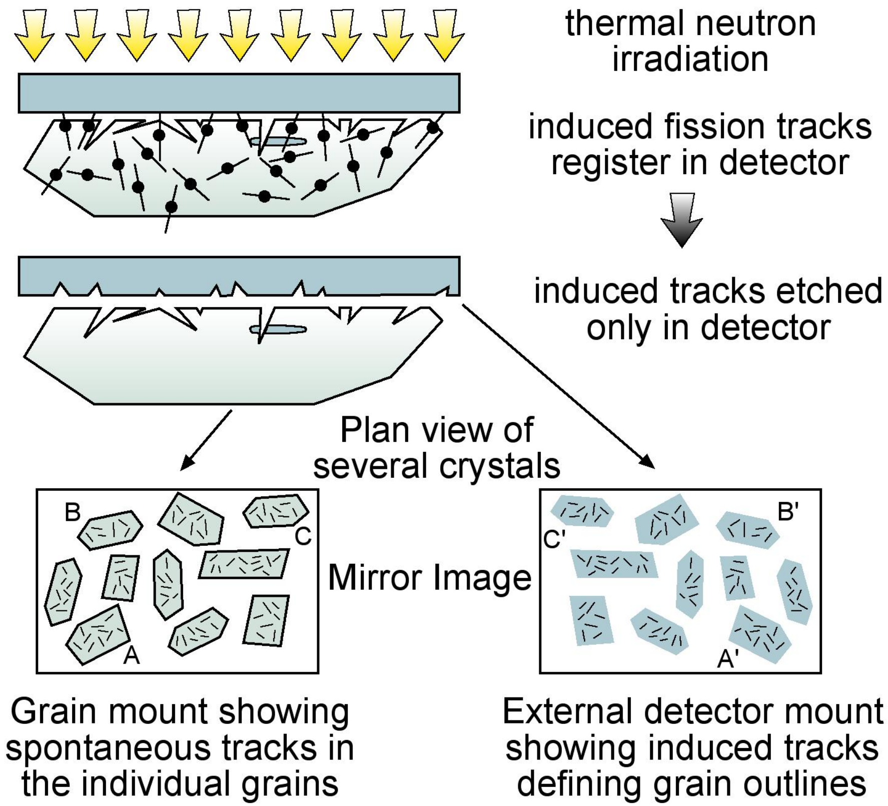




fossil track density

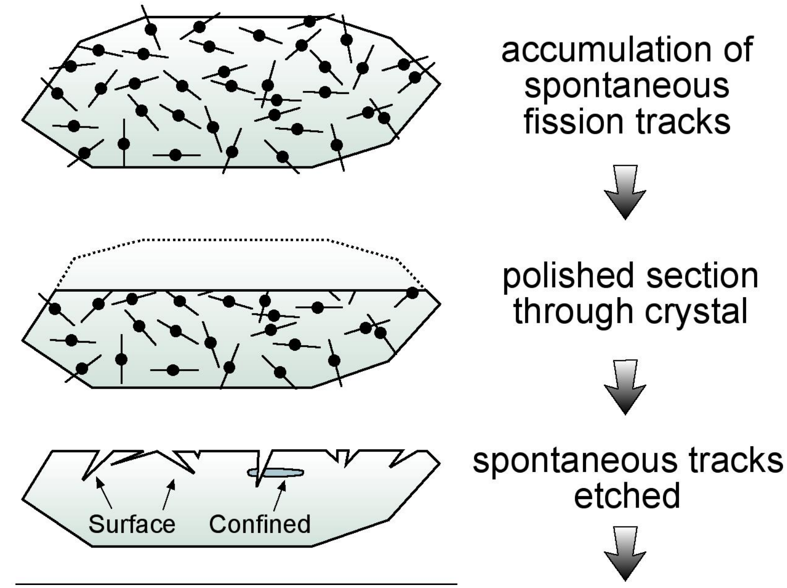
$\rho_s \sim\ ^{238}U\ \ \lambda_F\ \ t$

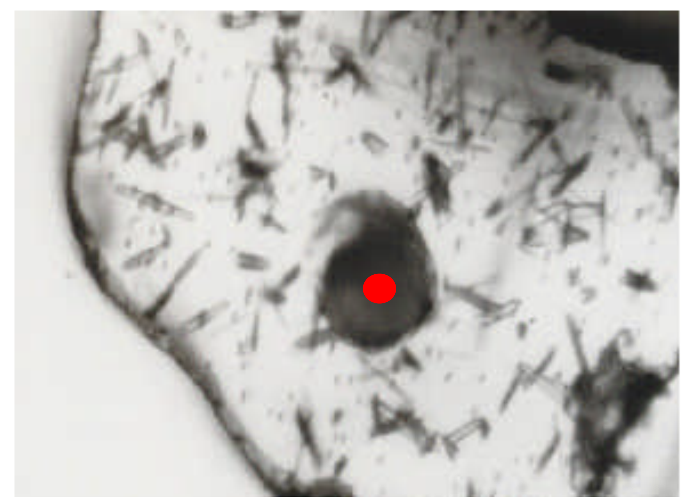
induced track density

$\rho_i \sim\ ^{235}U\ \ \phi\ \ \sigma$

Laser-Based Fission Track Method

- Laser is used to ablate the counted grain surface and measure the ^{238}U concentration with a ICP-MS
- Method was developed by Hasebe et al. (2004)
- Routinely used by many laboratories (Melbourne, UCL)





Laser spot

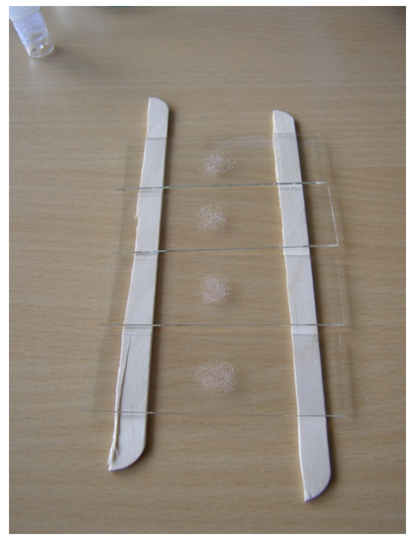
Fission Track Sample Preparation

- Crush with jaw crusher
- Sieve (<300 μm – very fine to coarse sand size)
- Concentrate heavy minerals with shaking table
- Sep from other mins using heavy liquid/magnetic techniques
  ⍰ Zr really heavy, Ap & Zr virtually non-magnetic

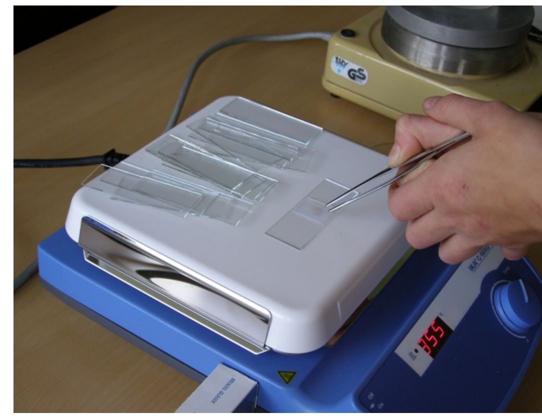
Fission Track Sample Preparation

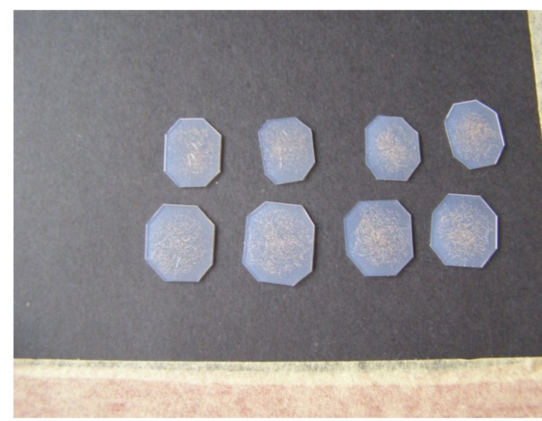
1. Make a mount of many apatite or zircon grains (>100), grind and polish, and etch to reveal the spontaneous tracks

apatite



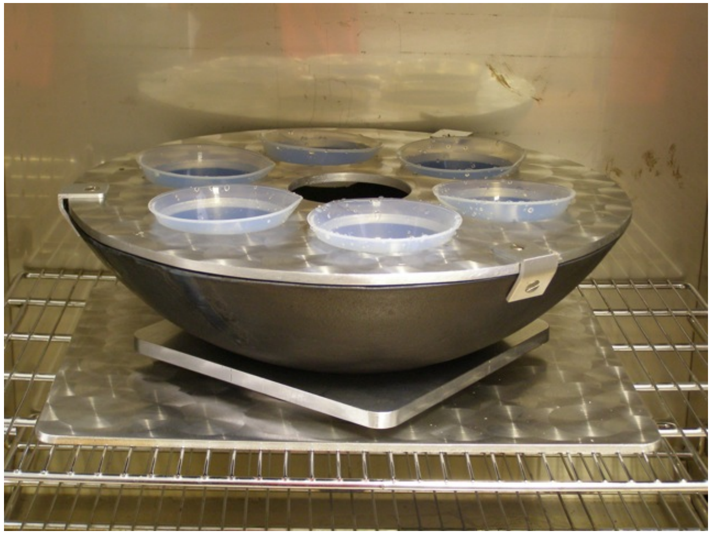
zircon





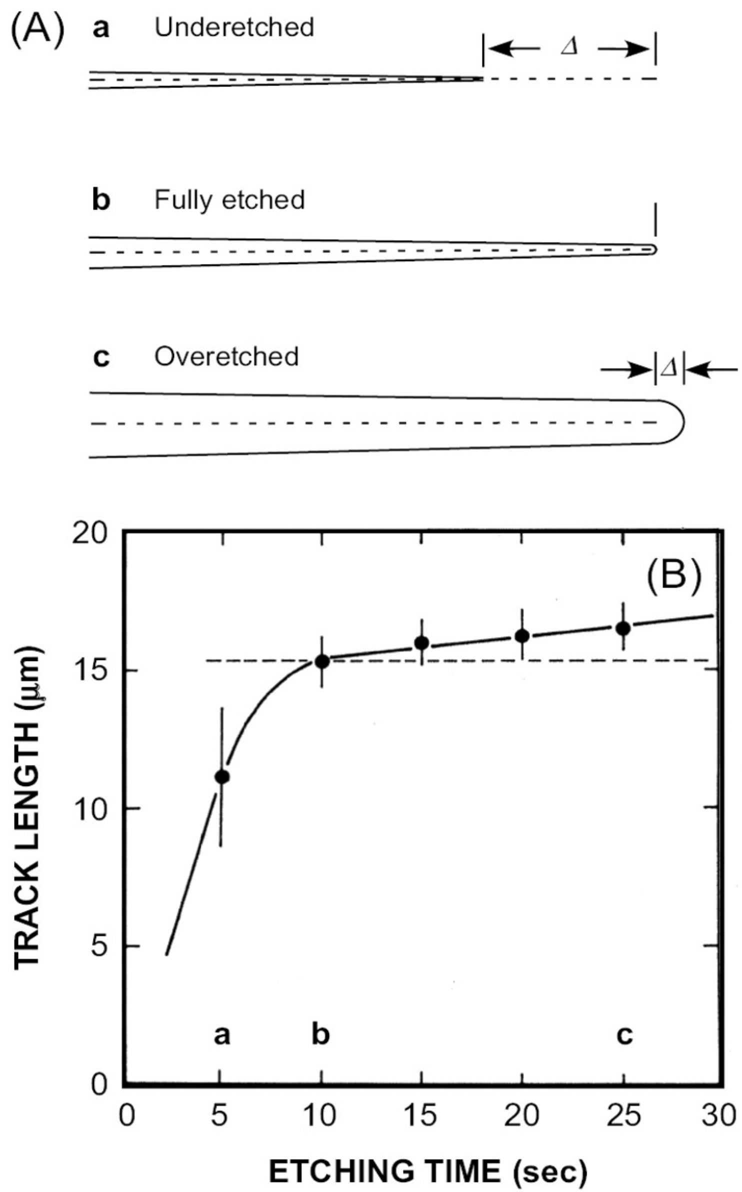
Fission Track Sample Preparation

- Apatite etching in 5.5 M HNO_3 for 20 seconds at 21°C
- Zircon etching in NaOH and KOH eutectic solution at 220°C for 6-150 hours
- Zircon etching time depends on accumulated radiation damage



Polishing apatite and zircon mounts

Fission Track Sample Preparation



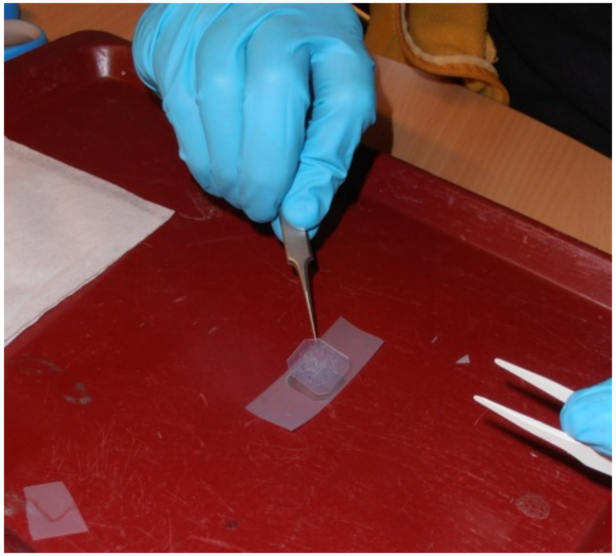
1. Natural tracks cannot be observed with a light microscope, but with e.g. TEM

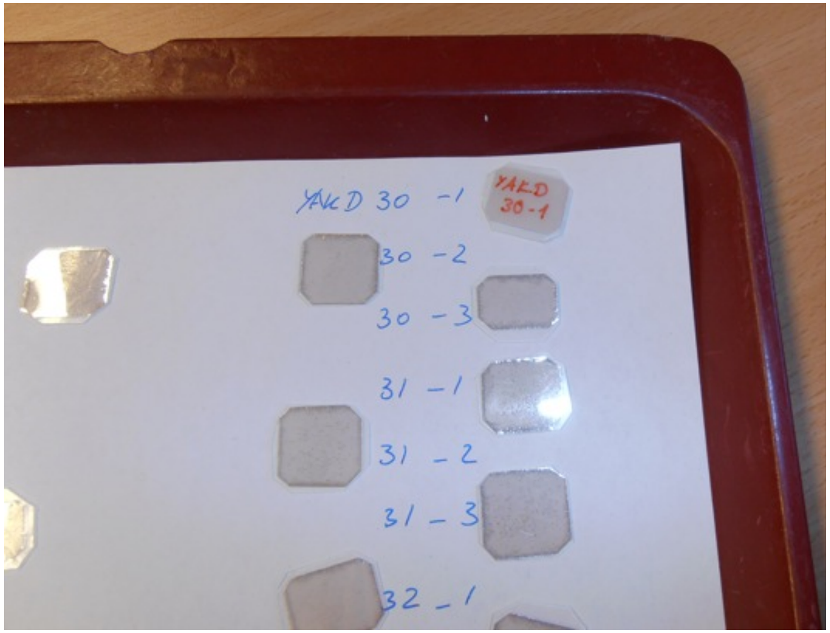
2. Bath in acid to enhance visibility
   - important to be precise in the time over which you etch!
   - it effects the track length…

Tagami & O'Sullivan, 2005, MSA volume

Fission Track Sample Preparation

2. Cover the etched grain mount with a muscovite external detector





Fission Track Sample Preparation

3. Thermal neutron irradiation to induce fission tracks

FRMII Garching, TU München

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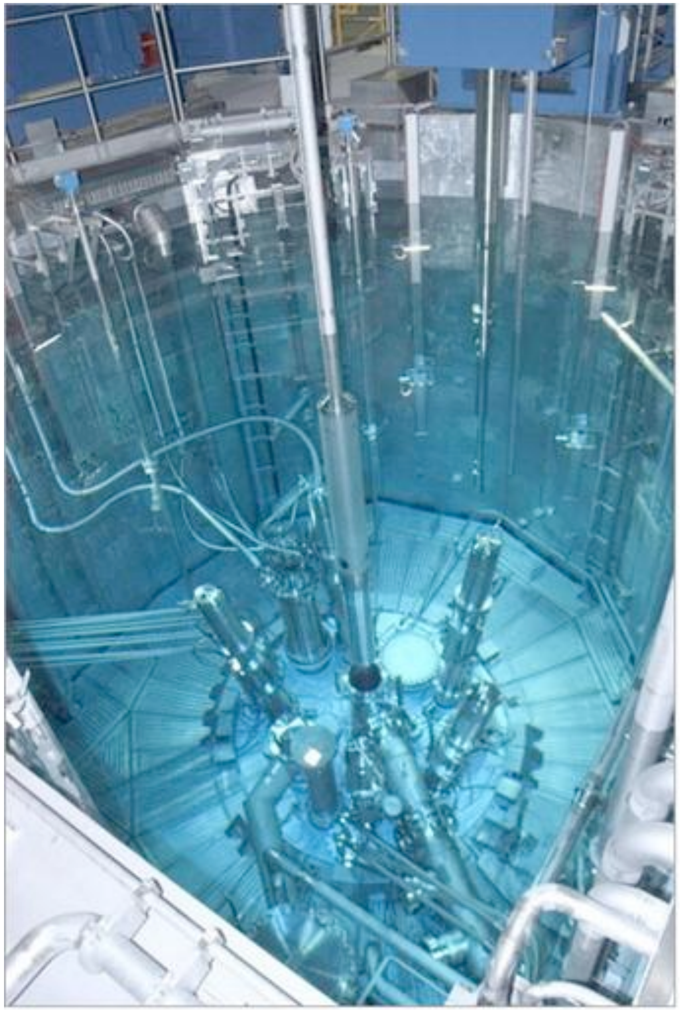
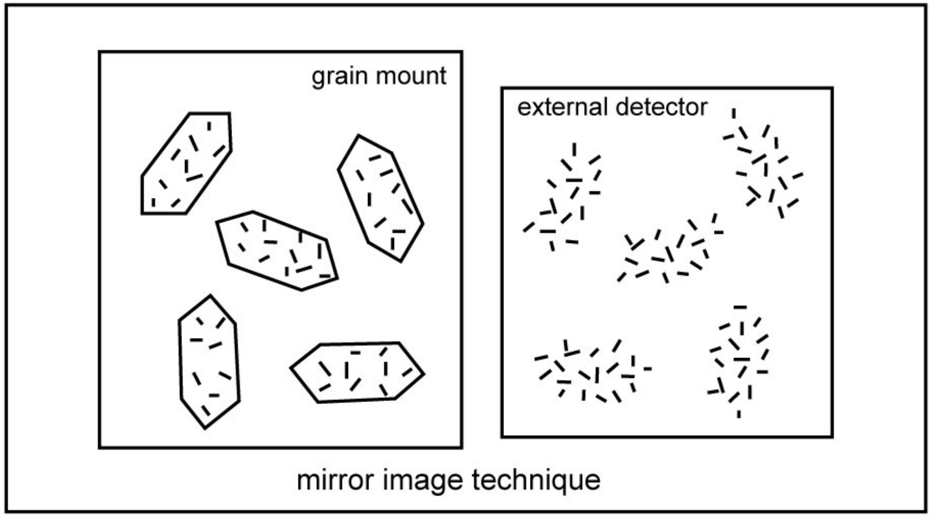
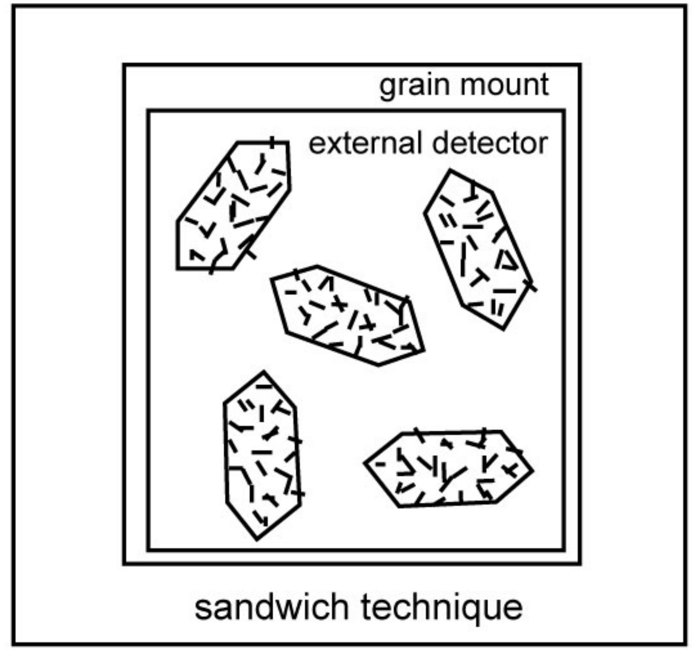


FRMII Garching, TU München

Count Fission Tracks

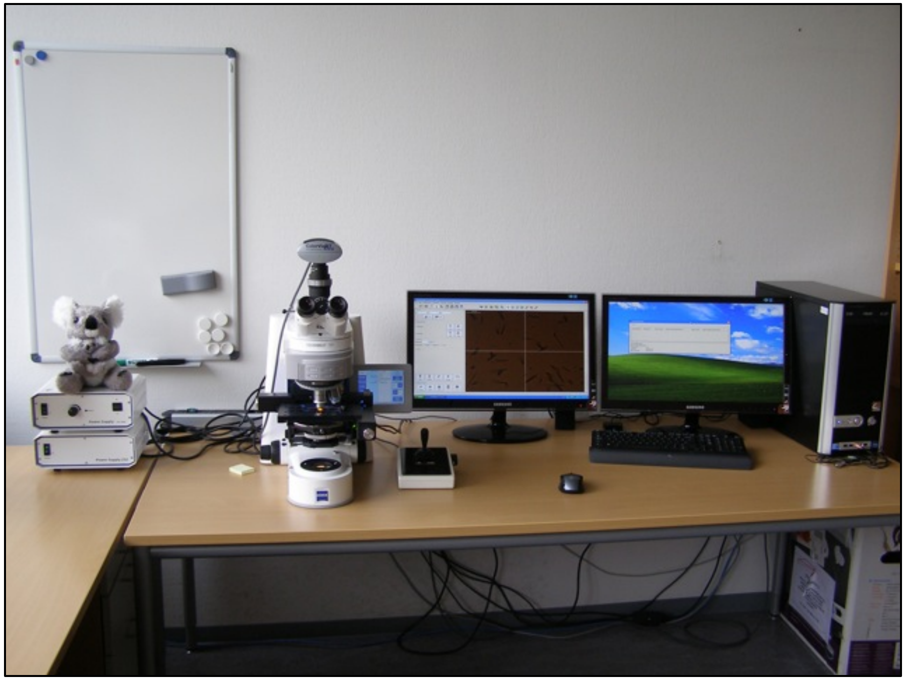


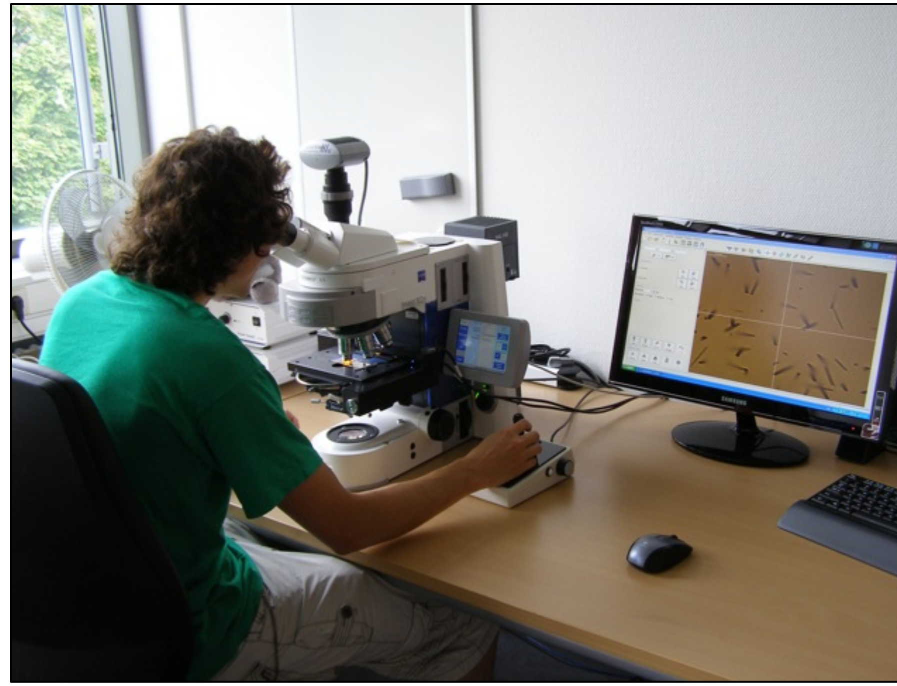


- You need to move right and left to count the spontaneous and induced tracks over a certain grain
- necessary for zircons

- You do not need to move the sample, you just focus down into the grain and up into the mica
- No stage alignment necessary

Count Fission Tracks





- Count spontaneous (and induced) fission tracks under a light microscope with ~1000 times magnification
- Software required to determine and save alignment between mount and external detector, counting tracks (manually - semi-automatic - automatic) and save images

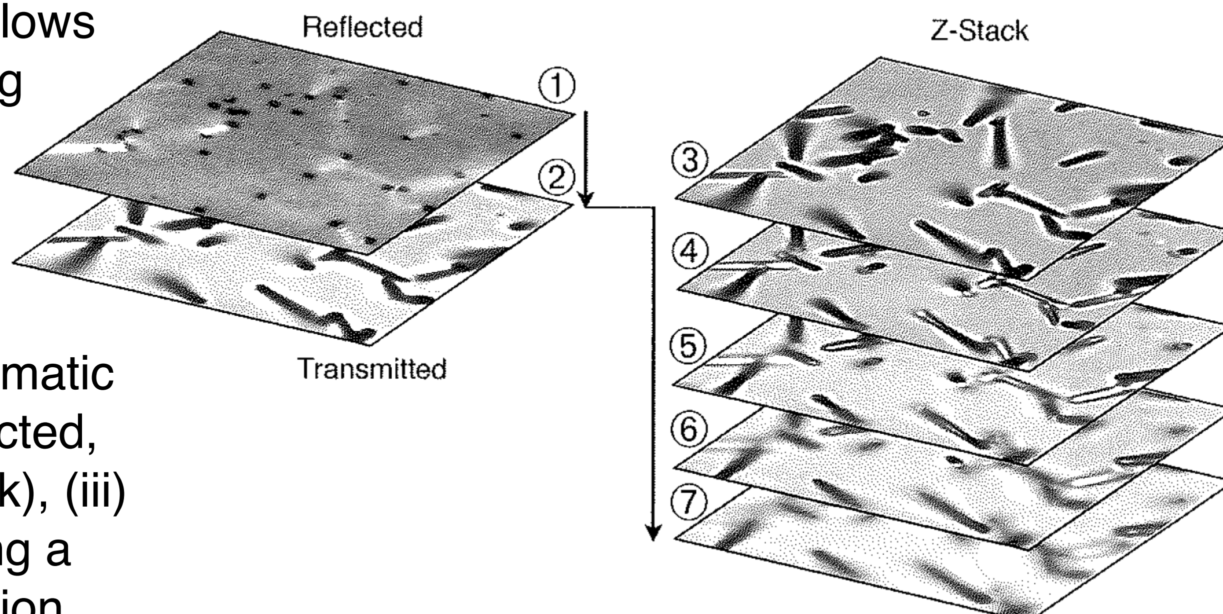
Automatic Fission Track Counting

Counting a sample can take several hours and do not require a high-level of operator skicks, could that be done automatically?

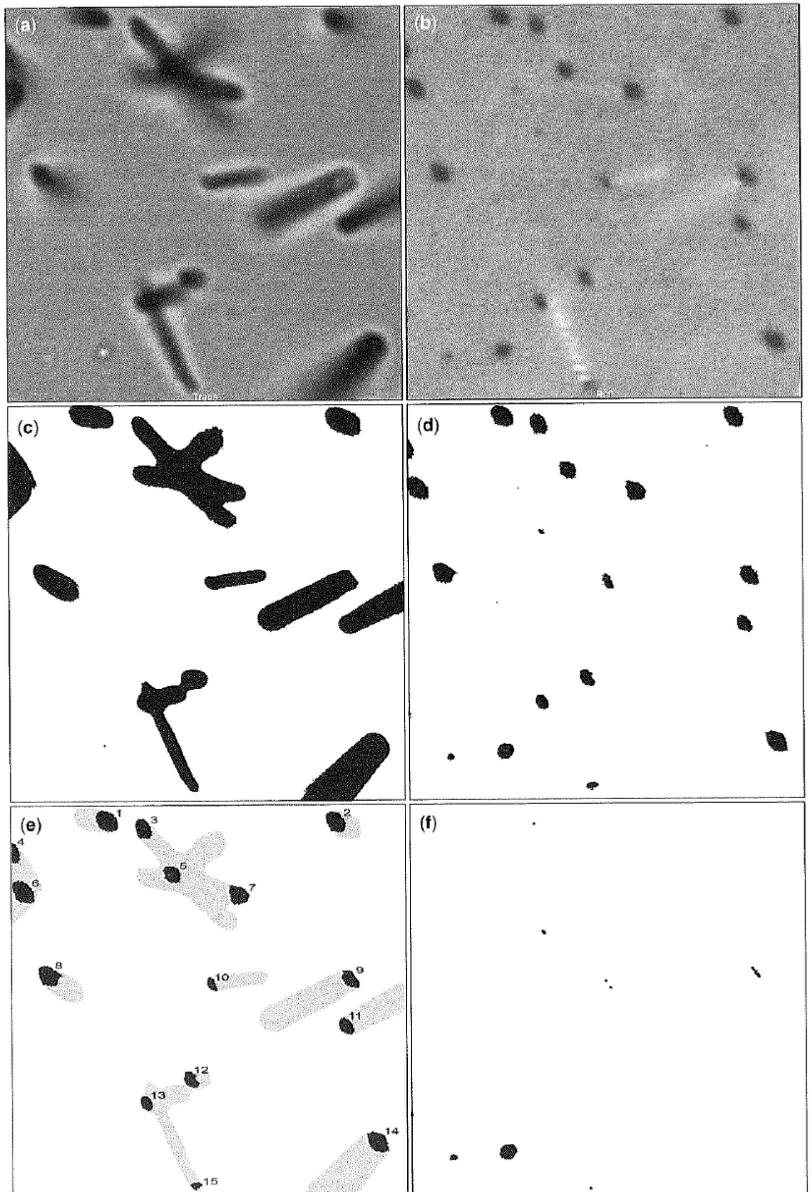
Problem: Distinguish between tracks and non-track features on the surface!

Autoscan has released a 'automatic' counting system (e.g. Gleadow et al. 2009):

- based on coincidence mapping, pair of transmitted and reflected images of the grain surface
- Reflected light image allows to recognize overlapping tracks
- Workflow includes (i) automatic detection of suitable grains (circular polarized light), (ii) automatic image acquisition (reflected, transmitted, image stack), (iii) automatic counting using a thresholding/segmentation, (iv) final review by the operator



Automatic Fission Track Counting



Example of automatically counted external (mica) detector:

Transmitted (a) and reflected (b) images

Binary image derived by thresholding and segmentation

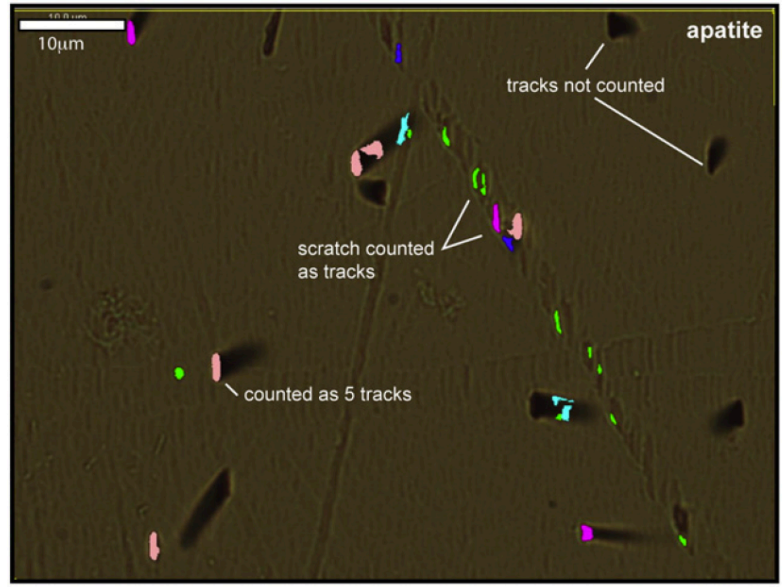
Overlay of binary images with detected tracks (e) and detected non-track features (f)

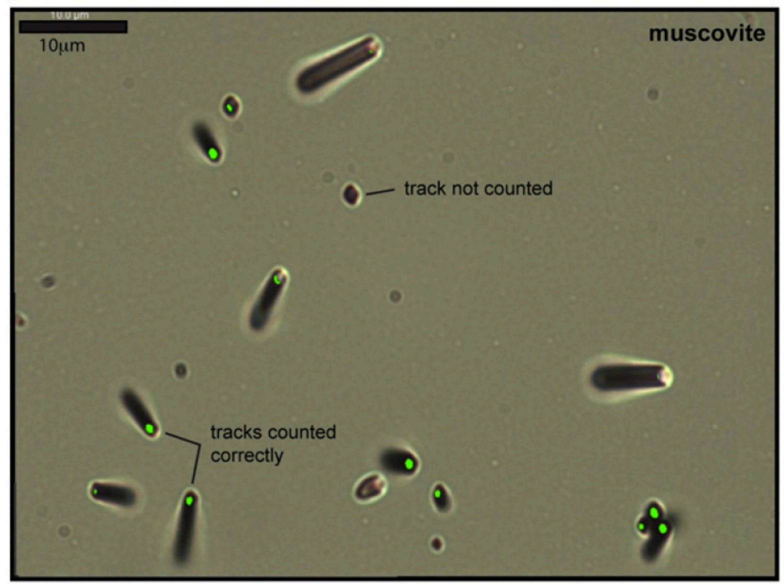
Automatic Fission Track Counting

Enkelmann et al. (2012) compared the counting results of automatic vs. manual counting for simple to difficult (to count) samples:

- The automatic counted grains do show larger scatter in the track densities
- Reasons:
    - Polishing scratches may be wrongly identified as tracks
    - Small tracks are not counted
    - Large tracks may be wrongly identified as multiple overlapping tracks
- Correcting for these scatter takes more time than manual counting

Maybe a small number of perfect samples can be counted more efficiently, but the large majority of samples require manual counting!





Enkelmann et al. (2012)

Important FT'er terminologies

- Latent tracks [?] are fission tracks that are not etched and therefore not visible with a optical microscope, you can see them with an electron microscope

- Etched tracks [?] are fission tracks that are etched because they intersect the surface, cracks or a track that is connected to the surface, you can see them under an optical microscope

- Spontaneous (fossil) tracks [?] tracks that formed due to the spontaneous fission decay of ^{238}U, and accumulated over geological times

- Induced tracks [?] tracks that formed due to the induced fission of ^{235}U due to neutron irradiation in the reactor

Important FT'er terminologies

- Dosimeter glass ⍰ are glasses that contain 10-50 ppm U, they are included in the neutron irradiation to monitor the neutron flux, the induced tracks are counted in the muscovite external detector

- FT standard ⍰ is a sample of known age, you start counting fission tracks on standards and use their reference age to calculate the zeta-calibration factor

Fission Track Age Equation

t	fission track age		yr (years)
λ_α	decay constant for α-decay of ^{238}U	$1.551 \cdot 10^{-10}$	yr^{-1}
λ_F	decay constant for spontaneous fission of ^{238}U	$8.46 \cdot 10^{-17}$	yr^{-1}
ρ_s	spontaneous track density	measure	cm^{-2}
ρ_i	induced track density	measure	cm^{-2}
I	isotopic ratio of $^{235}U/^{238}U$	$7.25 \cdot 10^{-3}$	–
ϕ	neutron flux	measure (ca. 10^{15})	$cm^{-2}\ s^{-1}$
σ	cross section factor for ^{235}U	$5.8 \cdot 10^{-22}$	cm^2
Γ	geometry factor	0.5 (EDM)	–

Fission Track Age Equation

FT age equation

$$t = \frac{1}{\lambda_\alpha} \ln\left[\frac{\lambda_\alpha}{\lambda_F} G \frac{\rho_s}{\rho_i} I\phi\sigma + 1\right]$$

t	fission track age		yr (years)
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Γ	geometry factor	0.5 (EDM)	–

Fission Track Age Equation

General radiometric age equation (Rutherford 1900):

$$N = N_0(e^{\lambda t} - 1)$$

Applying to fission track dating result in:

$$N_S = \frac{\lambda_f}{\lambda_\alpha} {}^{238}U(e^{\lambda_\alpha t} - 1)$$

Note: $\lambda_\alpha = \lambda_f + \lambda_\alpha$

Rearranging result in:

$$t = \frac{1}{\lambda_\alpha} ln\left(\frac{\lambda_\alpha}{\lambda_f}\frac{N_s}{{}^{238}U} + 1\right)$$

At present there are two principal dating protocols: EDM und LAFT

Fission Track Age Equation

EDM:

$$t = \frac{1}{\lambda_\alpha} ln\left(\frac{\lambda_\alpha}{\lambda_f}\frac{\rho_s}{\rho_i}\rho_d G I \Phi \sigma + 1\right)$$

U-doped glass and age standards are simultaneously irradiated to overcome accuracy issues with some parameters.

$$t = \frac{1}{\lambda_\alpha} ln\left(\lambda_\alpha \frac{\rho_s}{\rho_i}\rho_d G \zeta_{EDM} + 1\right)$$

The personal zeta value (Hurford and Green, 1982, 1983; Hurford, 1990) can be calculated with:

$$\zeta = \frac{e^{\lambda_\alpha t_s}}{\lambda_\alpha \frac{\rho_s}{\rho_i}\rho_d G} = \frac{I\Phi\sigma}{\lambda_f}$$

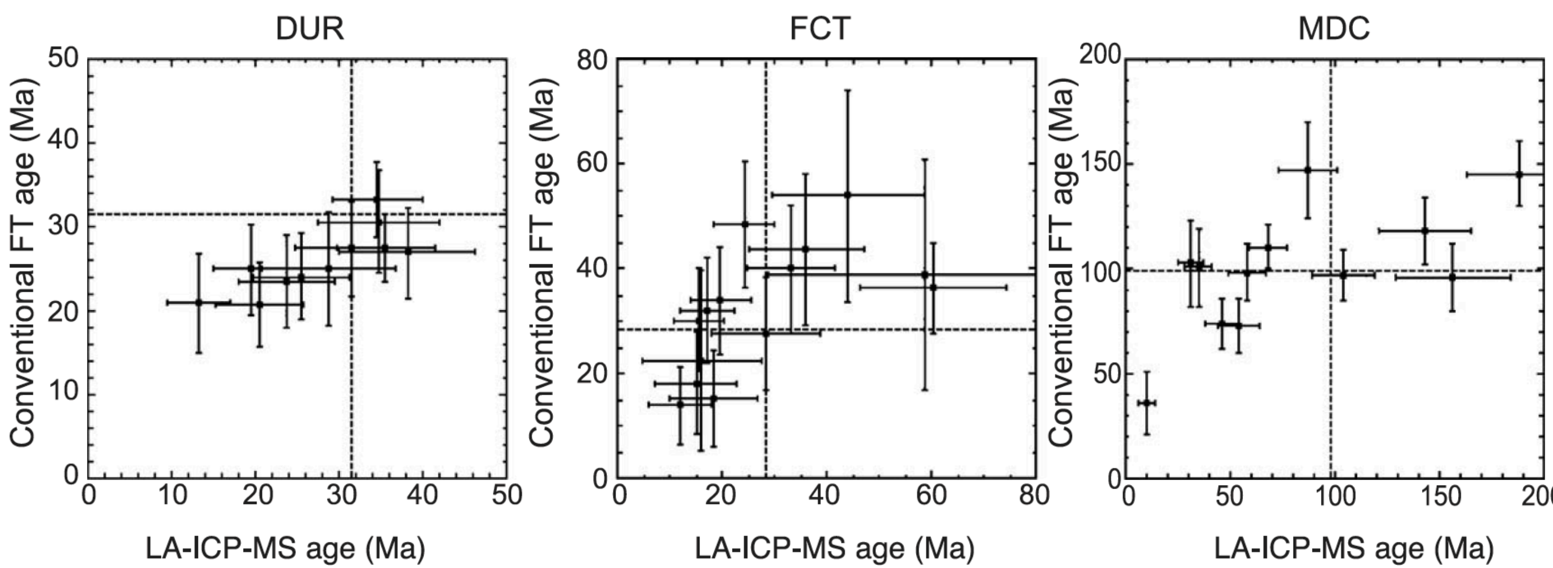
The zeta value is calculated by counting several mineral age standards from the same/other irradiation. Commonly used age standards are Durango apatite with an age of 31.44±0.18 Ma (McDowell et al. 2005) or Fish Canyon Tuff apatite and zircon with an age of 28.01±0.04 Ma (Phillips and Matchen 2013).

Fission Track Age Equation

LAFT (e.g. Vermeesch 2017):

$$t = \frac{1}{\lambda_\alpha} ln\left(\lambda_\alpha \frac{\rho_s}{\left[{}^{238}\widehat{U}/{}^{X}\widehat{X}\right]}\zeta_{LAFT} + 1\right)$$

Where ${}^{X}X$ stands for a stoichiometric isotope (${}^{43}Ca$ for apatite or ${}^{29}Si$ zircon) and ζ_{LAFT} is a session zeta determined by measuring mineral age standards during each session to account for any changes in the ablation and plasma conditions.



Hasebe et al. (2004)

Summary Fission Track Age Equation

You want to calculate a FT age of your sample following the ζ-calibration:

- First you need to count FT on age standards to determine the zeta-factor, for that you need to count >5 age standards and use the mean ζ-factor

- You need to count the induced track density over the U-glass dosimeter ? ρ_d

- Then you count induced and spontaneous tracks in 20-40 grains (reset bedrock sample) and calculate the age of your sample using the ζ- age equation

- A pooled age can be calculated assuming all counts derive from a huge grain and the age equation becomes:

$$t_{pooled} = \frac{1}{\lambda_\alpha} ln\left(\lambda_\alpha \frac{\sum N_{S,i}}{\sum N_{I,i}} \rho_d G \zeta_{EDM} + 1\right)$$

Summary Fission Track Age Equation

- analytical precision is based on the counting statistics, i.e. you need to count many fission tracks

- the general rule is to count 1000 spontaneous and 1000 induced tracks, to get error a theoretical error of <3%

- in practice FT-ages have 10% error (1σ)

- accuracy of the age depends from the use of age standards, the FT method is not an independent dating technique

- the reference age of age standards is used to verify analytical calibrations. Because a person is counting FT, each person needs to be calibrated first before analyzing unknown samples

Estimating the Age Spread in a Sample

The chi-squared test

also Green 1981), was developed to assess the validity. It was shown that results from the conventional formula give the best estimate of (ρ_S/ρ_I) and $\sigma(\rho_S/\rho_I)$, as long as the observed track counts are acceptable under a χ^2-criterion:

$$\chi^2 = \sum\left\{\frac{\left(N_{Sj} - P_{Sj}\right)^2}{P_{Sj}}\right\} + \sum\left\{\frac{\left(N_{Ij} - P_{Ij}\right)^2}{P_{Ij}}\right\} \qquad (19)$$

where $P_{Sj} = N_S(N_{Sj}+N_{Ij})/(N_S+N_I)$; $P_{Ij} = N_I(N_{Sj}+N_{Ij})/(N_S+N_I)$. Here the χ^2-value is tested at a desirable critical level, say 5%, with $(n-1)$ degree of freedom where n is the number of grains counted.

If the χ^2-value is unacceptable, it suggests that the data suffer from extra- Poissonian variation(s) due to a variety of experimental and geological factors (Burchart 1981; Green

Main result:

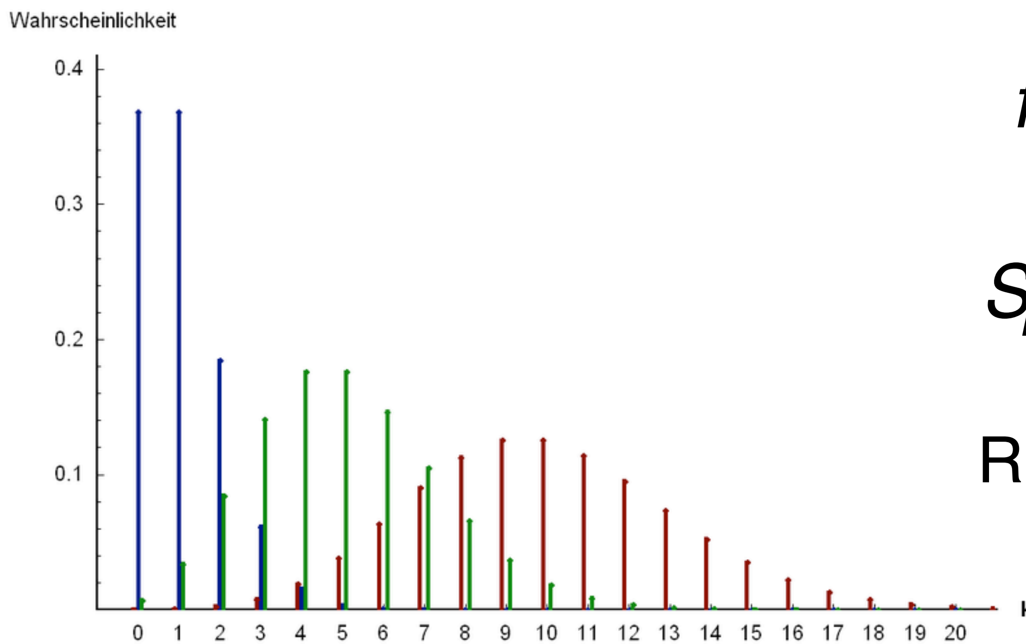
$P(\chi^2) = > 0.05$ – minor spread, things are fine

$P(\chi^2) = < 0.05$ – large spread, e.g. partial annealing

Error calculation

Poisson Distribution

Discrete and asymmetric distribution
described by one parameter μ



$$f(x) = \frac{\mu^x}{x!} e^{-\mu}$$

$$S_P = \sqrt{\mu}$$

$$RE = 1 / \sqrt{\mu}$$

Source: Wikipedia.org

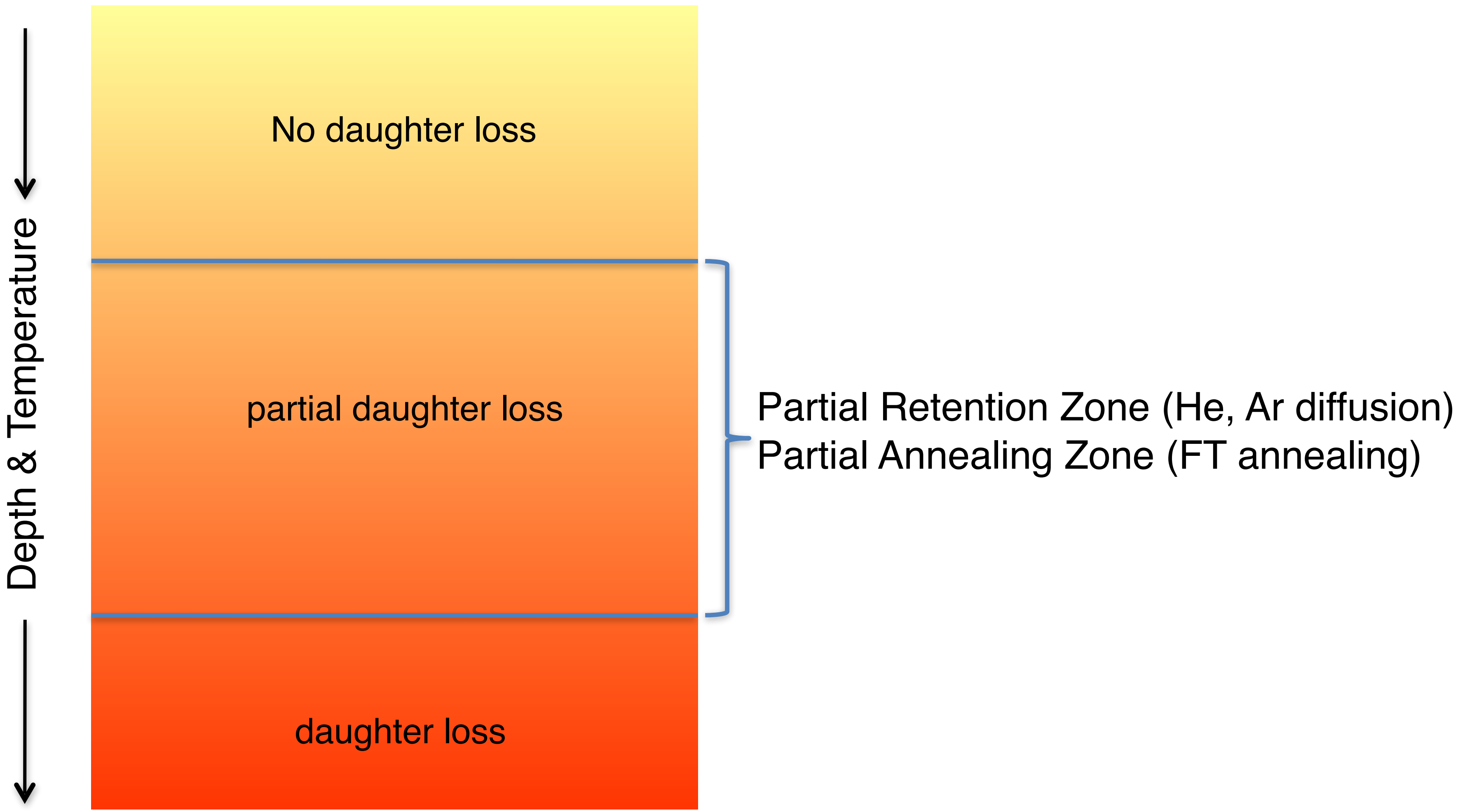
x: number of events
μ: average rate of process (e.g. number of tracks counted)
(e.g. number of decay events during a time interval)

Let’s count some grains

http://geography.kcl.ac.uk/geochron/ftc/

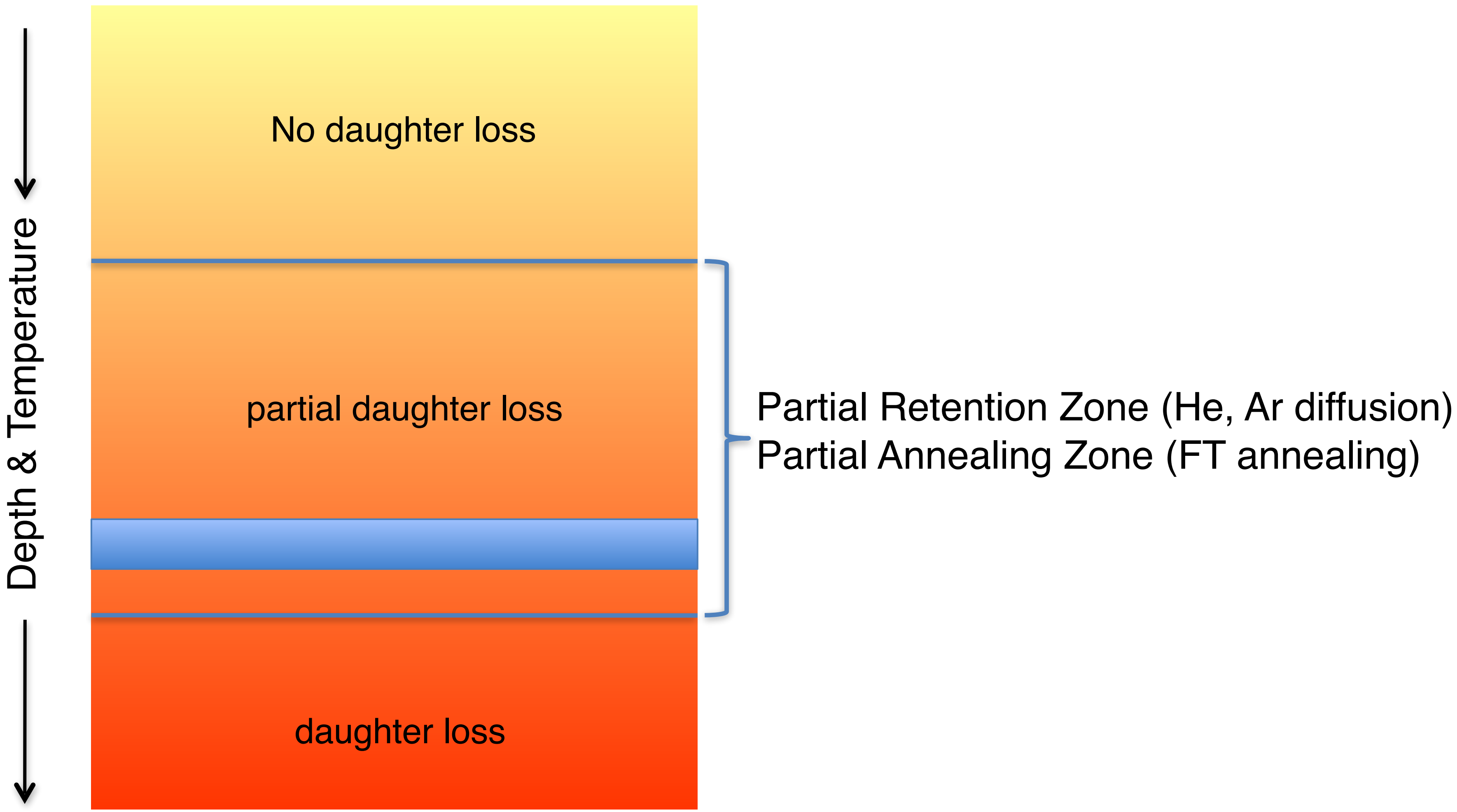
Thermal Sensitivity of FT

Cooling age = the time when the rock cooled for the last time below a certain temperature (closure temperature, T_C)



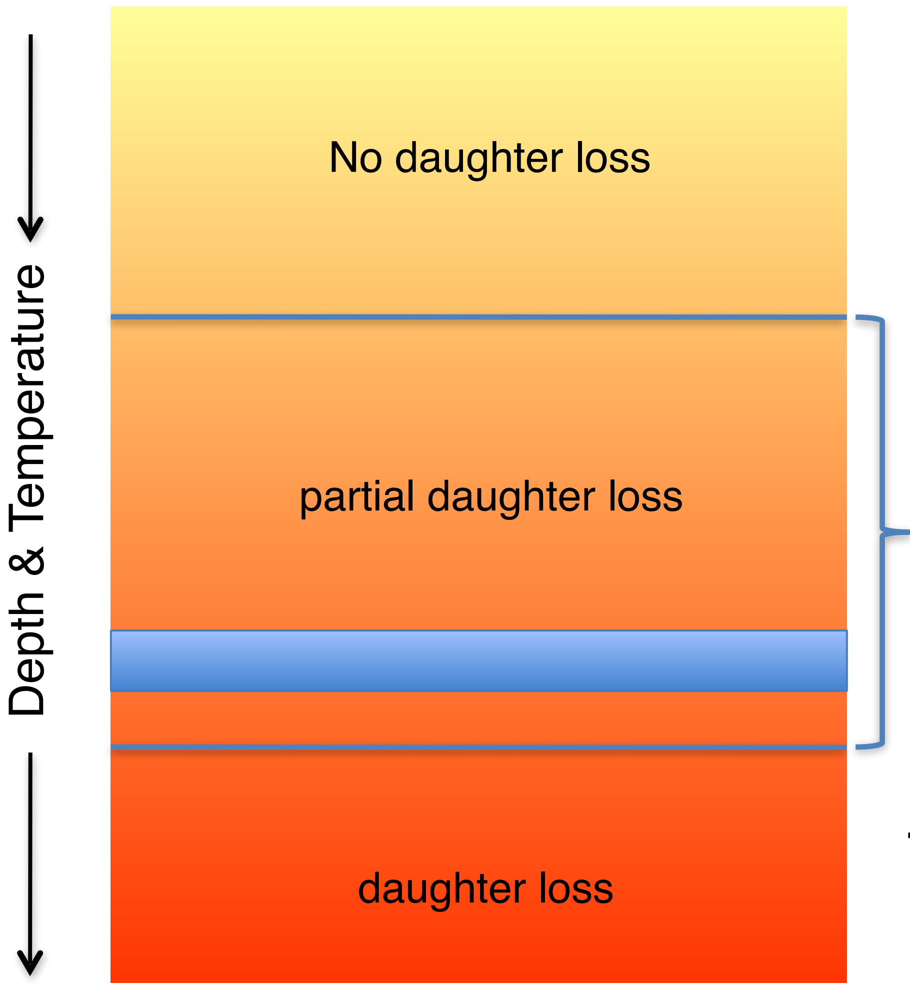
Thermal Sensitivity of FT

Cooling age = the time when the rock cooled for the last time below a certain temperature (closure temperature, T_C)



Thermal Sensitivity of FT

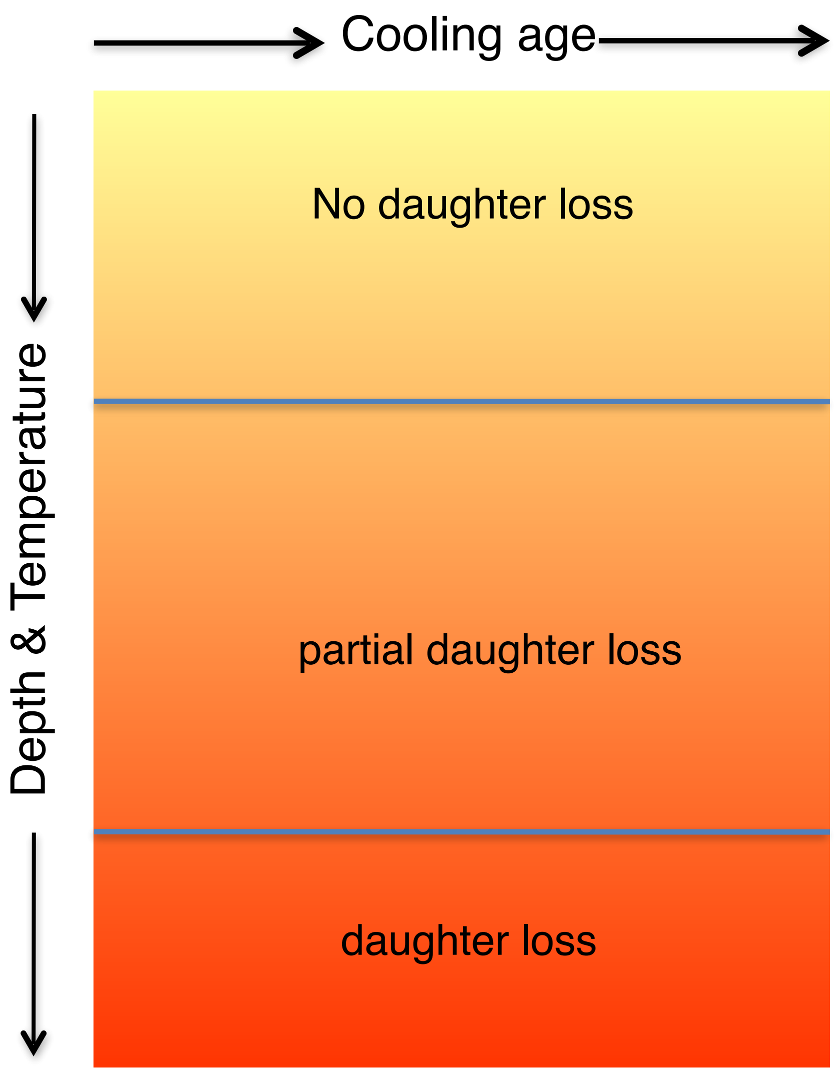
Cooling age = the time when the rock cooled for the last time below a certain temperature (closure temperature, T_C)



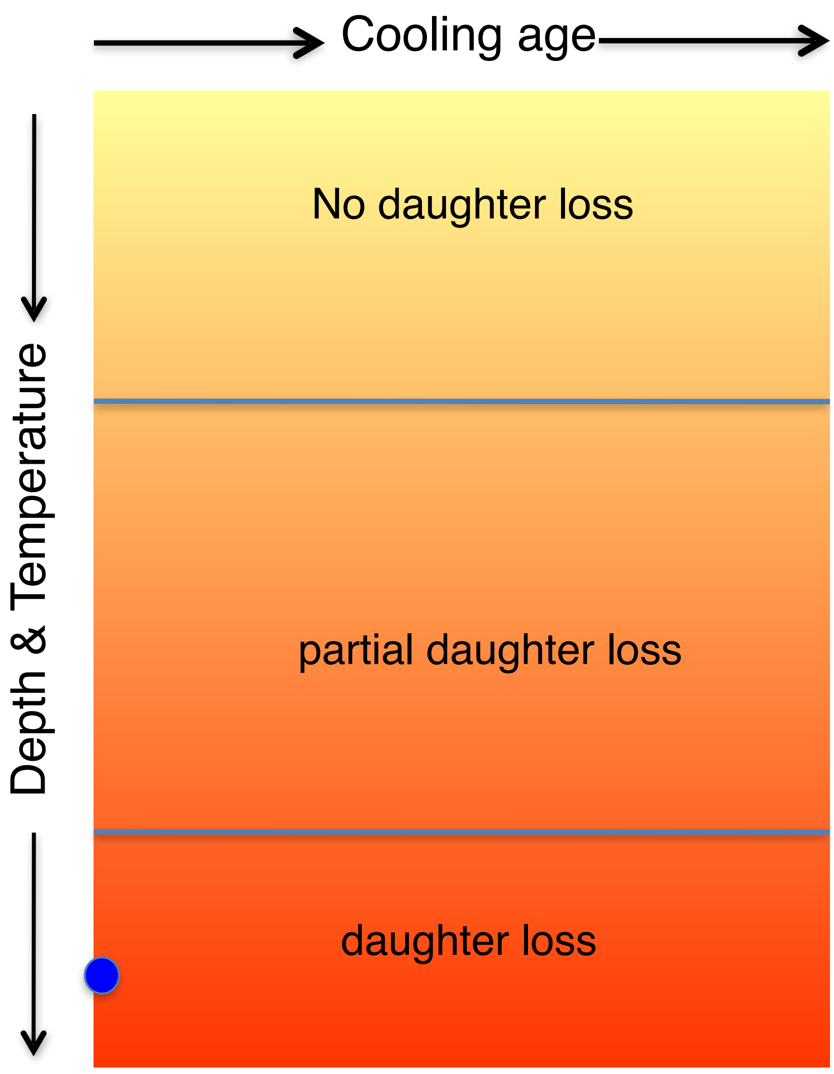
Partial Retention Zone (He, Ar diffusion)
Partial Annealing Zone (FT annealing)

T_c varies with cooling rate, chemistry, radiation damage, grain size

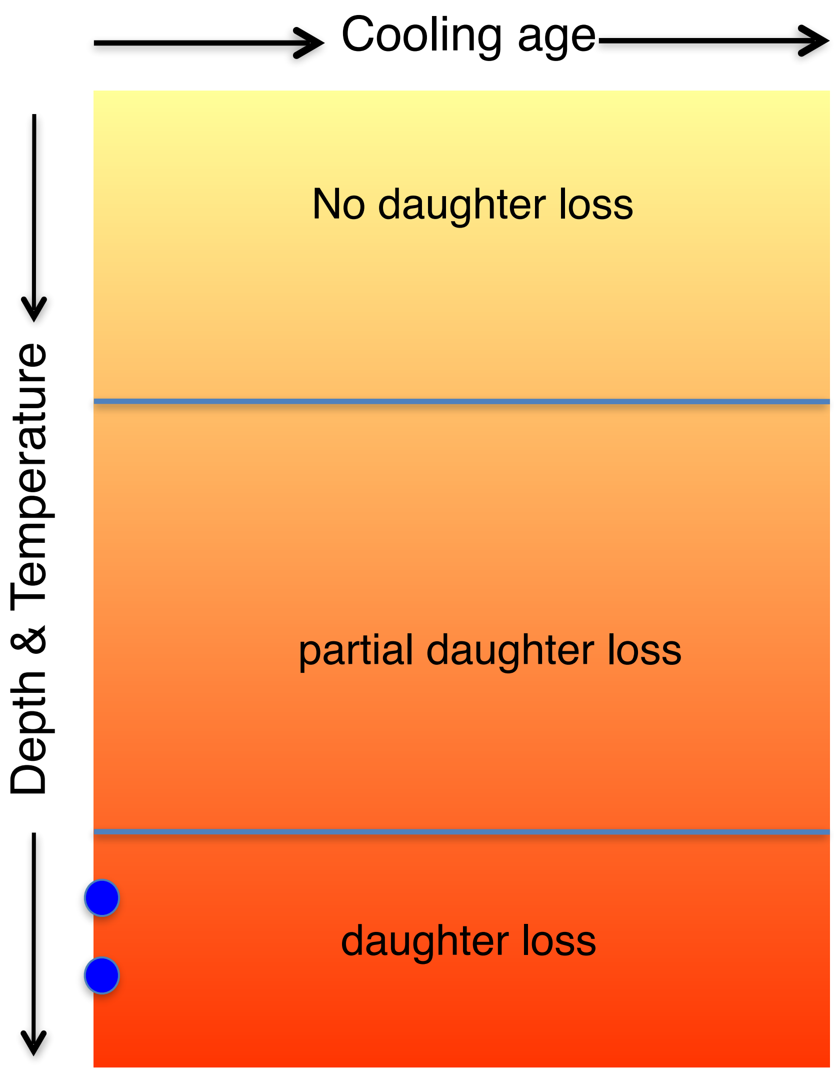
Thermal Sensitivity of FT



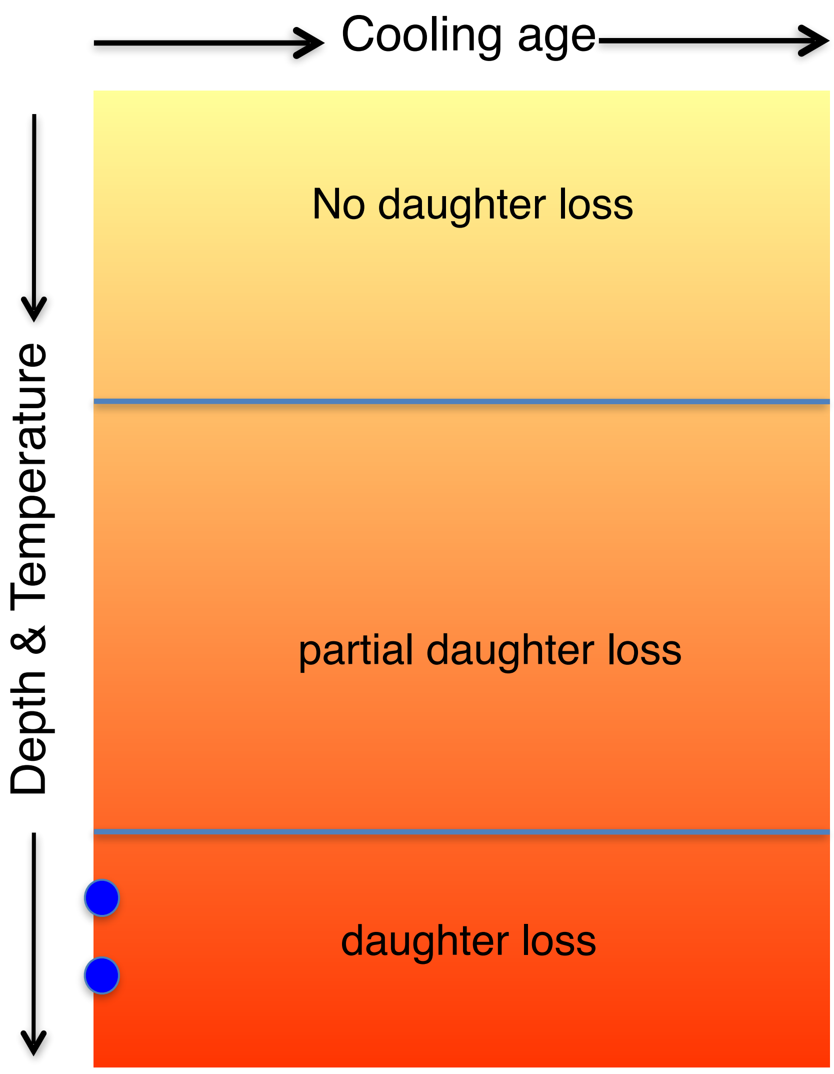
Thermal Sensitivity of FT



Thermal Sensitivity of FT

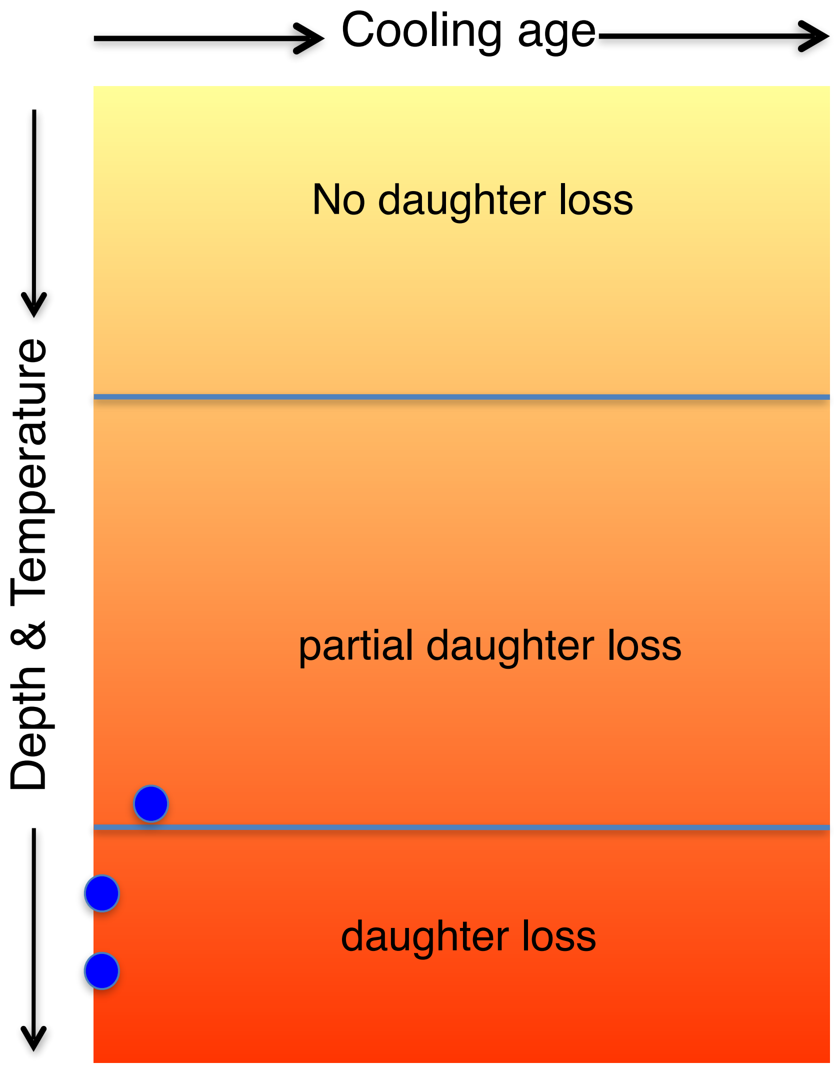


Thermal Sensitivity of FT



daughter isotopes are lost more quickly than they are produced = no accumulation

Thermal Sensitivity of FT



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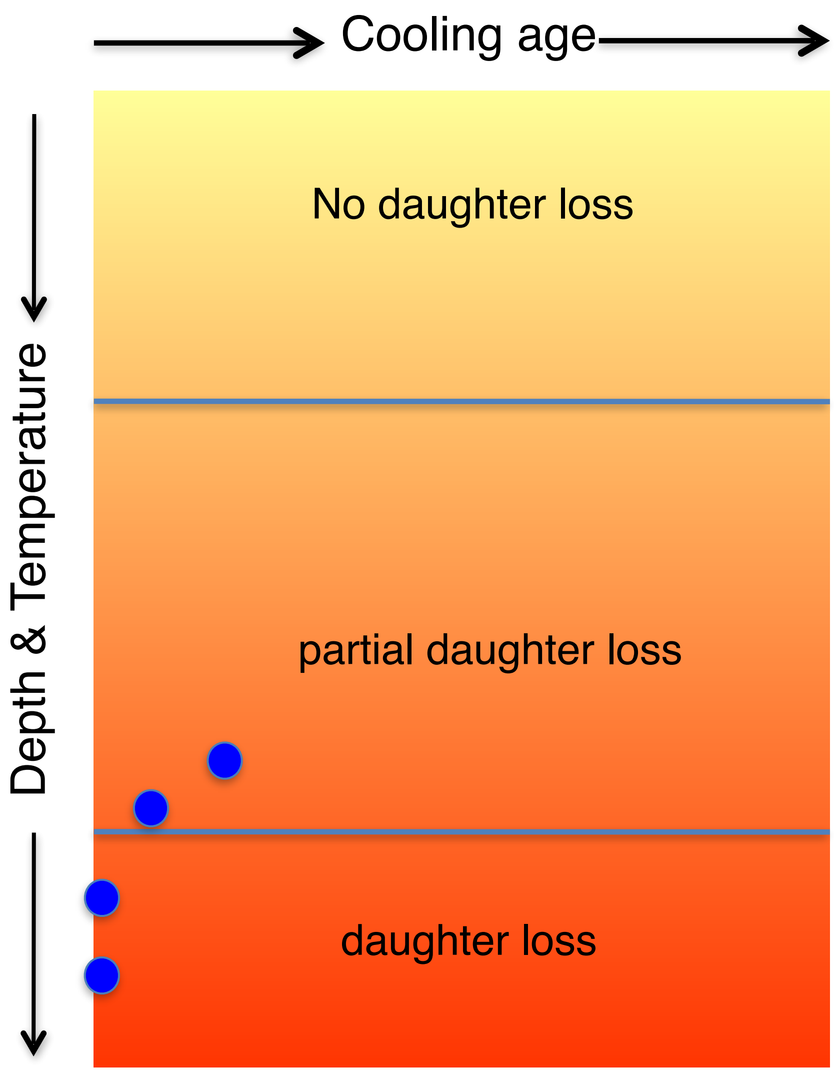
Thermal Sensitivity of FT



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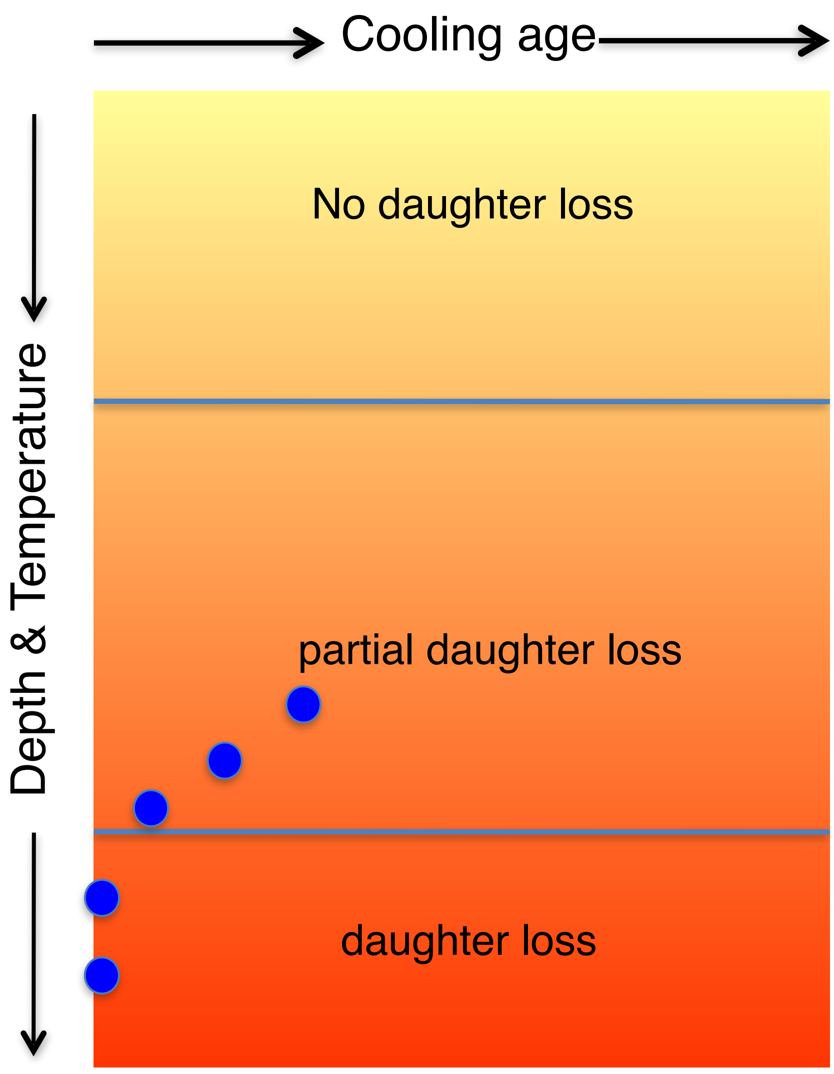
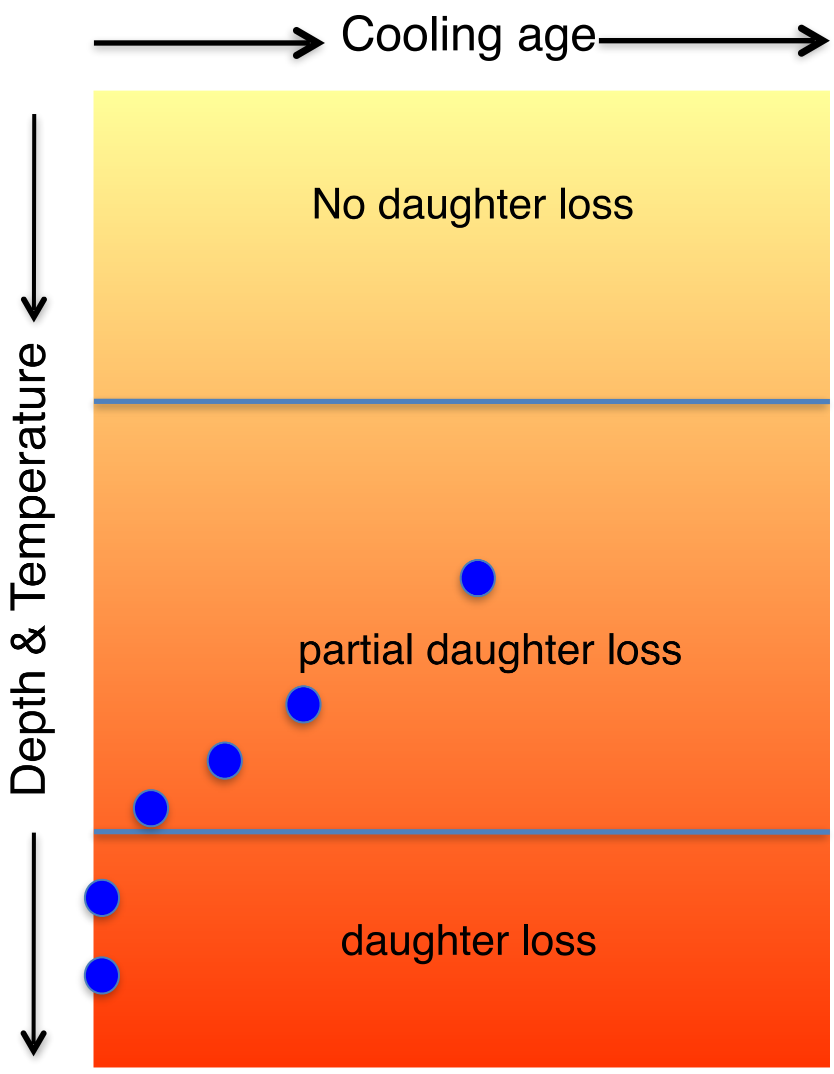
Thermal Sensitivity of FT



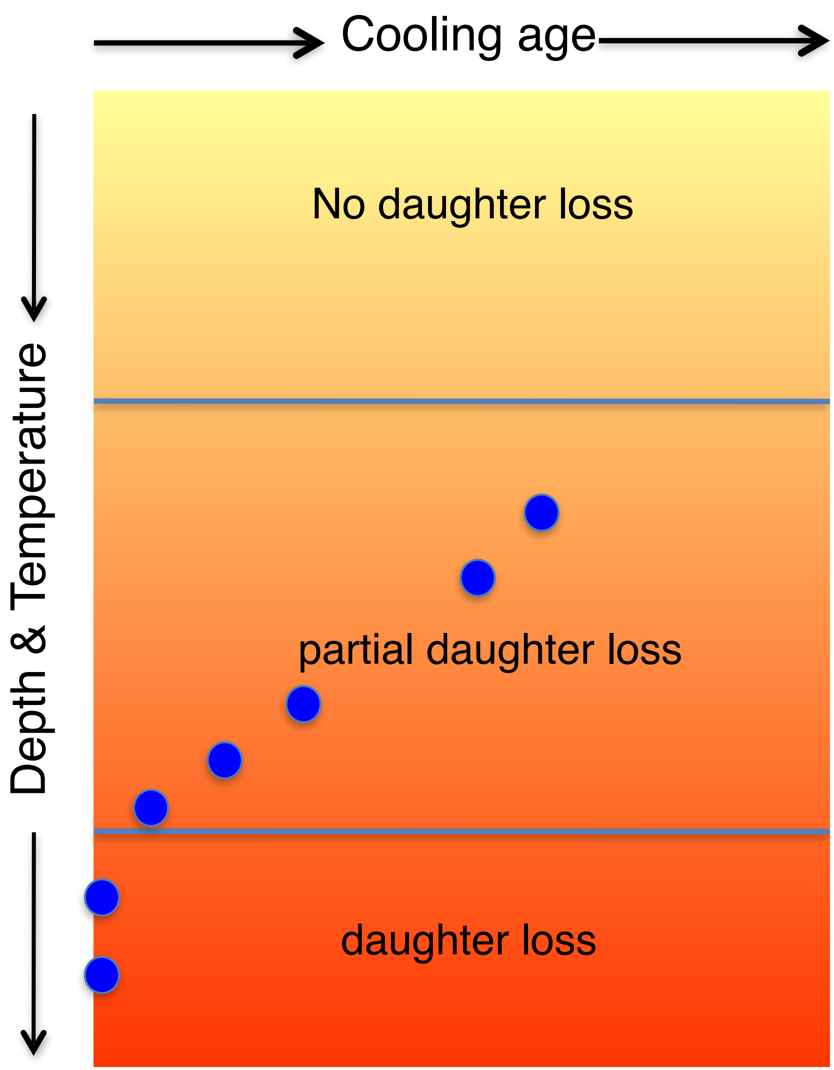
daughter isotopes are lost more quickly than they are produced = no accumulation

Thermal Sensitivity of FT



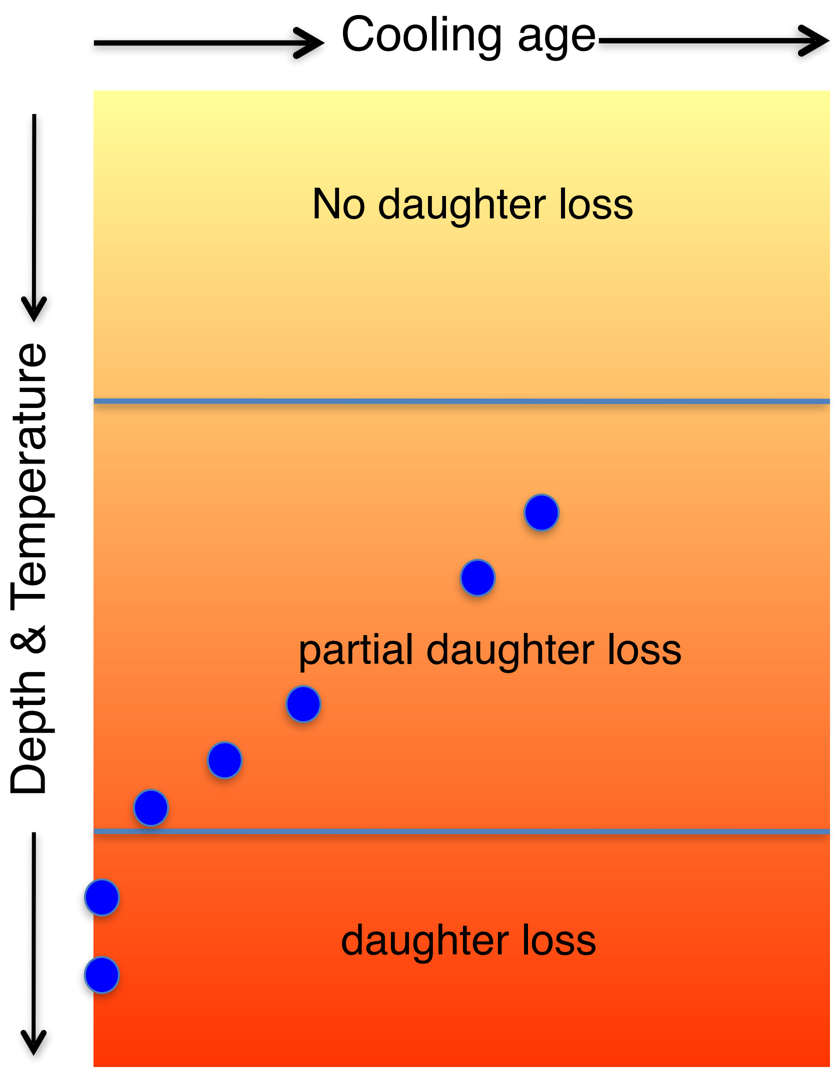
daughter isotopes are lost more quickly than they are produced = no accumulation

Thermal Sensitivity of FT



daughter isotopes are lost more quickly than they are produced = no accumulation

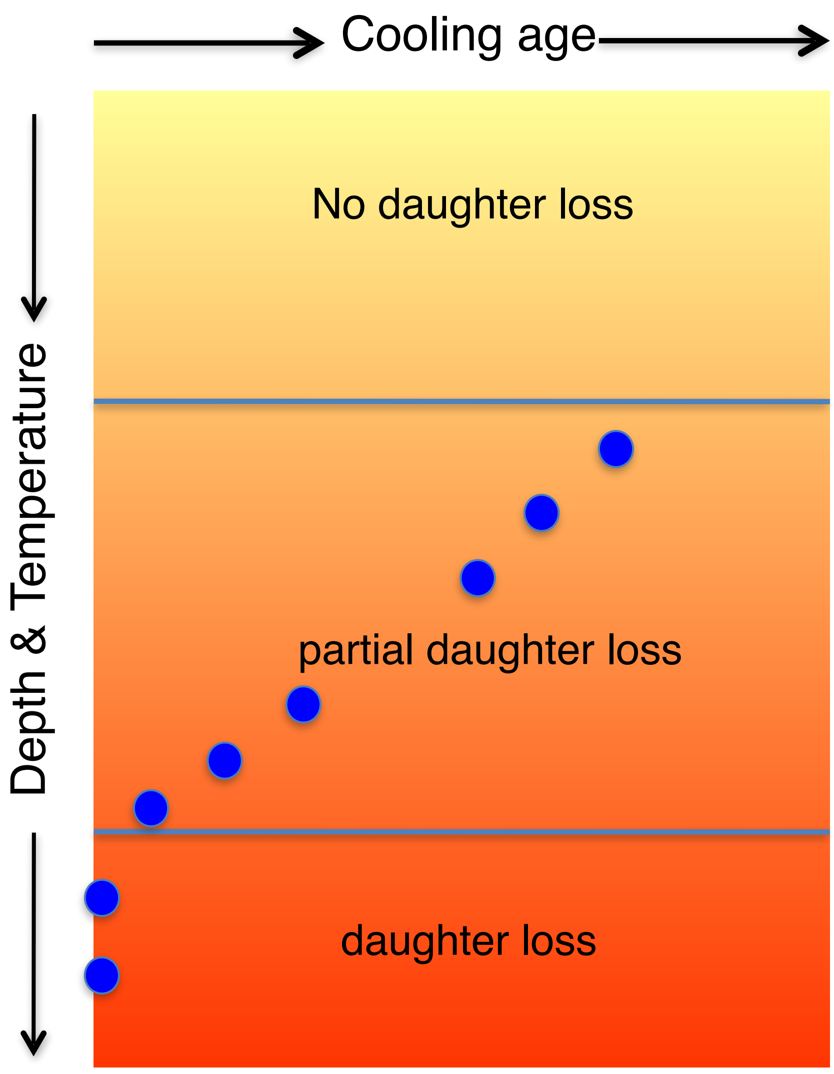
Thermal Sensitivity of FT



Increase in age as the daughter isotopes get increasingly accumulated

daughter isotopes are lost more quickly than they are produced = no accumulation

Thermal Sensitivity of FT



Increase in age as the daughter isotopes get increasingly accumulated

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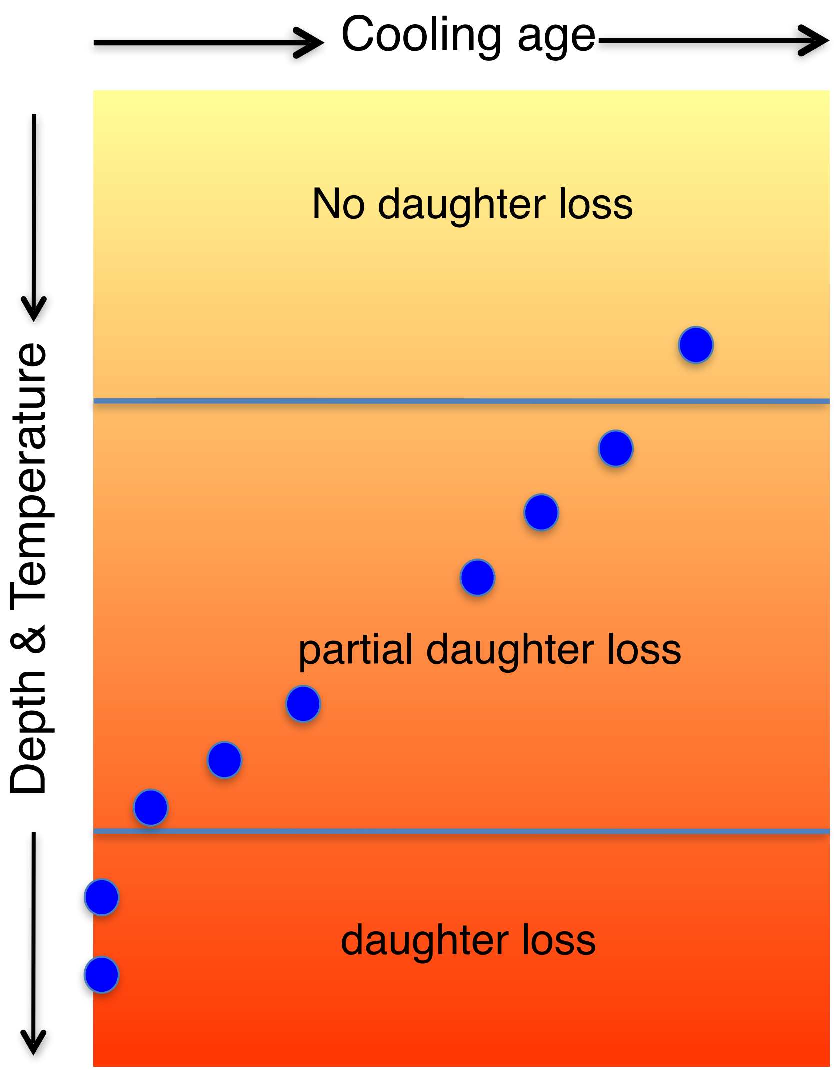
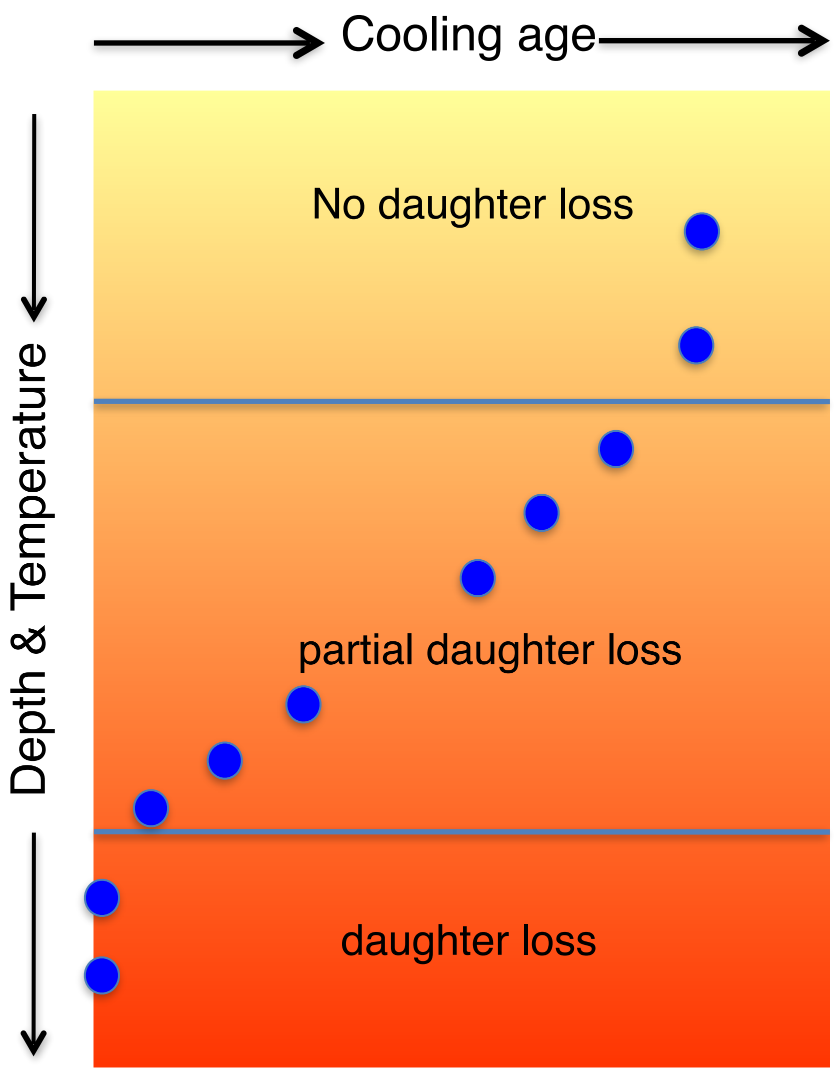
Thermal Sensitivity of FT



Increase in age as the daughter isotopes get increasingly accumulated

daughter isotopes are lost more quickly than they are produced = no accumulation

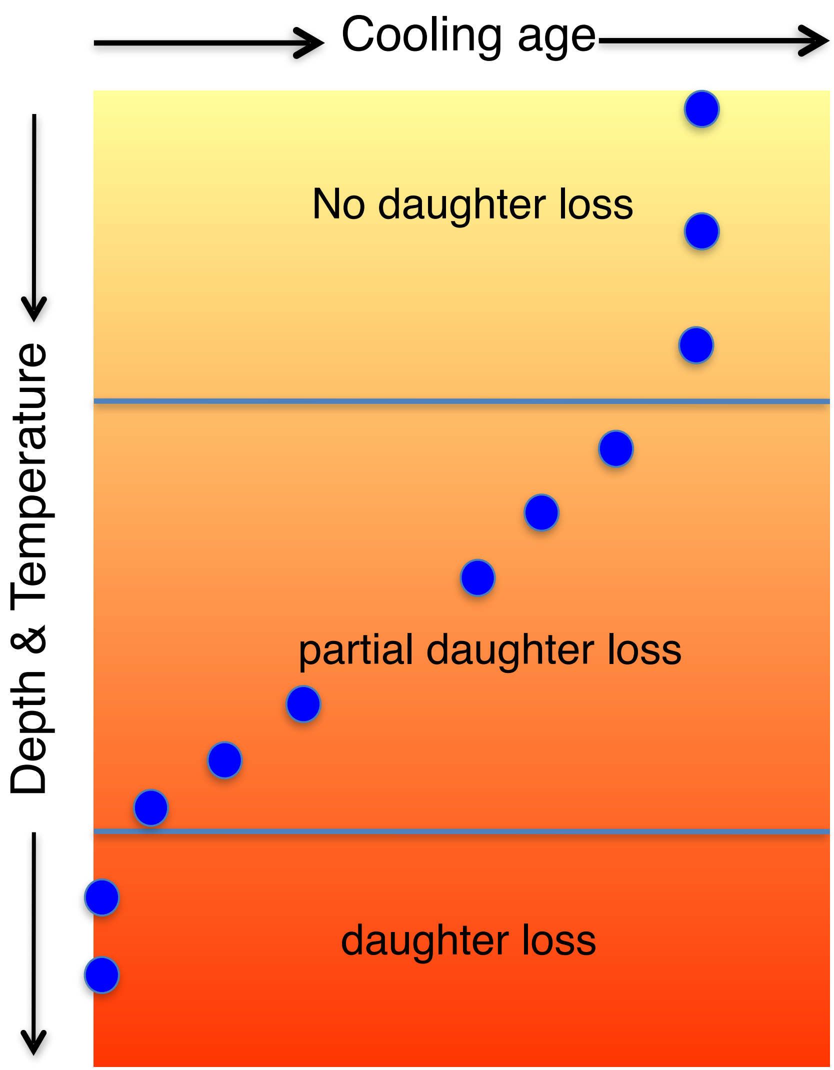
Thermal Sensitivity of FT



Increase in age as the daughter isotopes get increasingly accumulated

daughter isotopes are lost more quickly than they are produced = no accumulation

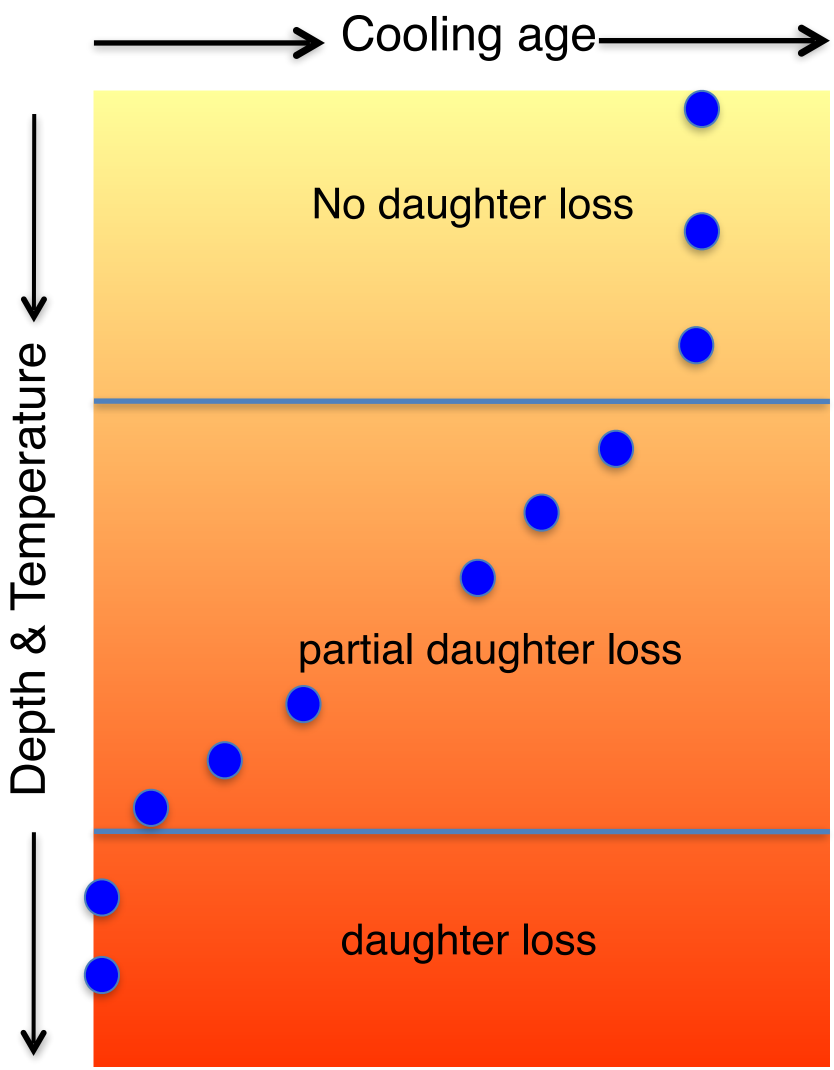
Thermal Sensitivity of FT



Increase in age as the daughter isotopes get increasingly accumulated

daughter isotopes are lost more quickly than they are produced = no accumulation

Thermal Sensitivity of FT

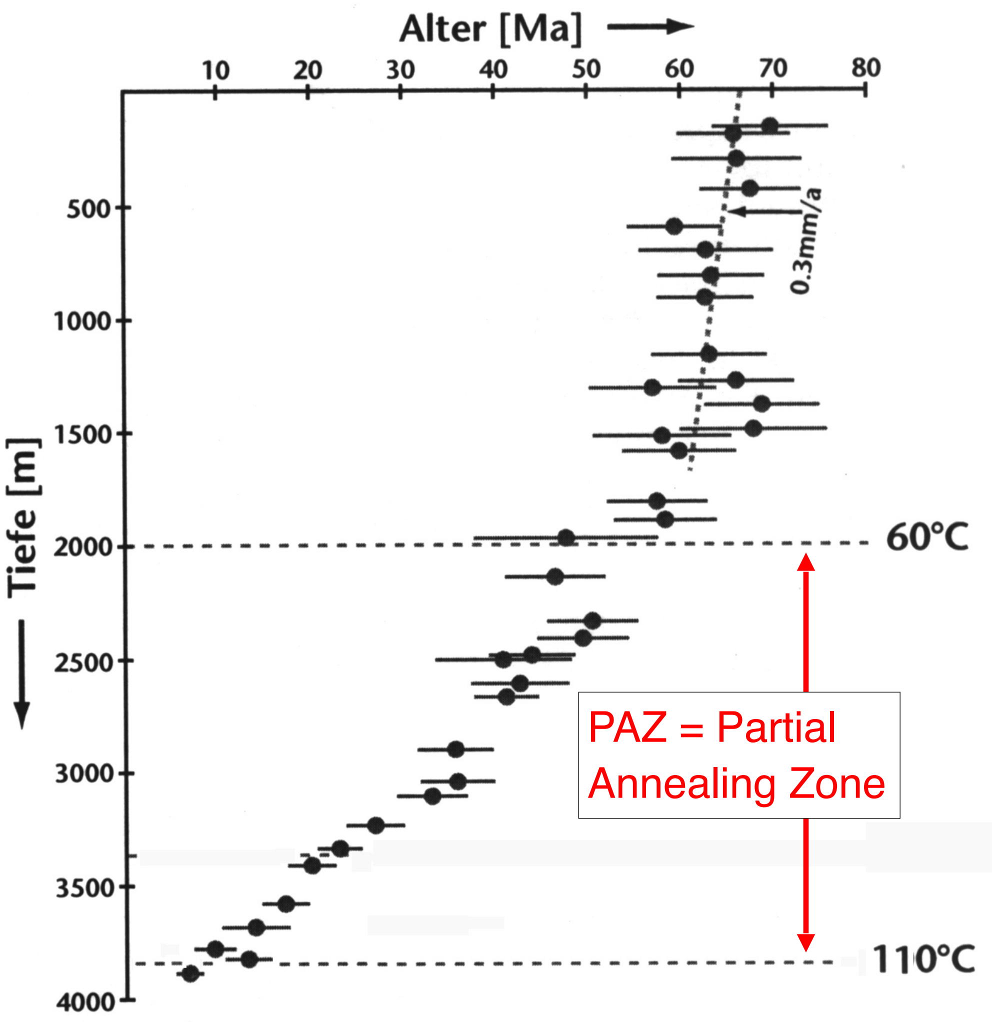


All daughter isotopes are retained and 100% accumulated

Increase in age as the daughter isotopes get increasingly accumulated

daughter isotopes are lost more quickly than they are produced = no accumulation

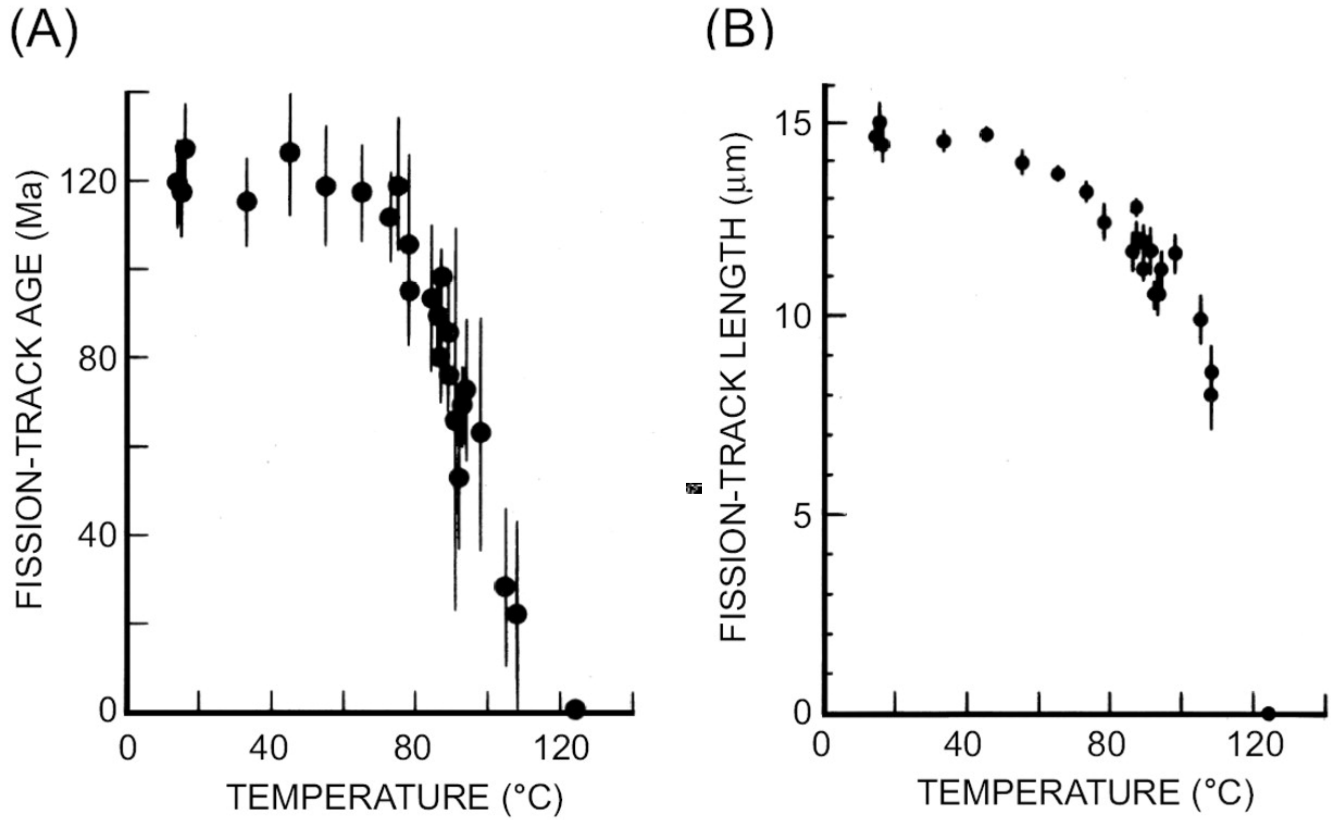
Thermal Sensitivity of FT



AFT ages of the KTB-drilling site in Bavaria, Germany

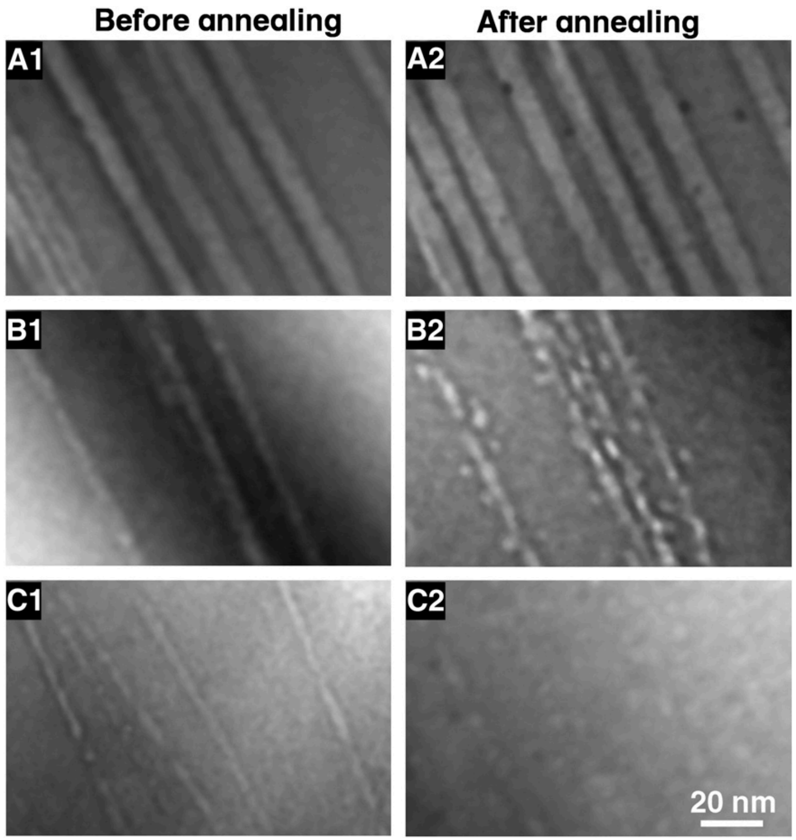
- Ages decrease constantly up to a depth of 2 km, where the slope correspond to the long-term exhumation rate between 60 and 70 Ma
- Ages decrease rapidly within the PAZ to nearly 0 Ma at 4 km

Thermal Sensitivity of FT

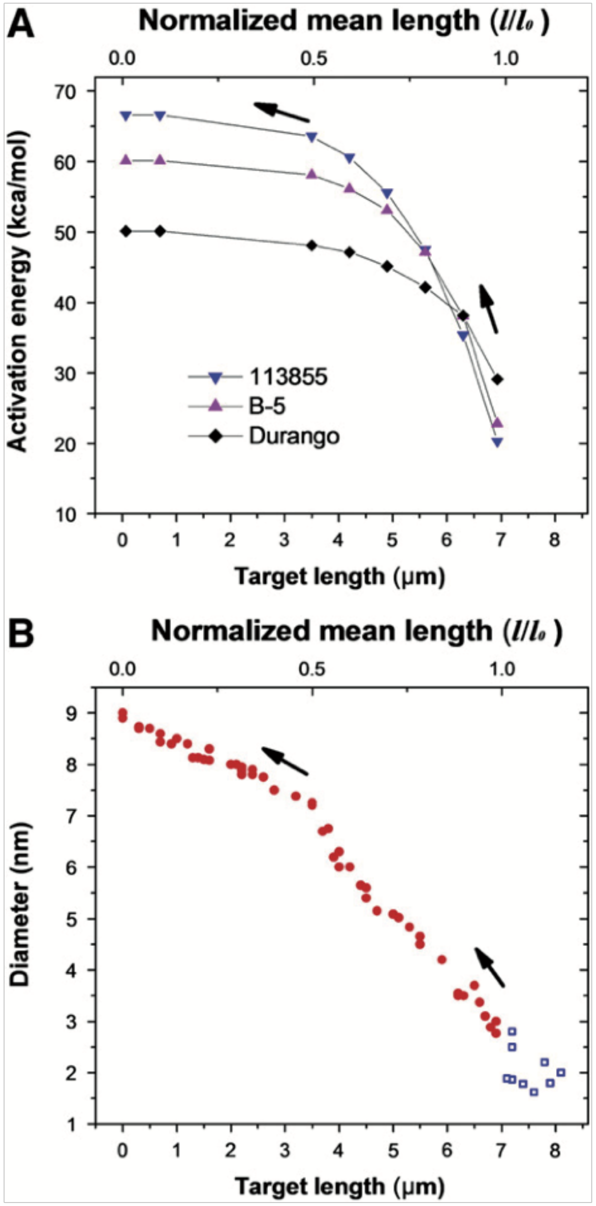


Long-term natural annealing of fission tracks in apatite observed in borehole samples from the Otway Basin, Australia, for which the geological evolution was well constrained (after Green et al. 1989a). Both fission-track age (A) and length (B) are reduced progressively down to zero in the temperature range of ~60–120 °C due to the increase in geothermal temperature with depth. Error bars are ± 2σ .

Fission Tack Annealing



Li et al. (2012)



Annealing does require more energy as annealing proceeds, the activation energy of annealing is increasing.

Fission Tack Annealing

- To understand how tracks anneal or shorten within the PAZ, we need to study the annealing behavior

- This annealing behavior is expressed in annealing equations

- Track annealing can be studied in the laboratory:
  - Annealing experiments
  - Short time and high temperatures

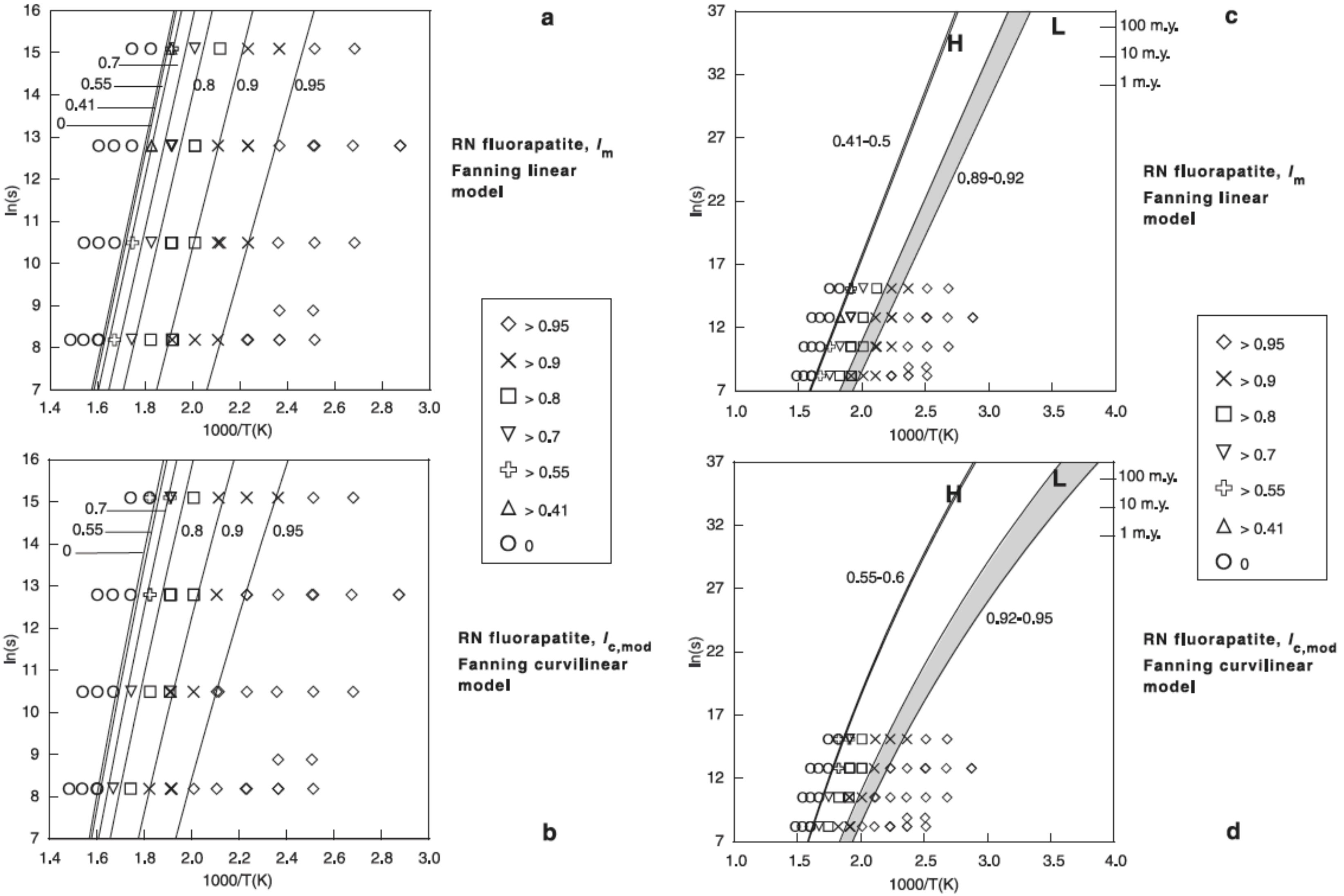
Fission Tack Annealing

Annealing experiments done on induced tracks:

1. Anneal all tracks by heating in an oven
2. Induce new tracks by irradiation in a reactor (^{235}U tracks)
3. Grains will be heated for a defined time and temperature and induced tracks shorten
4. Measuring resulting track length after etching
5. Annealing conditions on geological time scales will be estimated by extrapolating from laboratory time scales

- Common starting point
- 1) Assumes tracks from ^{238}U & ^{235}U are equivalent
- 2) Assumes pre-annealing process doesn't influence annealing behavior of the crystal
    - Assumption 1 is good – similar masses and energies
    - Assumption 2 – seems good for Ap, but not Zr – i.e. U/Th zonation & α-damage

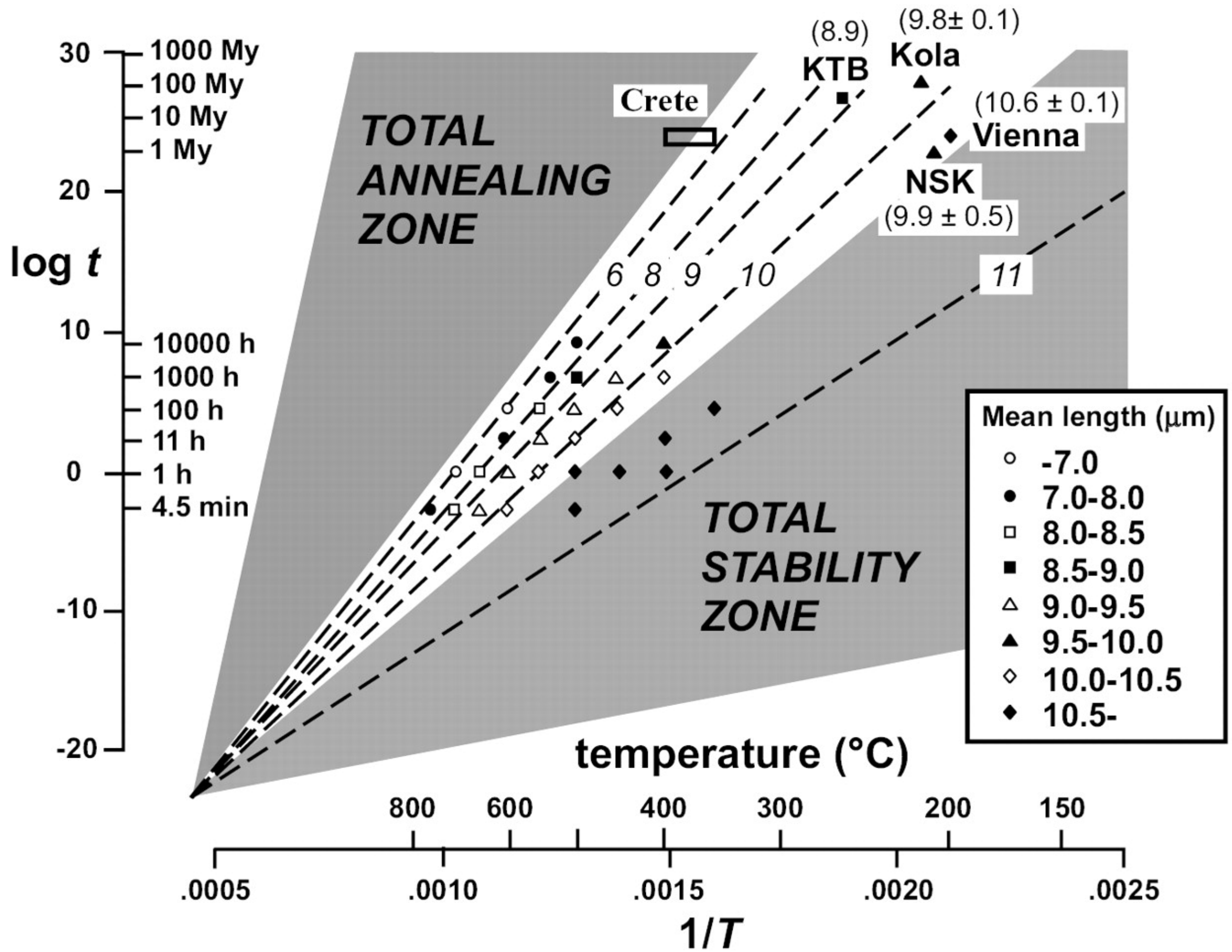
Fission Tack Annealing



Data can be fitted with a single function that estimates the length reduction for all tT-combinations.

Ketcham et al. (1999)

Fission Tack Annealing



Arrhenius plot showing the design points of the laboratory annealing experiments of spontaneous fission tracks in zircon as well as contour lines for the fitted fanning model extrapolated to geological time scale (Yamada et al. 1995b; Tagami et al. 1998; model after Galbraith and Laslett 1997). Note that only a few natural (long-term) annealing experiments from deep-sea sediments and sedimentary basins (boreholes) exist.

Angular Effects/Biasing

- Annealing of apatite fission tracks is anisotropic - faster perpendicular to the crystallographic c-axis, slower parallel to the c-axis
- Solution: Angle to c-axis need to be measured

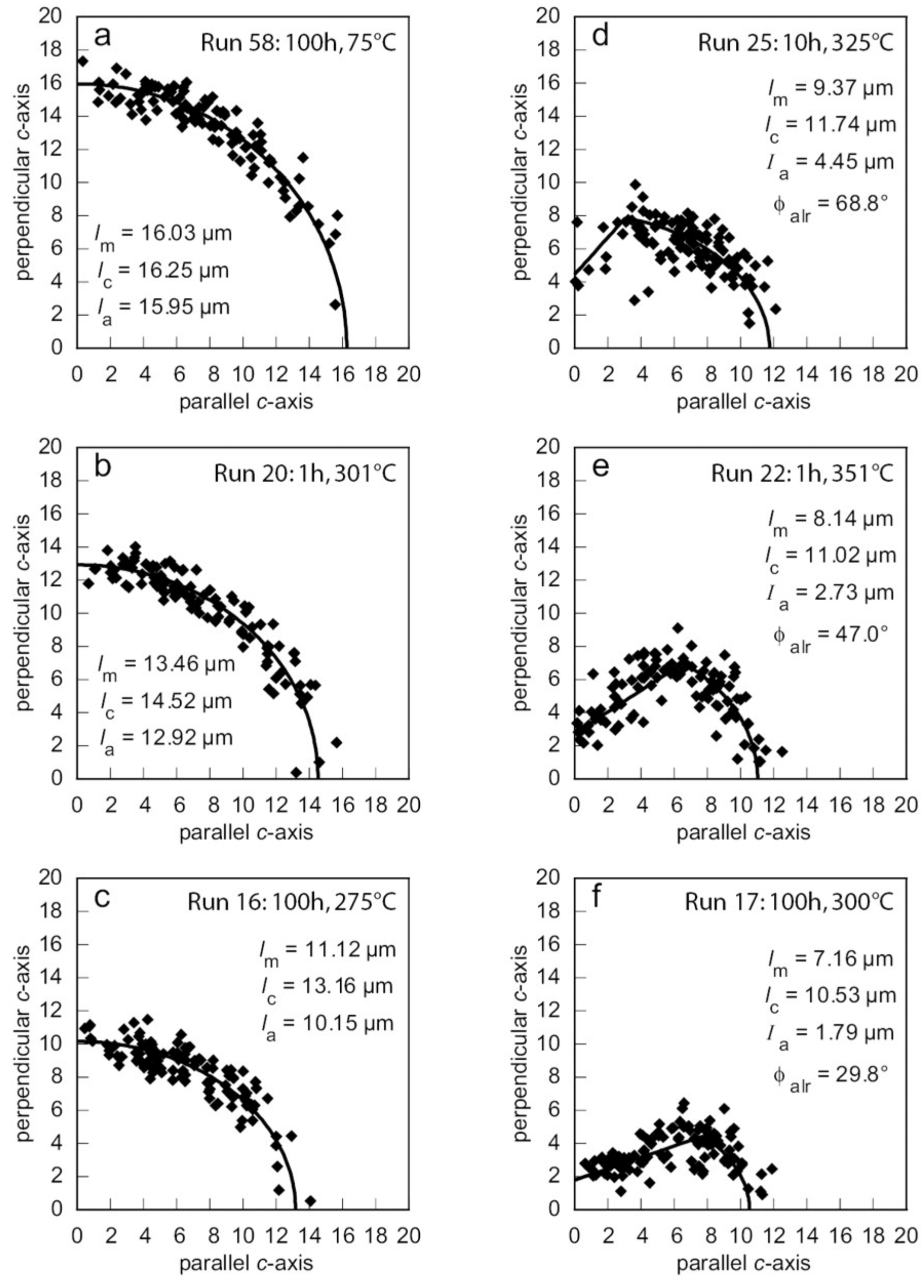


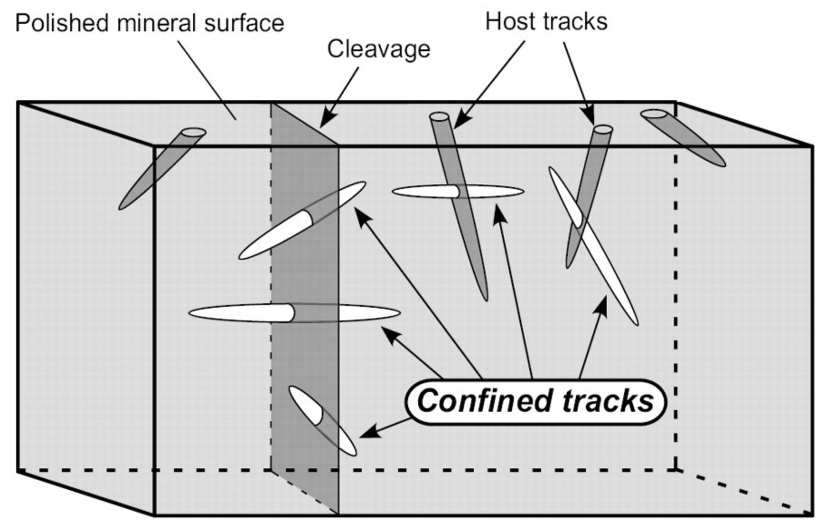
Figure 1. Polar coordinate plots of fission-track length measurements of Durango apatite at progressively higher levels of annealing, with fitted ellipses and line segments. Run refers to experimental annealing run from Carlson et al. (1999); lm is mean length; lc and la are c-axis parallel and perpendicular intercepts of fitted ellipses; la is c-axis perpendicular intercept of line segment fit to accelerated length reduction tracks; ϕalr is angle of onset of accelerated length reduction. From Donelick et al. (1999), with variable names changed according to Ketcham (2003b).

Track Length Measurement

Several types of targeted confined tracks:

- –TINT (track in track)
- –TINCLE (in cleavage)
- –TINDEF (in defect/ inclusion)

(A)



(B)

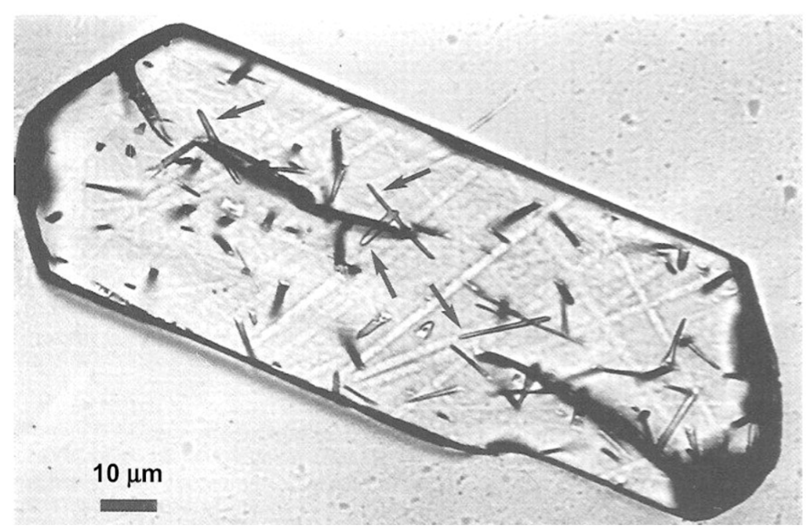
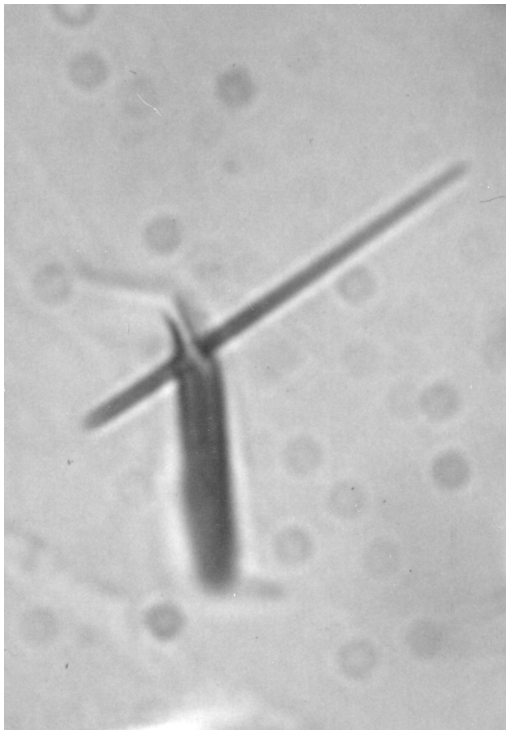
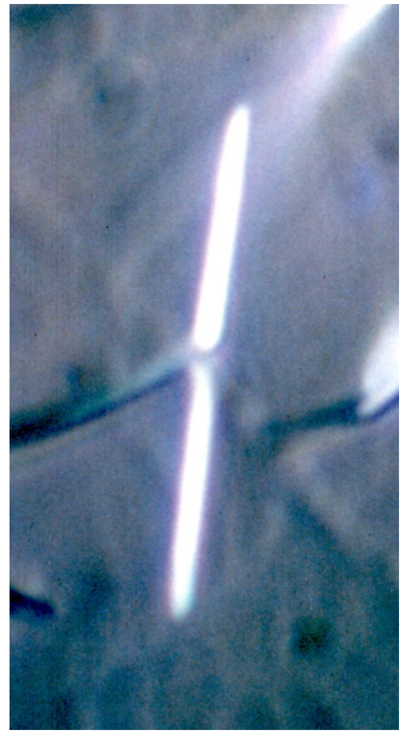


Figure 10. (A) A schematic illustration of an etched mineral that reveals confined tracks of different dimensions, i.e., tracks-in-cleavage (TINCLEs) or tracks-in-track (TINTs). (B) A top-view photograph of etched spontaneous tracks on a polished internal surface of apatite crystal (after Gleadow et al. 1986). Most of the visible tracks are surface-intersecting spontaneous tracks, which are used for age determination. Arrows point to four individual confined tracks.

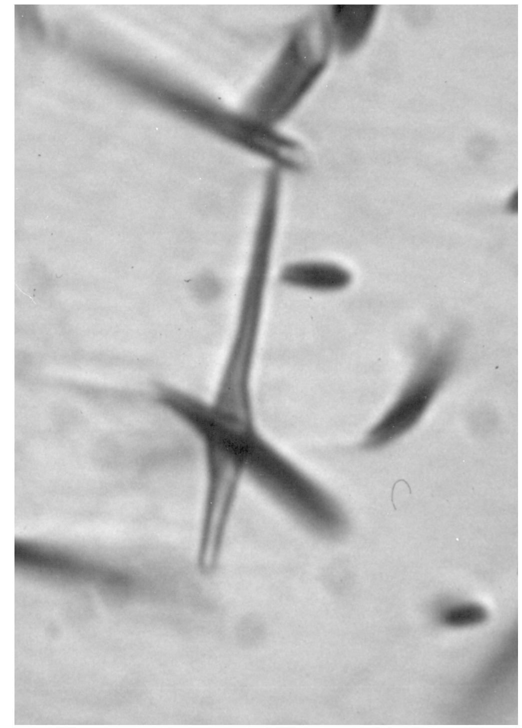
Track Length Measurement



Transmitted light



incident light

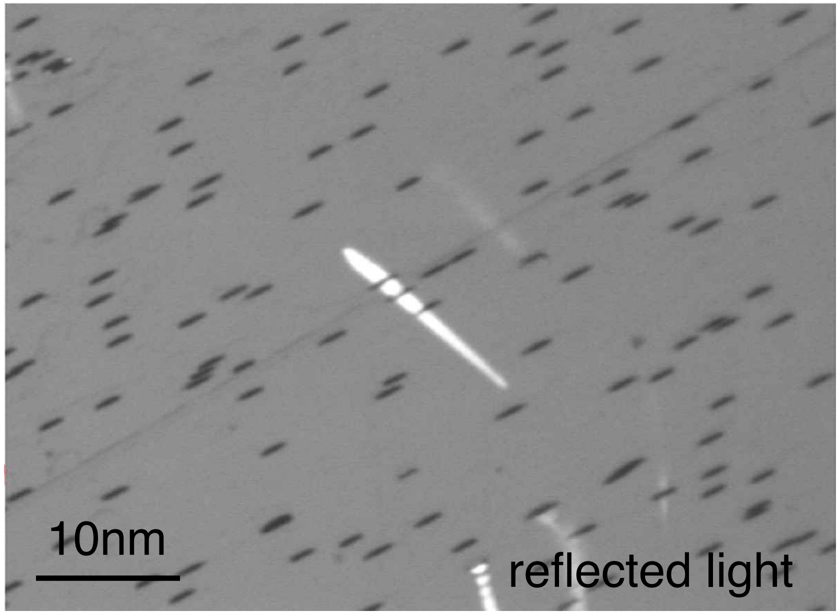


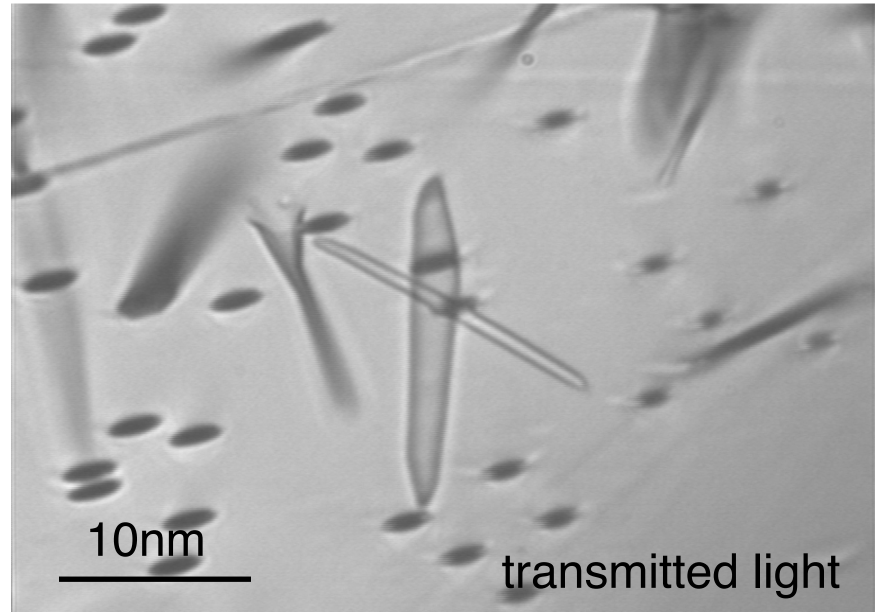
Transmitted light

~10μm

Horizontal confined fission tracks are measured under transmitted and incident light at ~1000x magnification. Roughly 100 track length measurements are needed to approximate the real track length distribution. Number of confined tracks can be enhanced by Cf-irradition.

Heavy Ion Irradiation





artificial surface tracks

^{252}Cf-irradiation (Donelick & Miller, 1991)

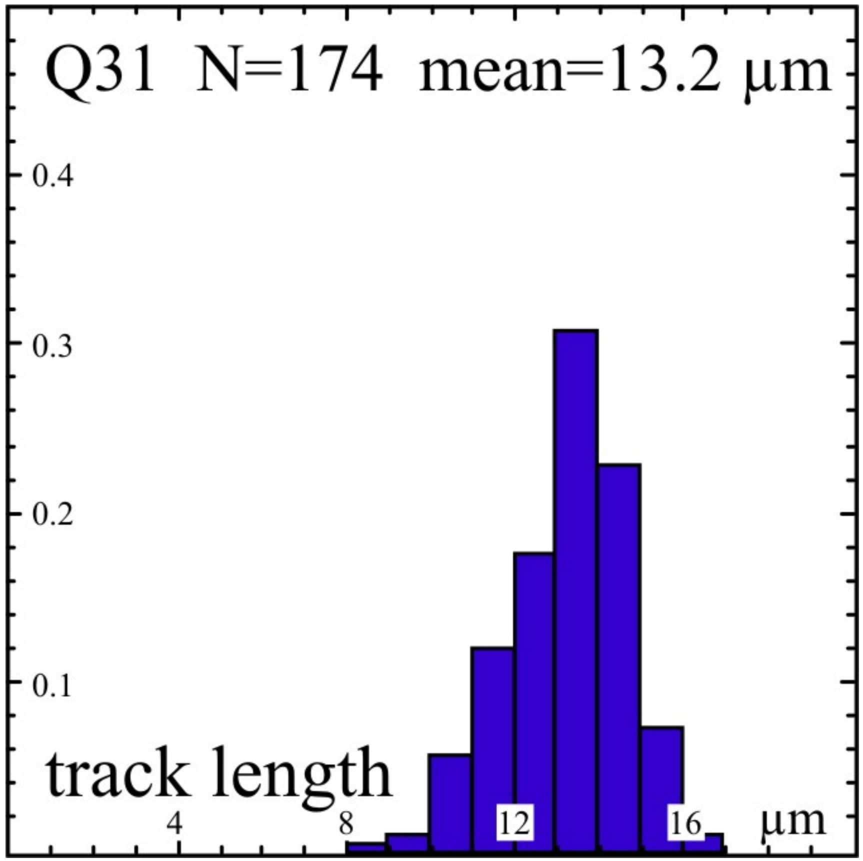
→ increasing number of confined fission-tracks up to fourfold

(Jonckheere et al., 2006)

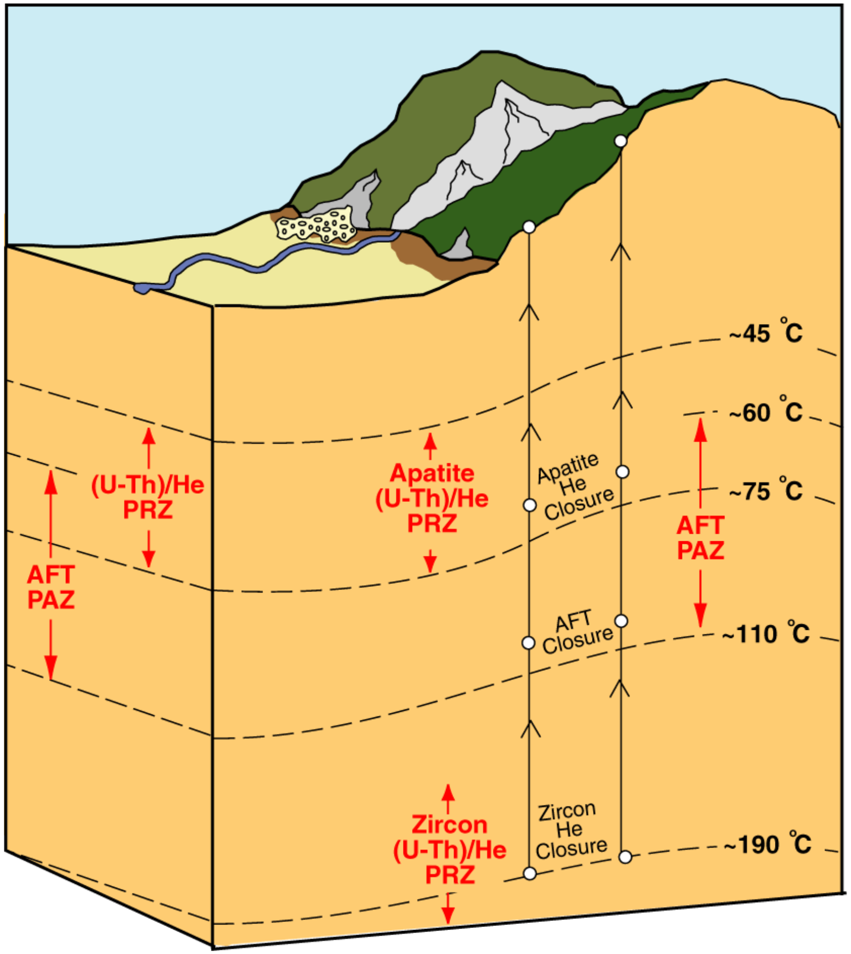
Find a confined track

http://geography.kcl.ac.uk/geochron/ftc/

Track-Length Distribution



The Power of Track Lengths



a) Chronology

1. Parent (^{238}U content)

Daughter (fission track)

Known decay rate

[?] gets you an age!

b) Thermal

- Daughter begins to be retained below Temp (Tc)
- Daughter partially retained in T zone Tc – Tx (PAZ)

[?] for fission tracks, this means they shorten (anneal)

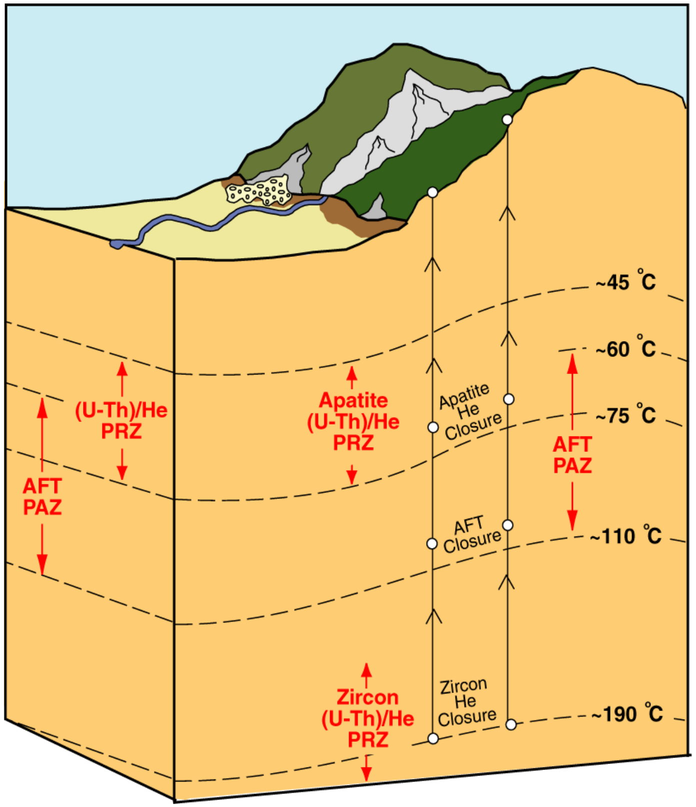
What does the age represent?

Age since sample cooled below a given temp -> “cooling” ages.

The Power of Track Lengths

[?] They will have a distribution that reflects their cooling history

Review, if tracks:
1) Form above Tc: totally anneal (heal) right away
2) Form below Tc:
    a) In PAZ, shorten (anneal)
    b) Below PAZ, stay original length



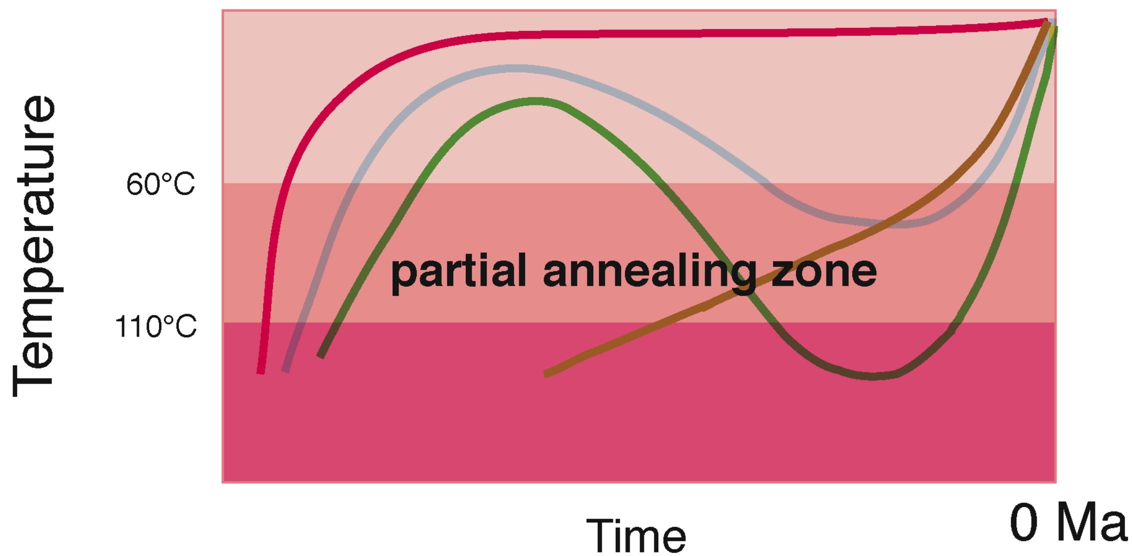
General rules of thumb:

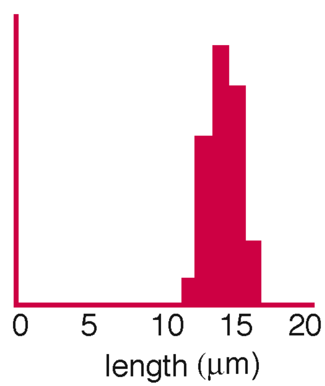
Fast cooling means? Long tracks…
-not much time in PAZ

Slow cooling means? Some short tracks..
-more time in PAZ

The Power of Track Lengths

à tracks will have a distribution (shown by histogram) that reflects the sample cooling history



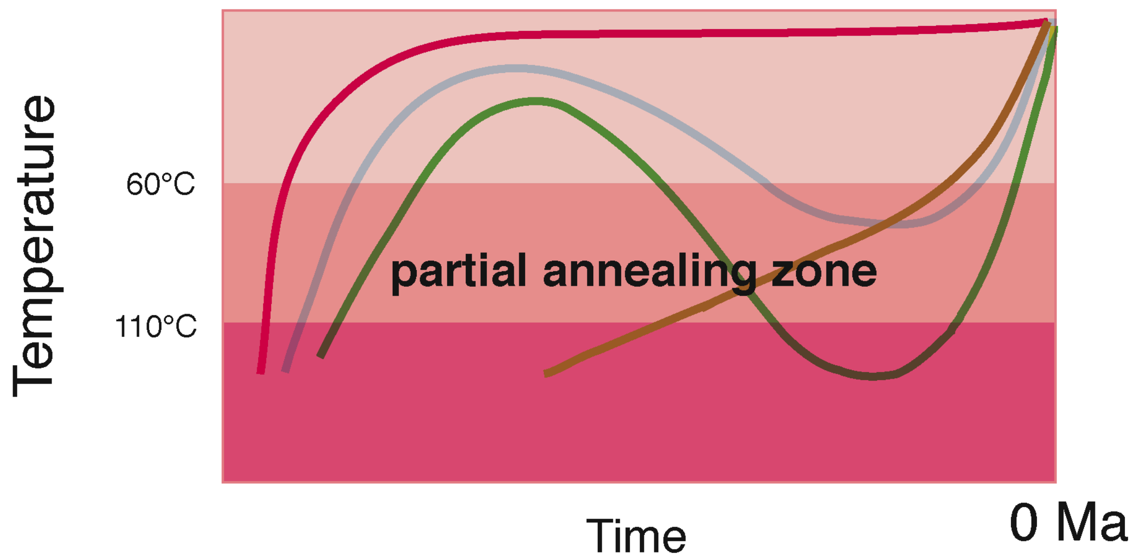


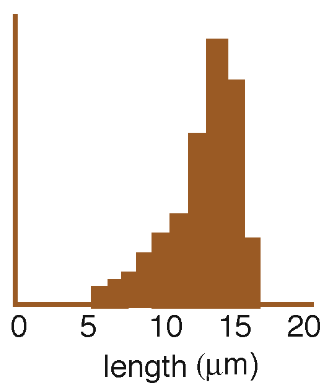
Red t-T history
- AFT tracks form initially at ~16 µm
- Which tracks formed 1st, which last in this histogram?

Next: the Brown t-T history?!?!?!

The Power of Track Lengths

à tracks will have a distribution (shown by histogram) that reflects the sample cooling history



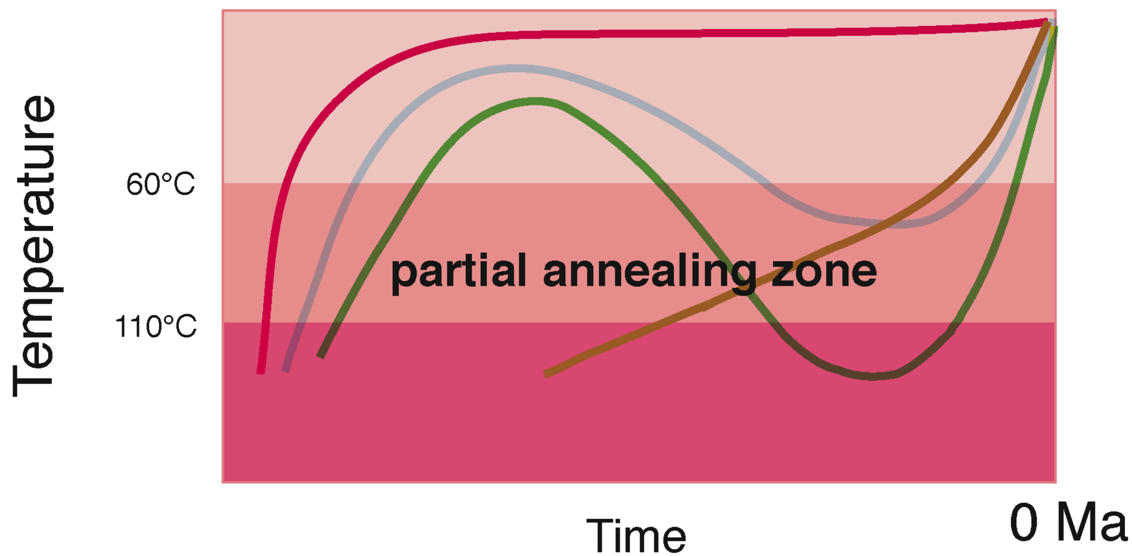


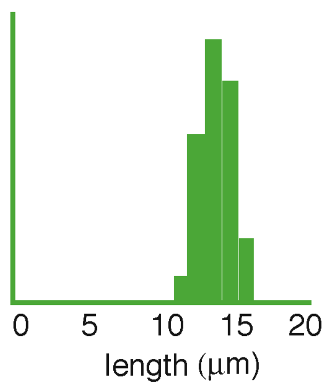
Brown t-T history

Next: the green t-T history?!?!?!

The Power of Track Lengths

à tracks will have a distribution (shown by a histogram) that reflects the sample cooling history



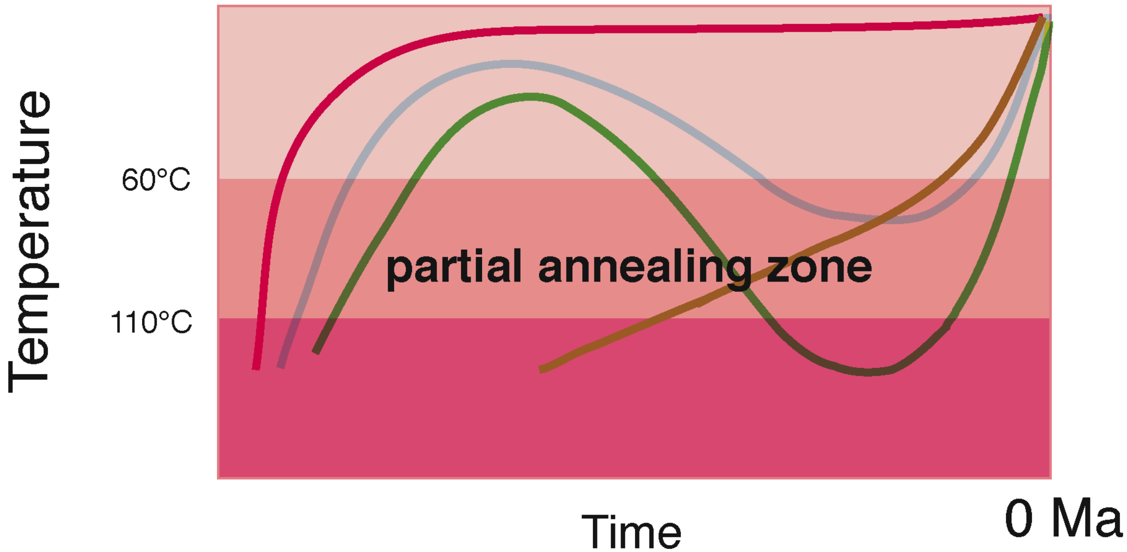


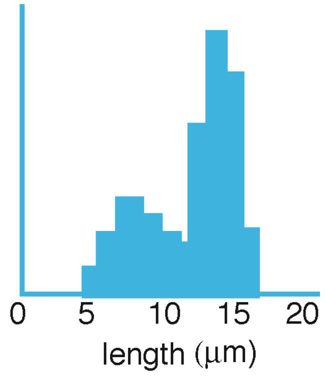
Green t-T history
- Does this look familiar?

Next: the blue t-T history?!?!?!

The Power of Track Lengths

à tracks will have a distribution (shown by a histogram) that reflects the sample cooling history

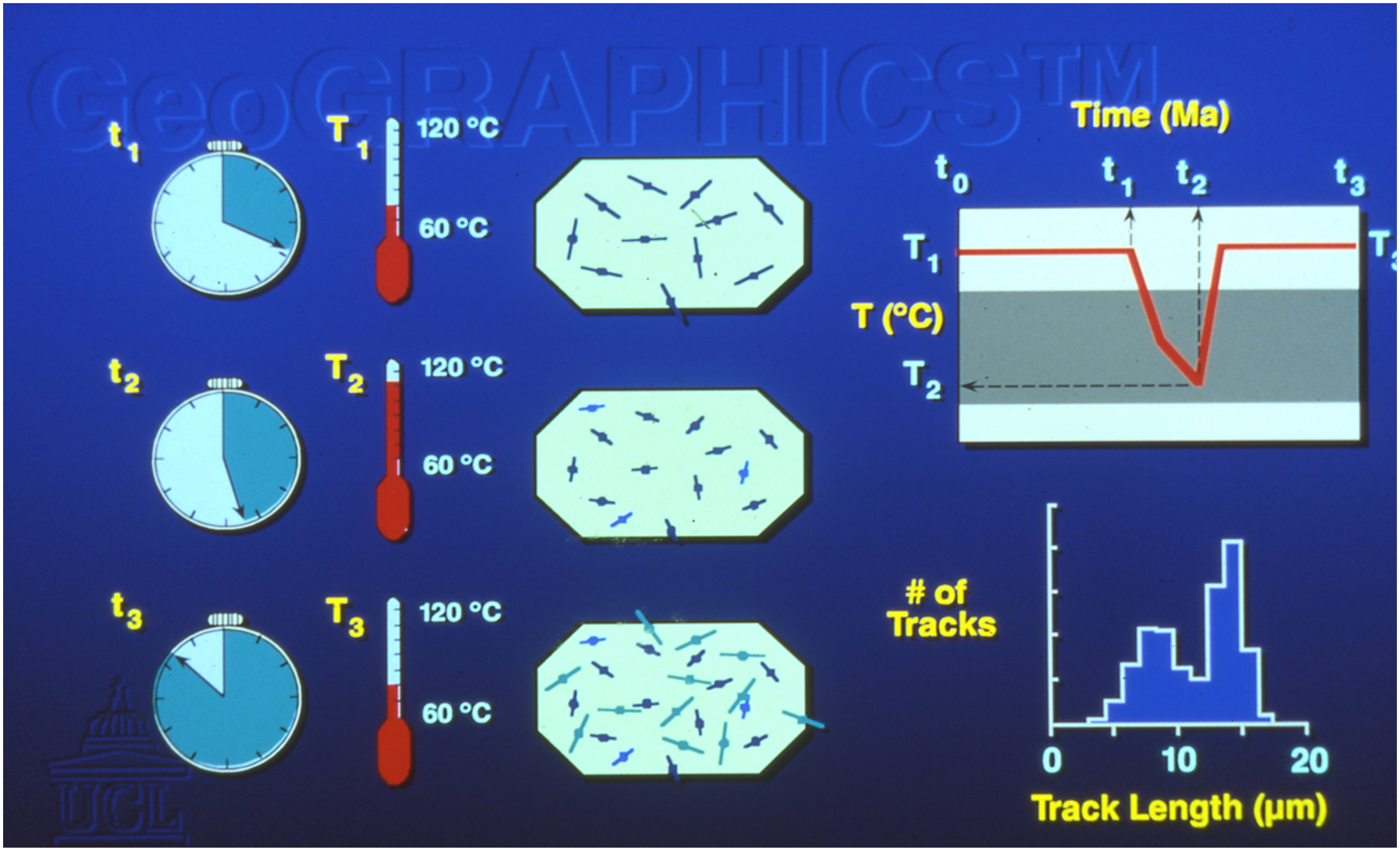




blue t-T history
- bimodal distribution
- typical of partially reset (buried) samples

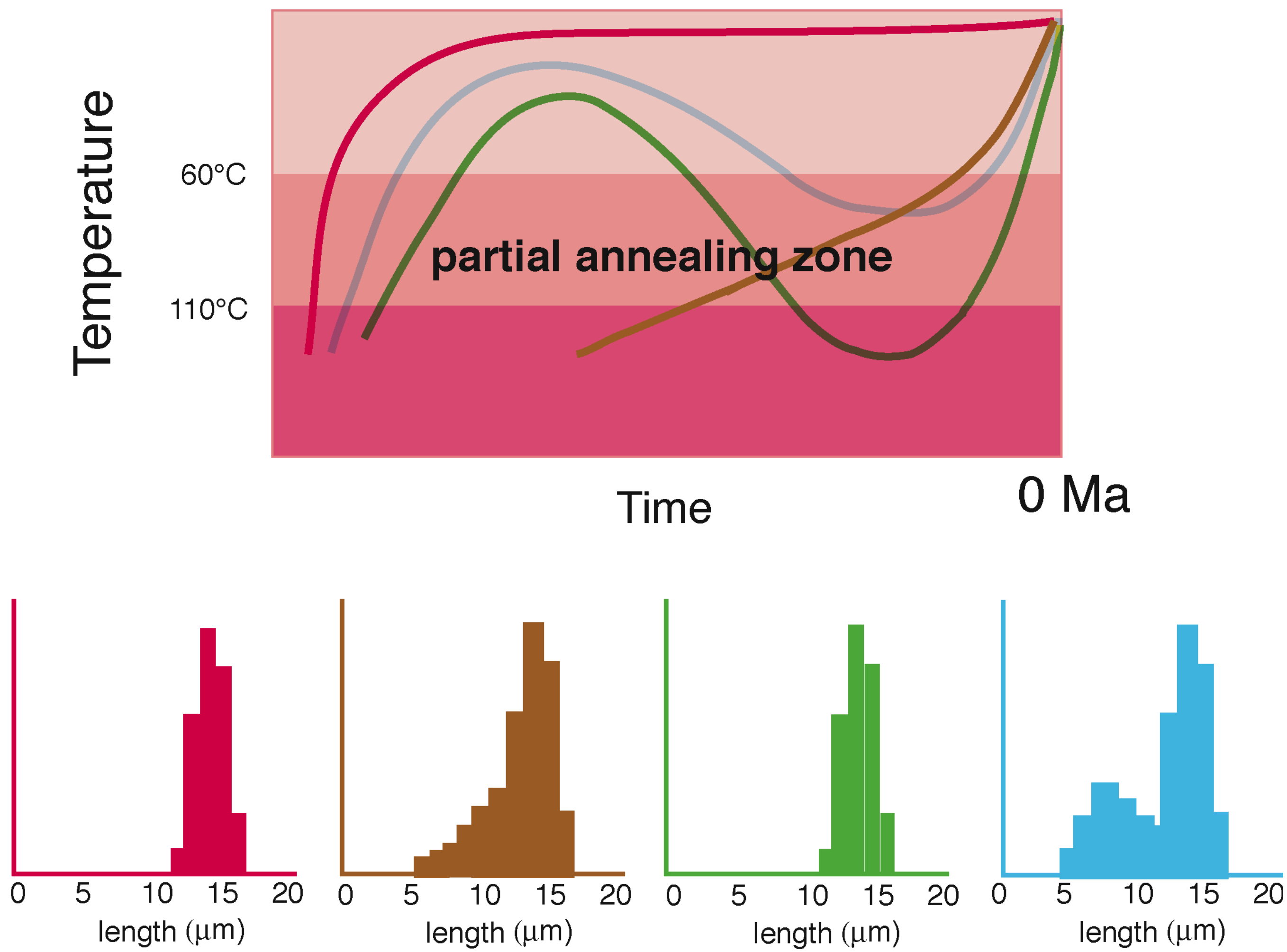
The Power of Track Lengths

How to obtain a bimodal track length distribution?



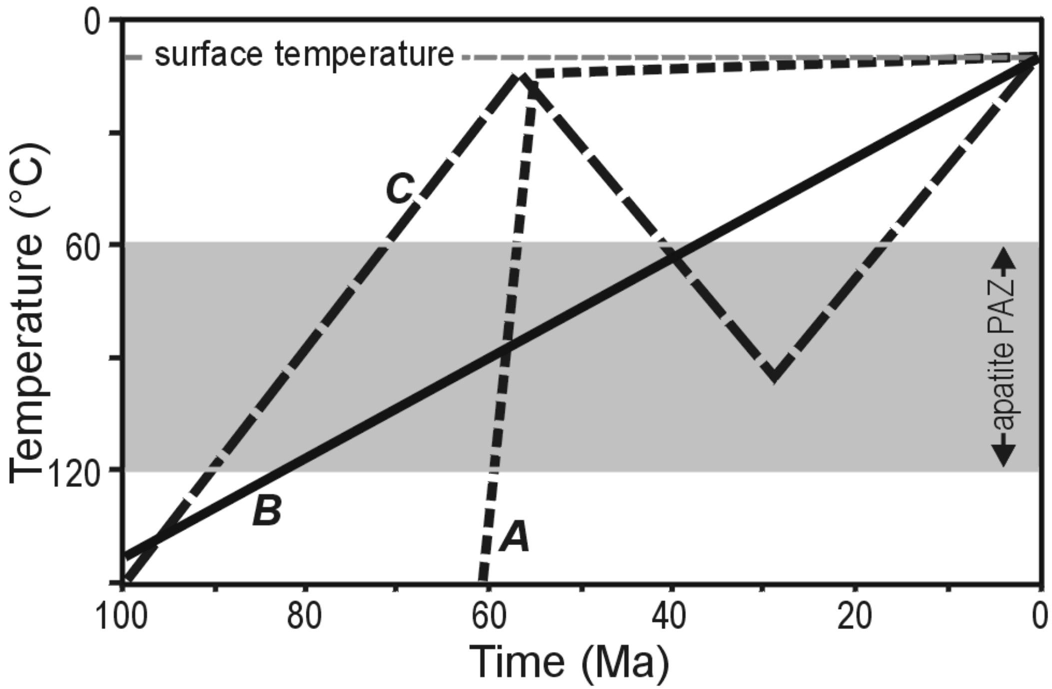
The Power of Track Lengths

à What about the associated cooling ages with each history?



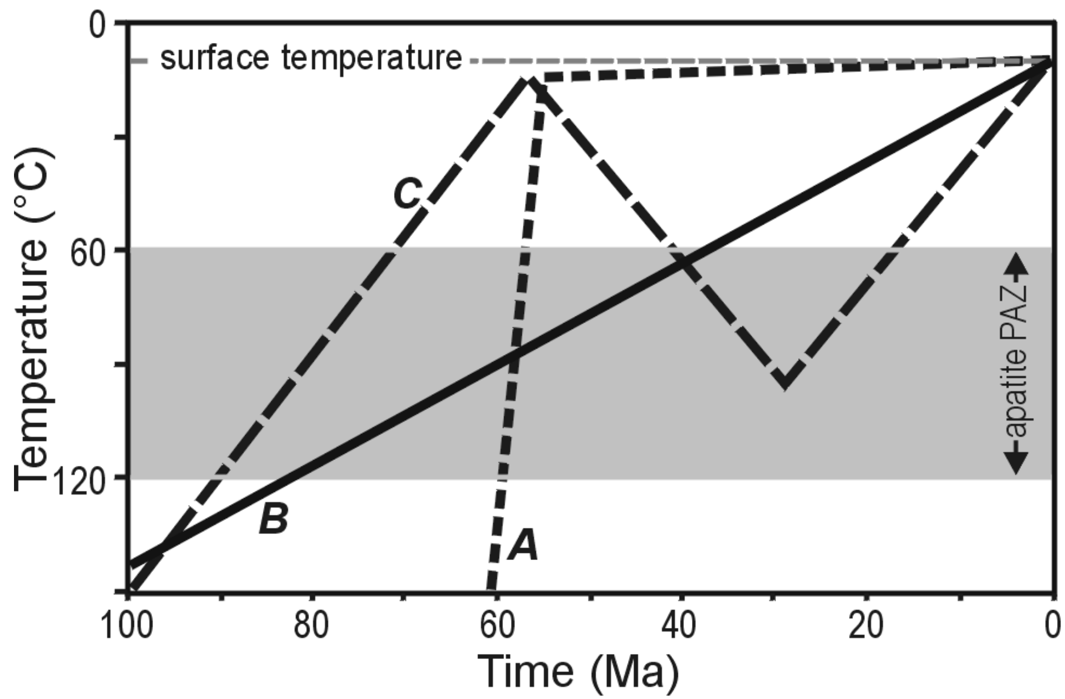
The Power of Track Lengths

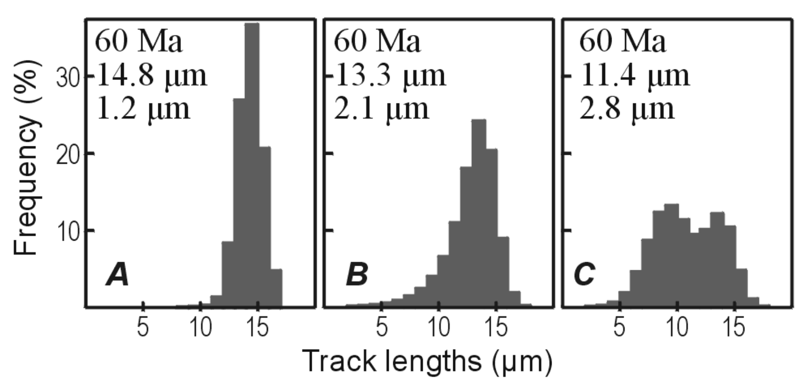
à What about the associated cooling ages with each history?



The Power of Track Lengths

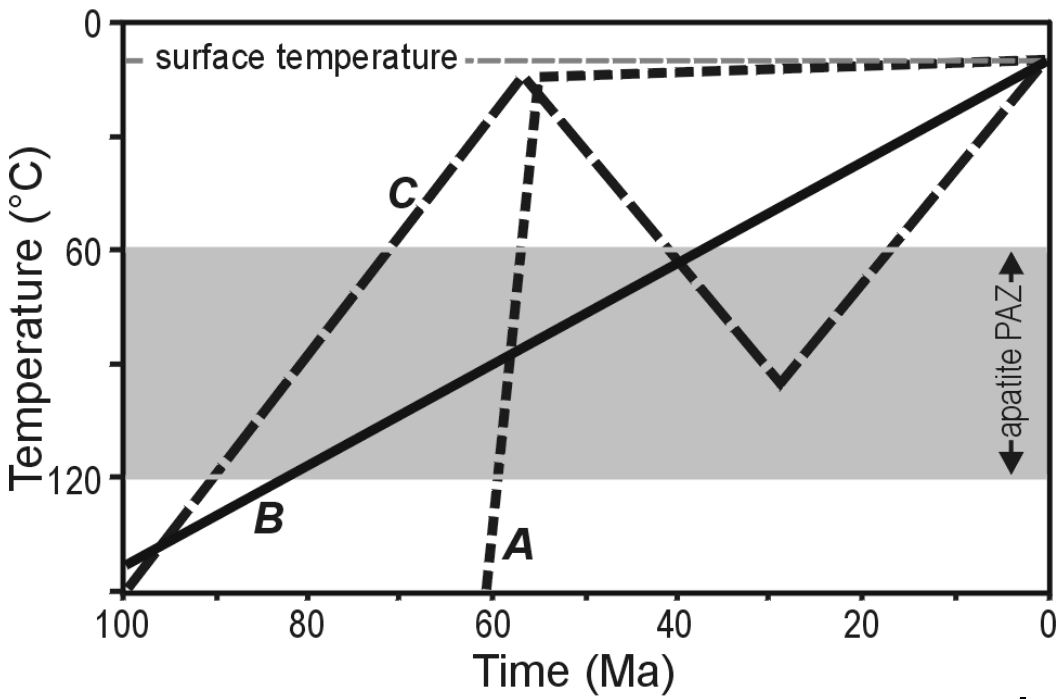
What about the associated cooling ages with each history?

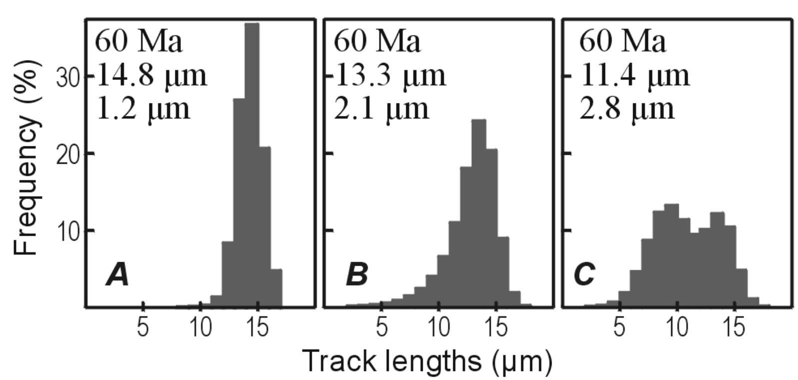




The Power of Track Lengths

What about the associated cooling ages with each history?





A thermochronological age without additional information about the cooling history (AFT track lengths or other thermochronometers) is not very informative.

Approximate the Annealing Kinetics of Apatite

Apatite composition

$Ca_5(PO_4)_3(F,Cl,OH)$

Why care?

Affects thermal properties:

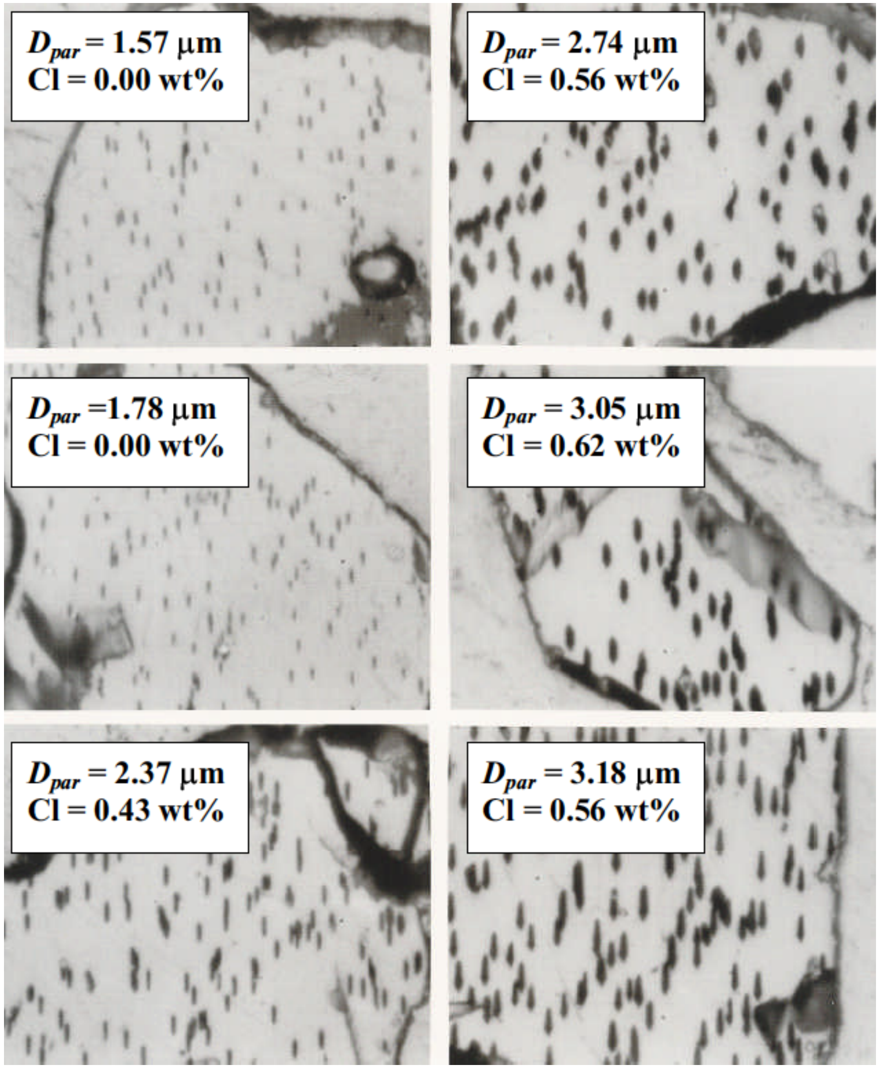
- F-rich apatite T_c (10°C/Ma) as low as 90°C
- Cl-rich apatite T_c (10°C/Ma) as high as 160°C

Measure composition in 2 ways:

1. Directly via electron microprobe
2. Indirectly via track etch pit geometry

Dpar : width of track etched pit

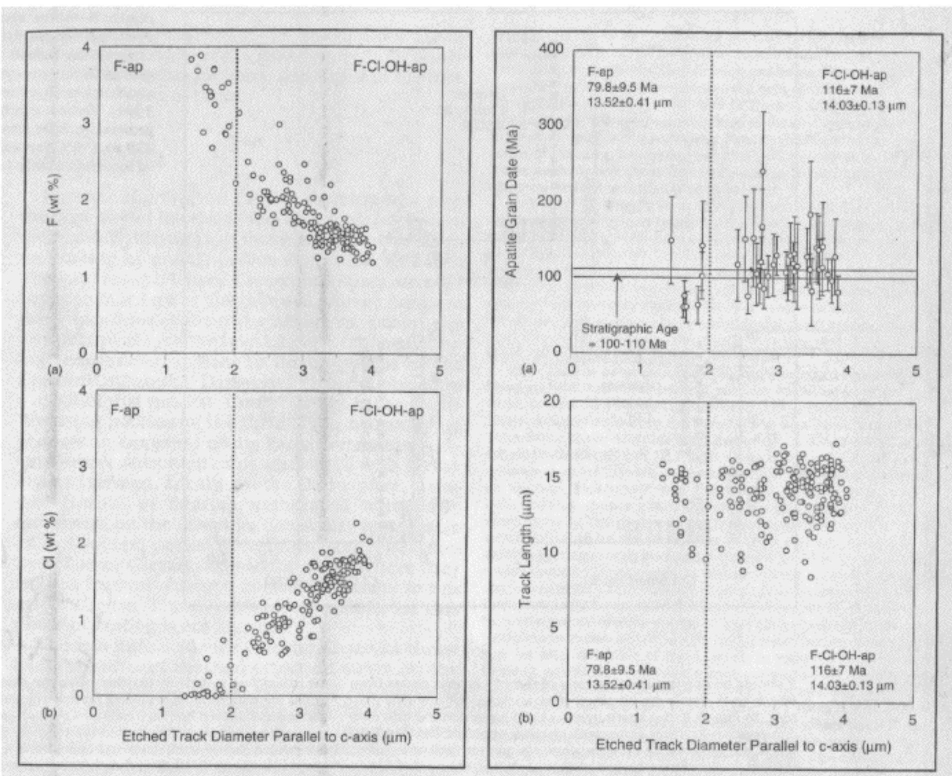
- Proxy for composition



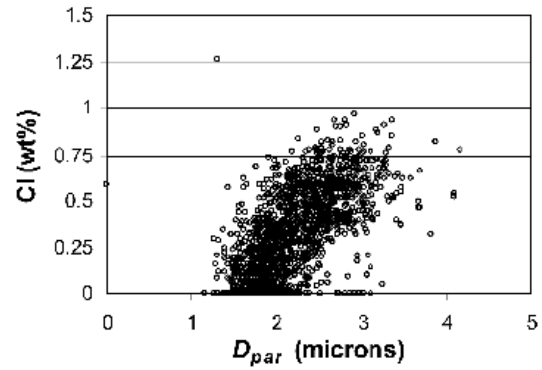
Approximate the Annealing Kinetics of Apatite

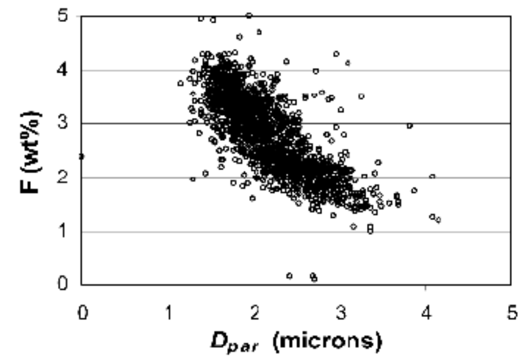
Dpar : width of track etched pit is proxy for composition

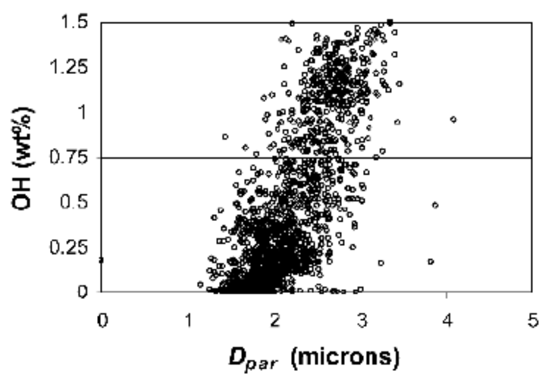
F-rich apatite: Dpar < 2 μm
Cl-rich apatite: Dpar > 2 μm
Hydroxyl apatite: Dpar > 2 μm



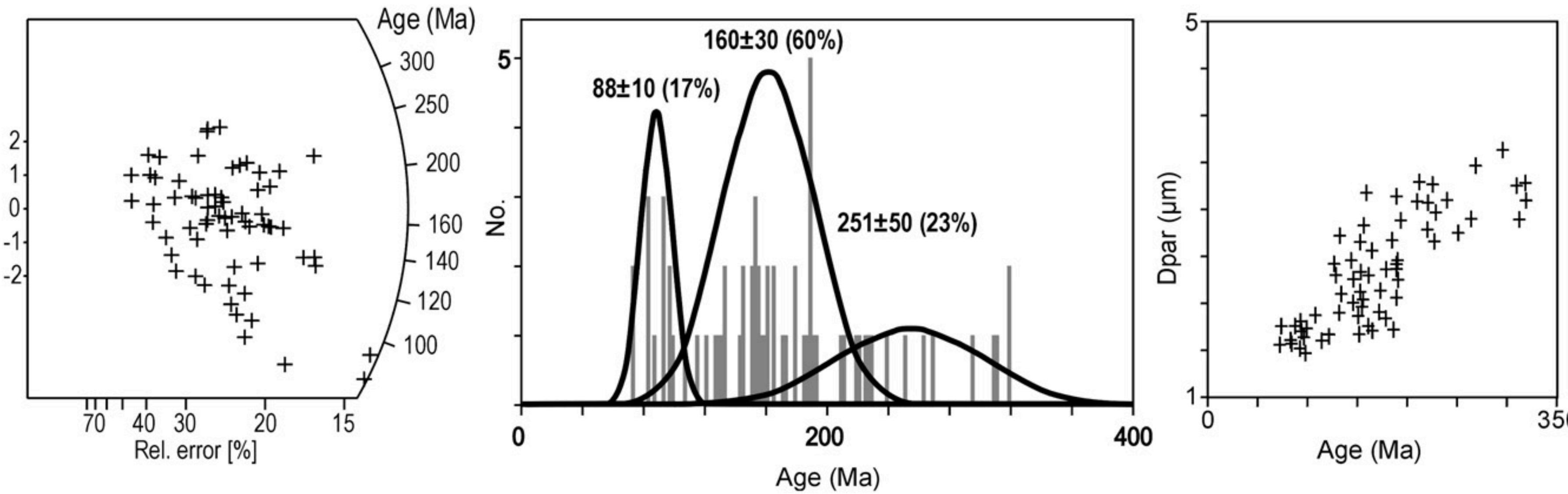
Burtner et al. 1994







AFT Age vs. Annealing Kinetics

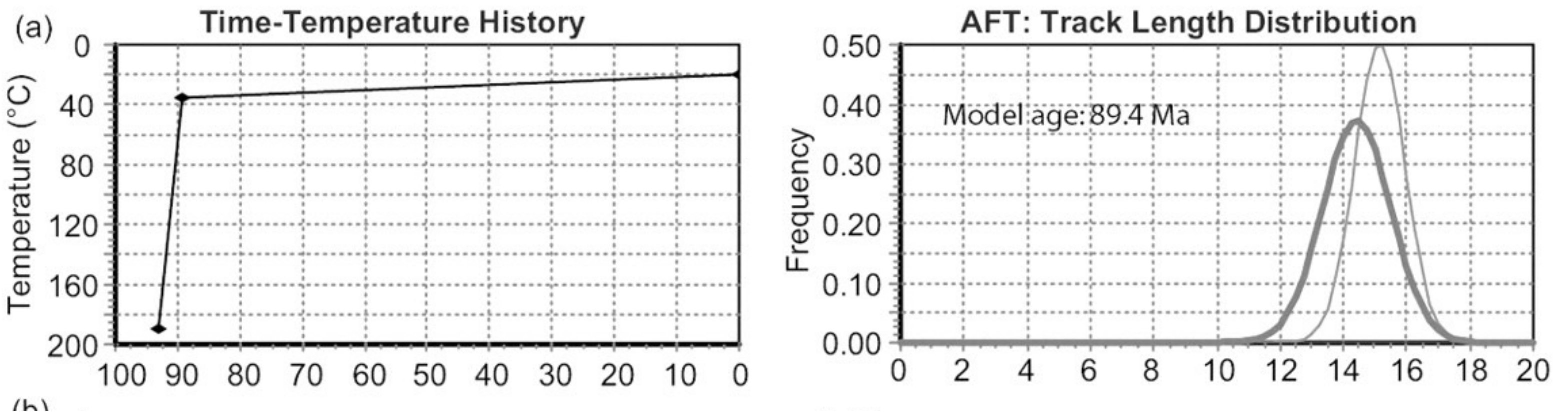


Danišík et al. (2008)

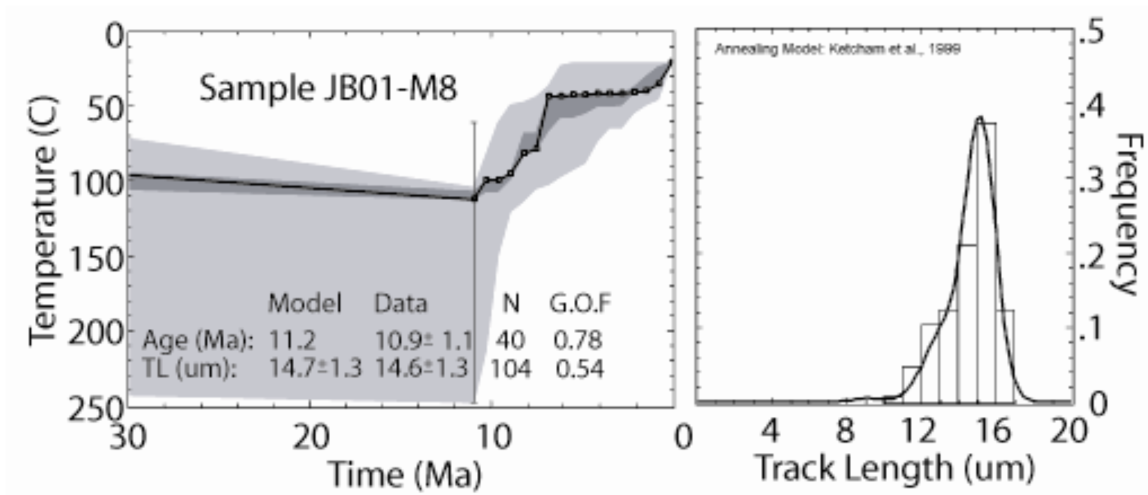
Large scatter in AFT ages of a basement sample caused by slow cooling and large variations annealing kinetics - modeling such data requires to divide the sample in sub-classes with similar annealing kinetics.

Forward/Inverse Modeling

Forward : Test a known/assumed t-T history and compare misfit.



Inverse : known final condition, assume the initial condition, reconstruct the intervening t-T histories consistent with the final conditions.



Forward/Inverse Modeling

Major components:

1. Theoretical annealing model – length/age evolves as f(t-T)
2. Algorithm for calculating evolution over t-T paths
3. Statistical means of comparing observations to predictions
4. Strategy for inverse modeling
5. Graphical representation of the range of t-T histories consistent with the data

3. Length distribution Goodness of Fit

•K-S test – 2 parameters: max separation between predictions/observations and N

- •Probability a set of random samples from predicted distribution has a greater max. separation from the predicted than is observed between the predictions/observations
- •K-S = 0.5 = 50% ? acceptable fit
- •K-S = 0.05 = 5% (or 95% confidence interval) ? good fit

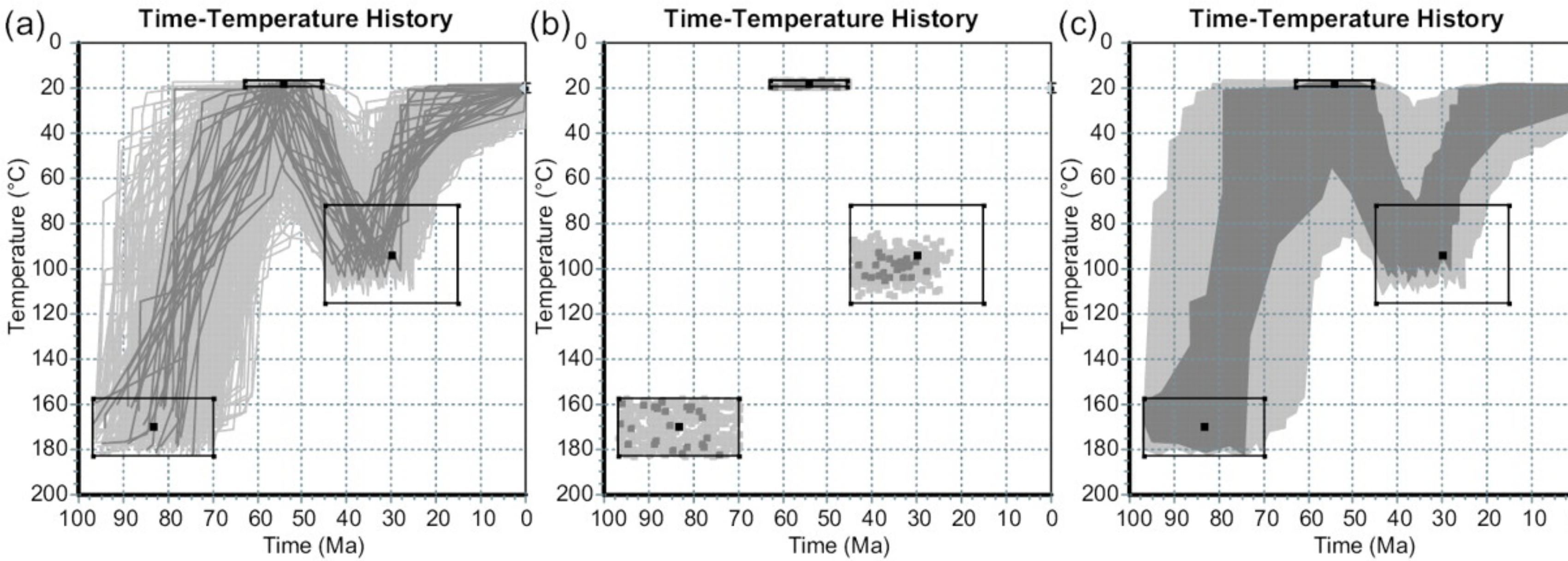
3. Age Goodness of Fit

•Similar to K-S test

- •GOF = 0.5 = 50% or expected for random samples ? acceptable fit
- •GOF = 0.05 = 5% (or 95% confidence interval) ? good fit

Forward/Inverse Modeling

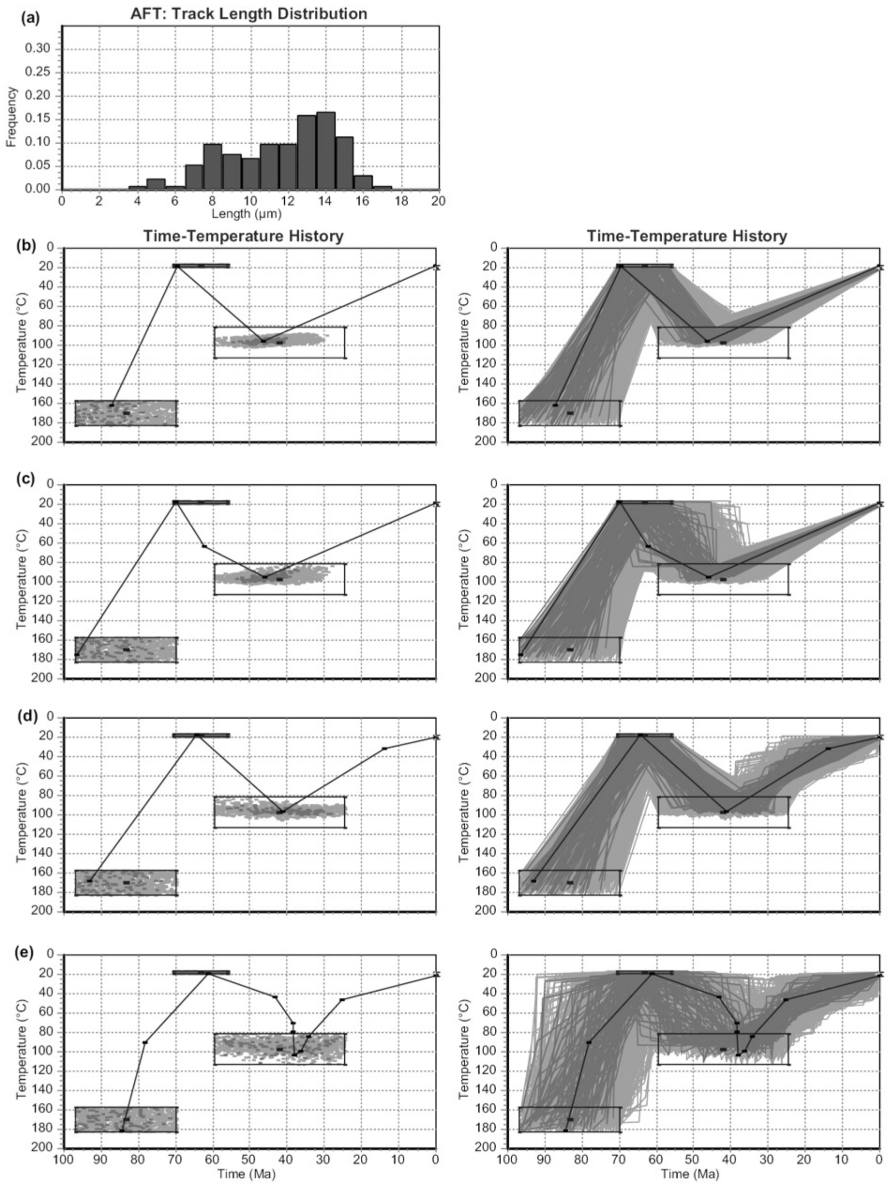
Visualizing model results (t-T-histories):



Various methods for displaying inversion results. In all cases, light = acceptable fit, dark = good fit. (a) All paths. (b) Minimum and maximum t-T points. (c) Envelopes around all paths fitting each criterion.

Ketcham et al., 2005

Forward/Inverse Modeling



How complex should the model be?

Example of various fits to bimodal apatite fission-track distribution shown in (a); measured age = 58.5 ± 4.8 Ma. (b) Only nodal points within constraints allowed. (c) One extra nodal point along reheating path. (d) One extra nodal point along final cooling path. (e) One extra node along initial cooling paths, and three along reheating and final cooling paths. For each inversion, random paths were generated until 100 "good" paths were found.

Ketcham et al., 2005

Let’s invert fission track data

Model t-T-histories for two samples (BC and Sevier) with HeFTy, start by opening the file FT_exercise.docx and follow the instructions…