(U-Th)/He dating: principles and applications

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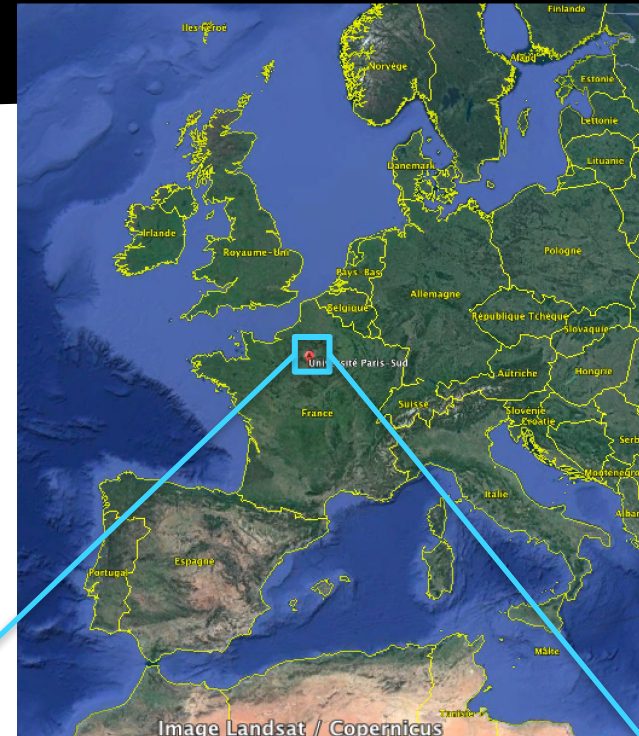
Paris universities

University of Paris Notre Dame (Sorbonne) was born in 1150 (2nd university in Europe)

=> Introduced several academic standards such as doctoral degrees



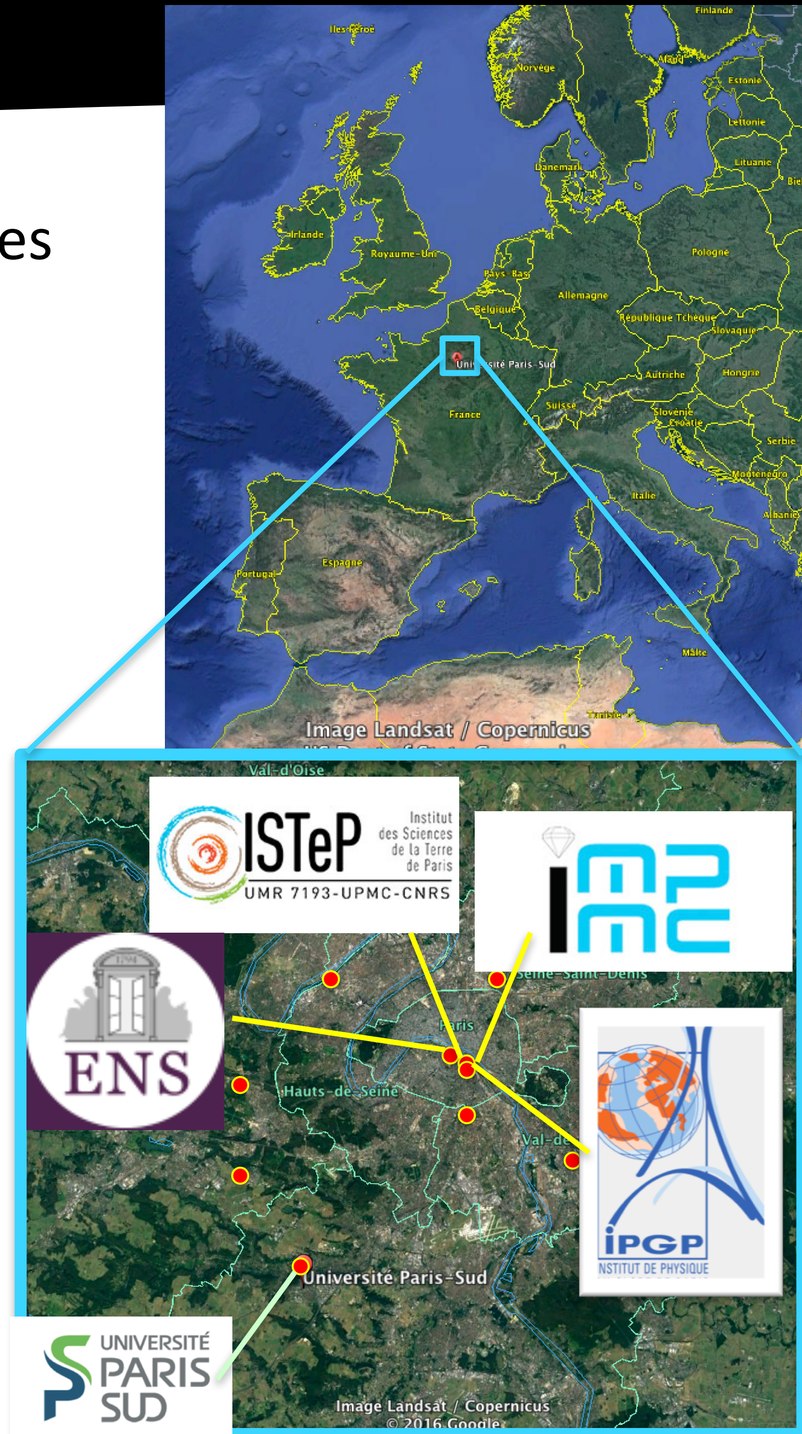
Paris universities

After 1968 => 15 autonomous universities

More than 7 universities with a Geosciences department

University <u>Paris Sud 11</u> was born in 1955

- 30 000 students from 125 nationalities
- 2500 researchers (40 in the Earth Science department)
- Pluridisciplinary research



(1) (U-Th)/He dating system

I. Introduction, generalities

II. (U-Th)/He principles (chronometer vs thermochronometer)

(2) How to get an (U-Th)/He age

(3) Applications

III. Apatite (U-Th-Sm)/He (AHe) method

IV. Other applications (zircon, iron oxides,…)

(4) Exercises (Tc, ejection, weight, Rs), thermal modeling

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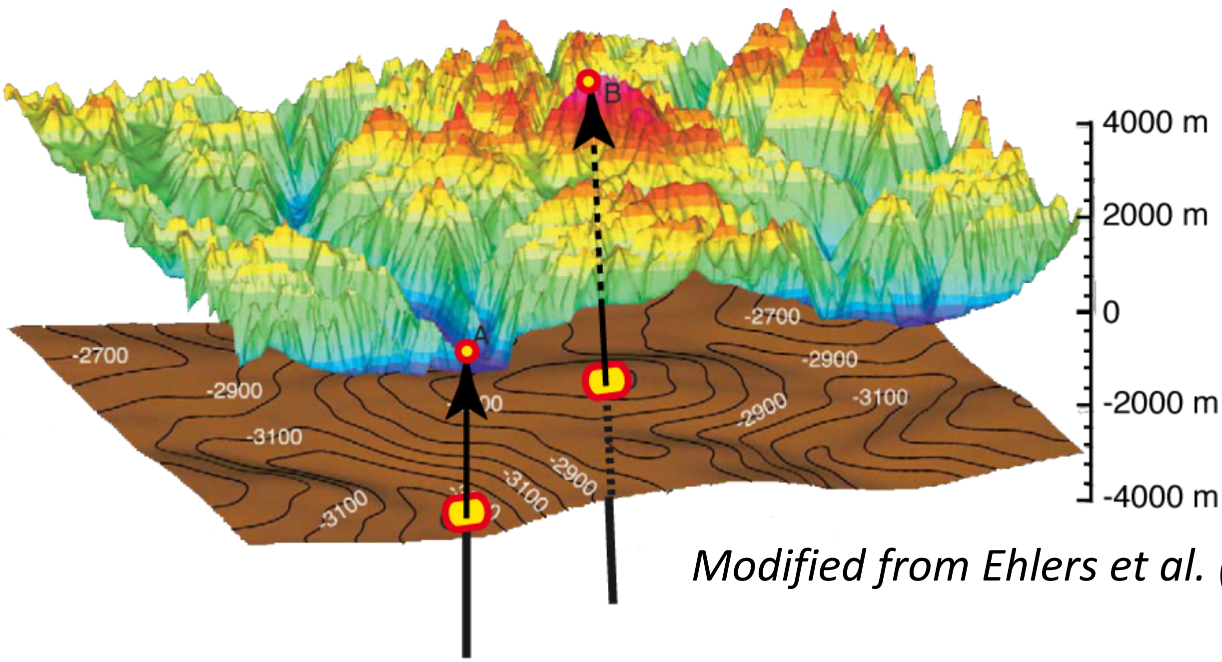
I. Quantification of rocks thermal evolution through time



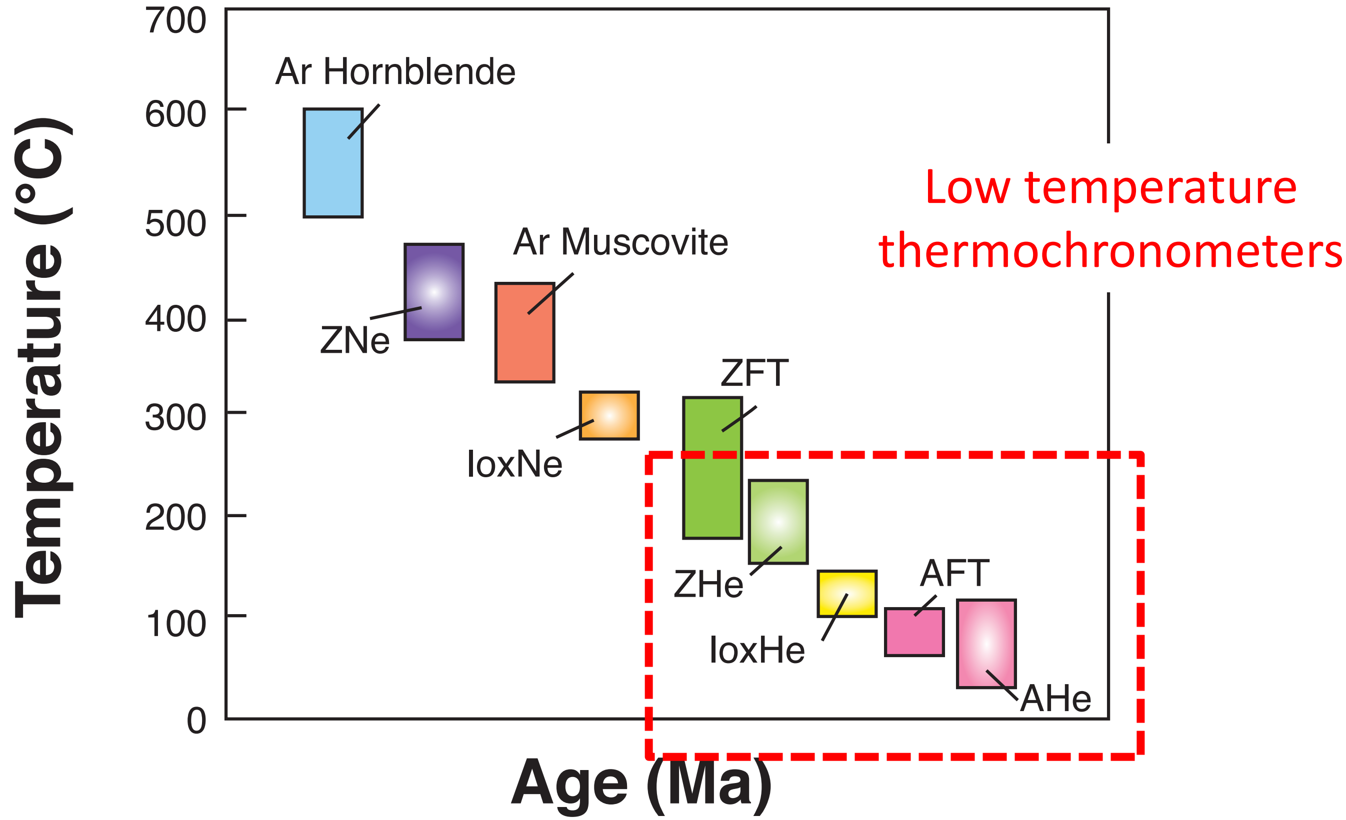
Modified from Ehlers et al. (2003)

U-Th-Sm (parent) => He (daughter)

Complete daughter retention **=> chronometer**

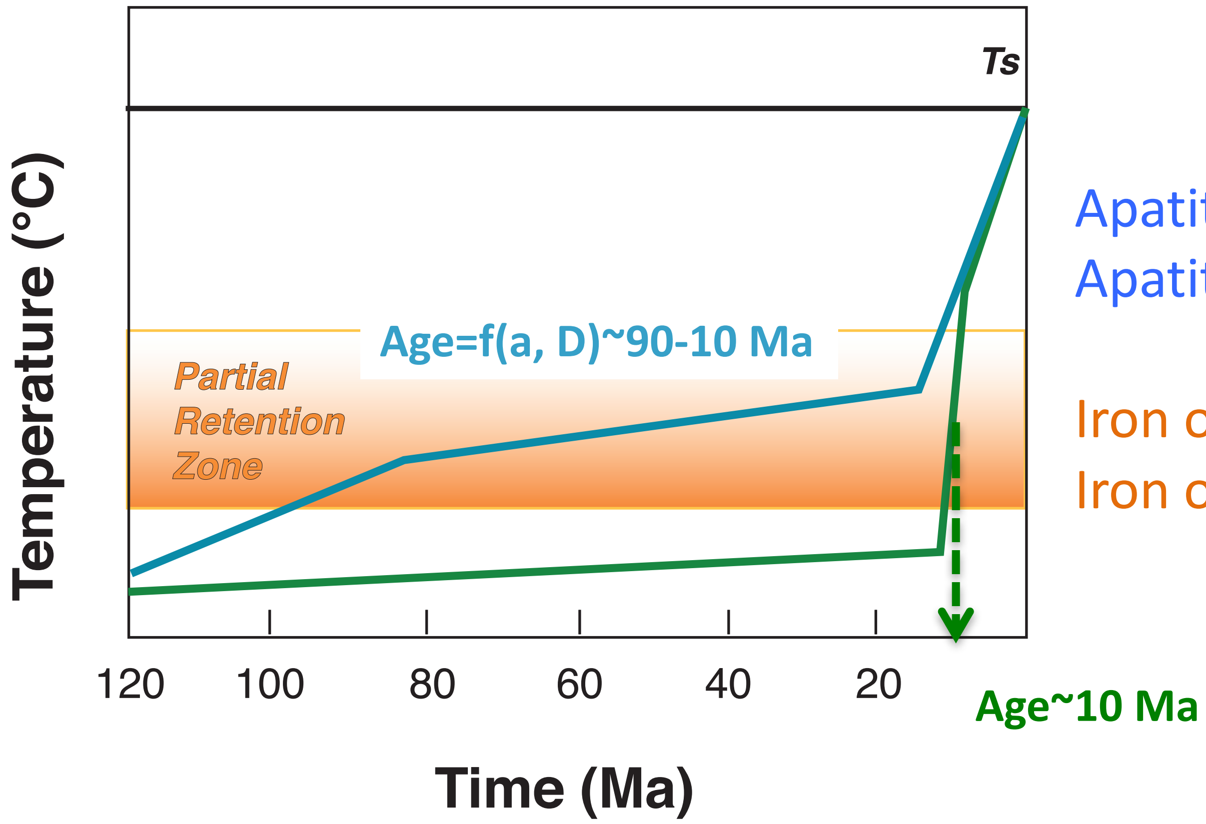
Daughter loss by diffusion **=> thermochronometer**
(Closure temperature and Partial Retention Zone)

I. Thermal sensitivity of thermochronometers



- **(U-Th)/^{4}He** method applied on apatite, zircon and iron oxides
- Thermal sensitivity from 40 to 200°C

I. Meaning of thermochronological ages



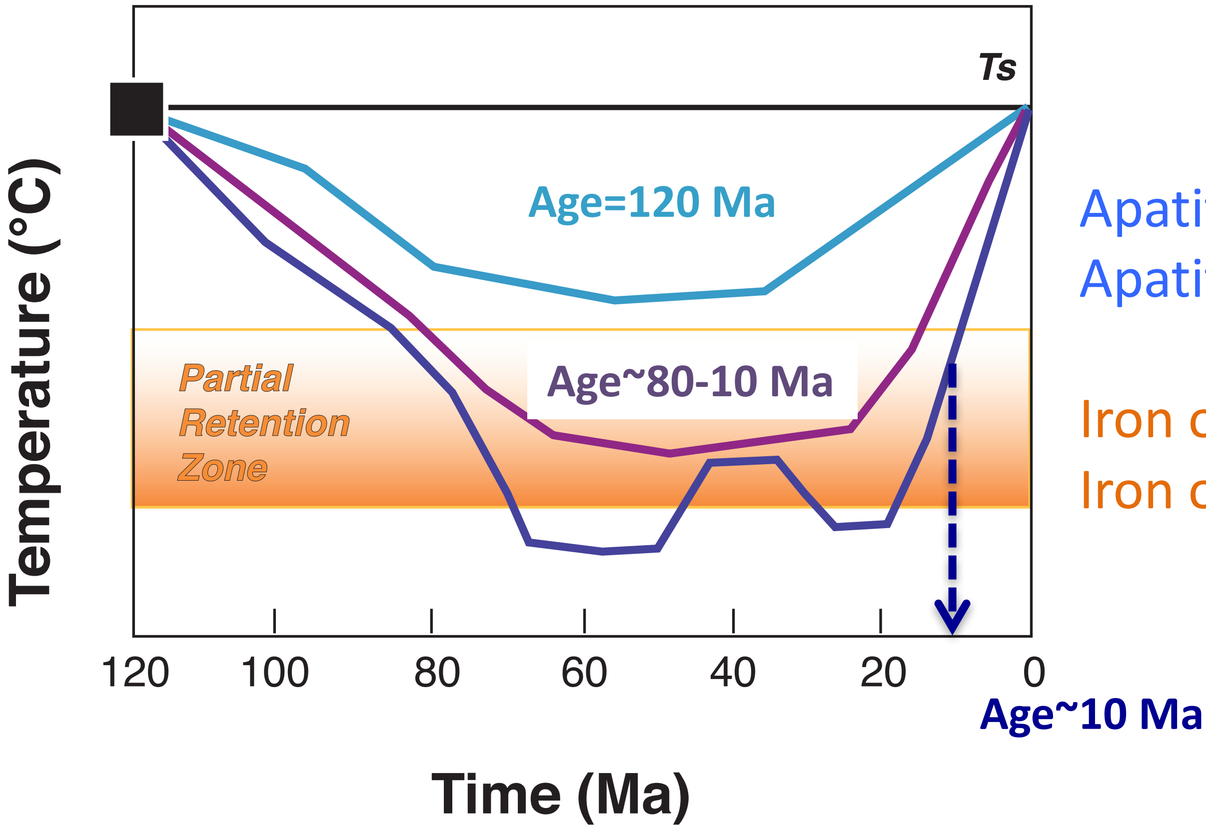
Apatite He: 40-120°C
Apatite FT: 60-120°C

Iron oxides He: ~110°C
Iron oxides Ne: ~300°C

Plutonic rock example:

Rock formation age > thermochronometric age

I. Meaning of thermochronological ages



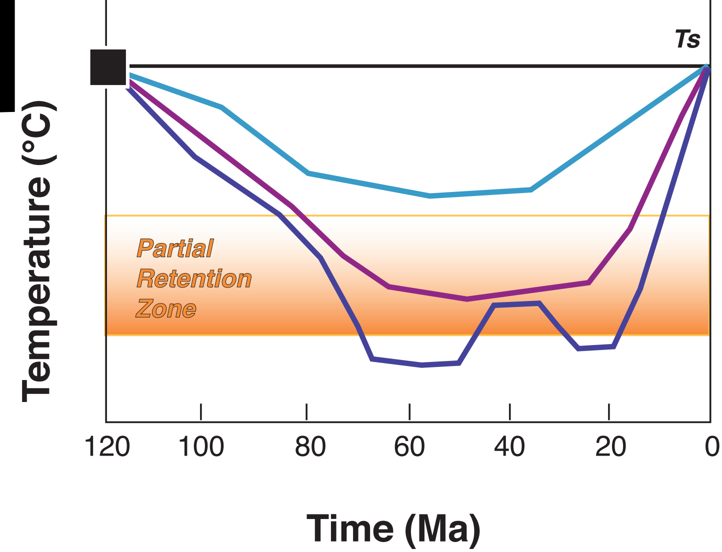
Apatite He: 40-120°C
Apatite FT: 60-120°C

Iron oxides He: ~110°C
Iron oxides Ne: ~300°C

Sedimentary, volcanic rock or iron oxides duricrust examples:

Rock formation age ≥ or ≤ thermochronometric age

I. Meaning of thermochronological ages



TAKE HOME MESSAGE:

- A thermochronological age (or date) is an **apparent** age
- Need to apply some **corrections** (alpha ejection, diffusion)
- ^{4}He accumulation in crystal lattice reflects **= f (thermal history, diffusion coefficient, grain size, …)**

I. Quantification of erosion and weathering processes

- **Apatite, zircon, titanite…** can be used to quantify **rock thermal history** and **erosion processes …**

- **Iron oxides (hematite, goethite)** can be used to quantify **weathering episodes** (paleosurfaces), **timing of ore deposits** …

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- **II. (U-Th)/He principles (chronometer vs thermochronometer)**

(2) How to get an (U-Th)/He age

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- **III. Apatite (U-Th-Sm)/He (AHe) method**

- **IV. Other applications (zircon, iron oxides,…)**

(4) Exercises (Tc, ejection, weight, Rs), thermal modeling

II. (U-Th-Sm)/He dating method principles

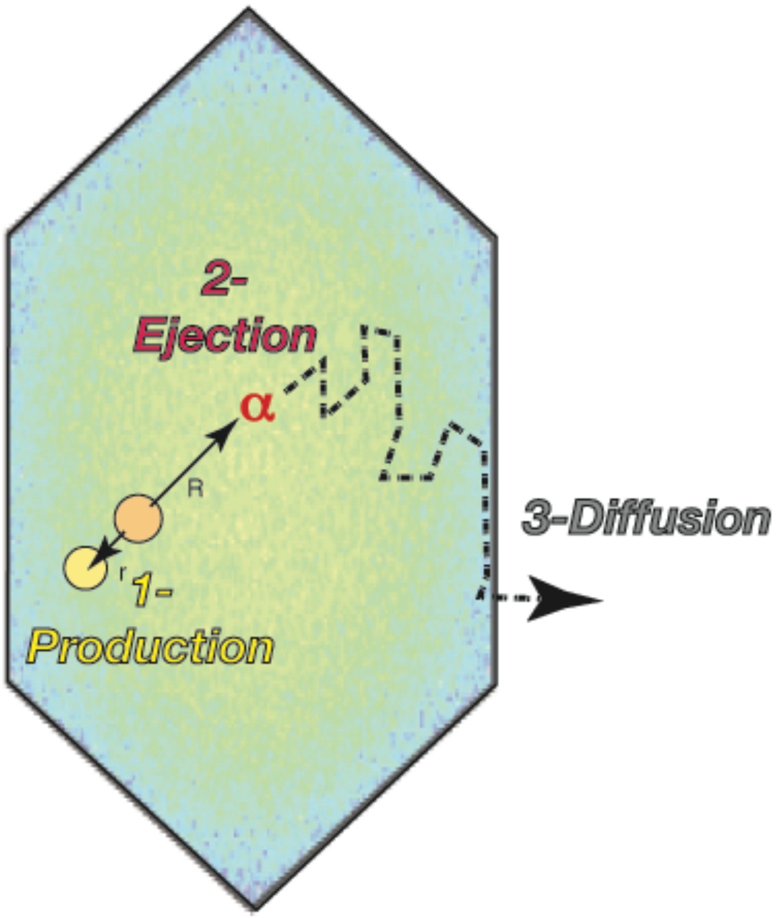
1) He atoms <u>production</u> in minerals during U, Th, Sm decay

2) Long alpha <u>ejection</u> (15-20 μm)

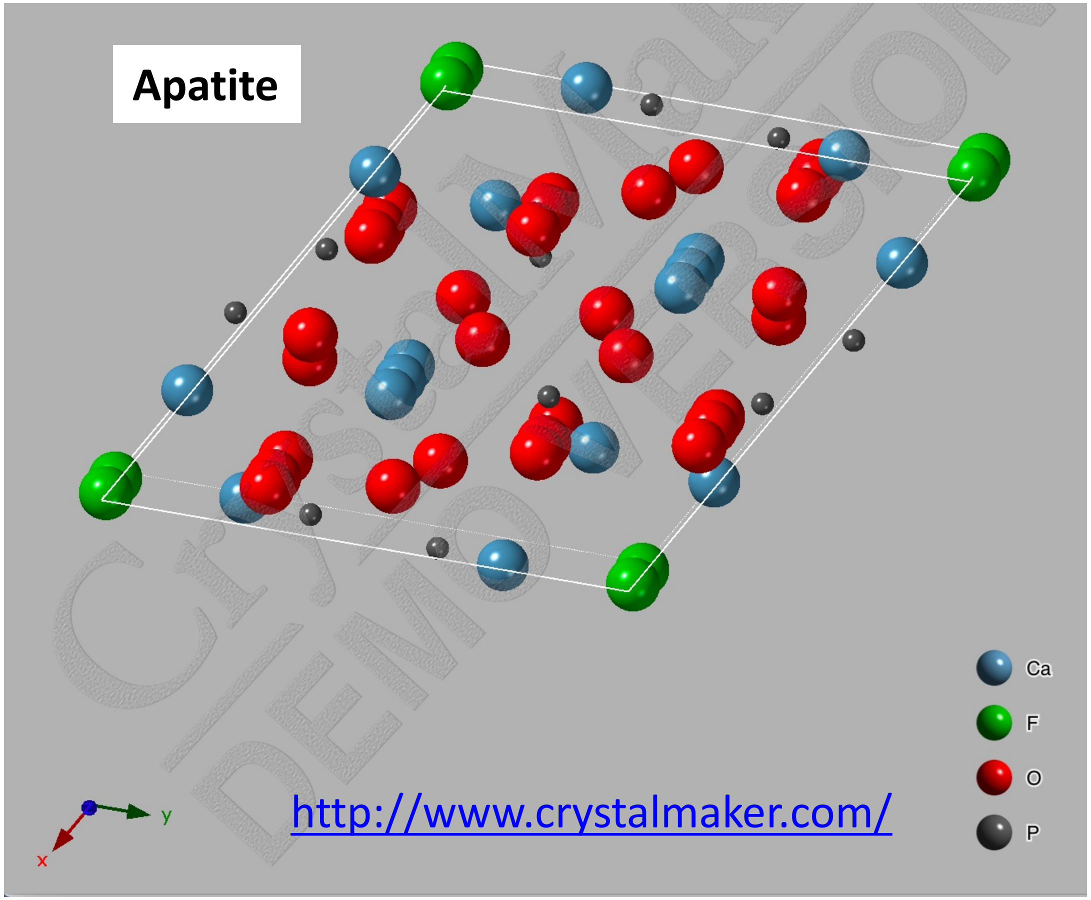
3) Possible <u>diffusion</u> in the crystal, depending on :

a) diffusion coefficients and

b) thermal history



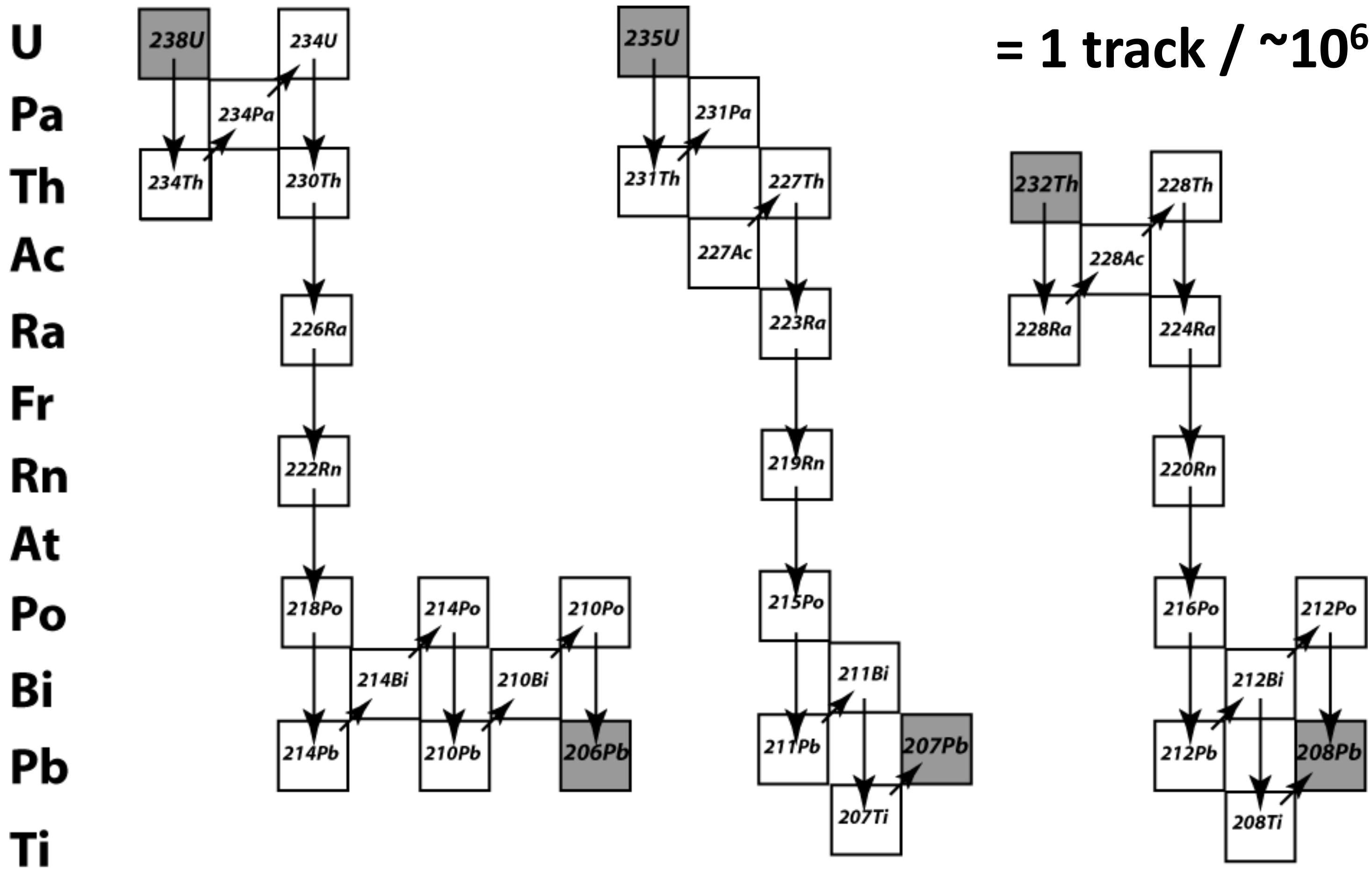
II. U-Th-Sm incorporation in crystal lattice



U, Th and Sm incorporation (substitution or cluster) in almost any crystal lattice:

- **U** = 0.01 - 1000 ppm; **Th/U** = 0.1 - 20; **Sm** = 10 - 3000 ppm

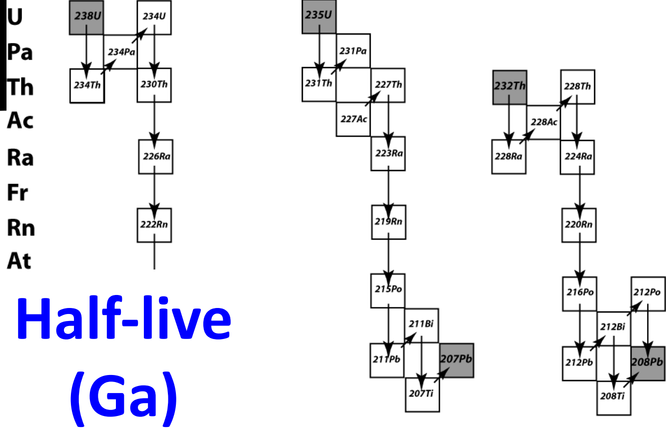
II. U-Th-Sm radioactive natural decay



^{238}U natural fission
= 1 track / ~10^{6} alphas

- **^{235}U + ^{238}U** = 99.99% U; **^{232}Th** = 100 % Th and **^{147}Sm** = 0.15 % Sm

II. U-Th-Sm radioactive natural decay

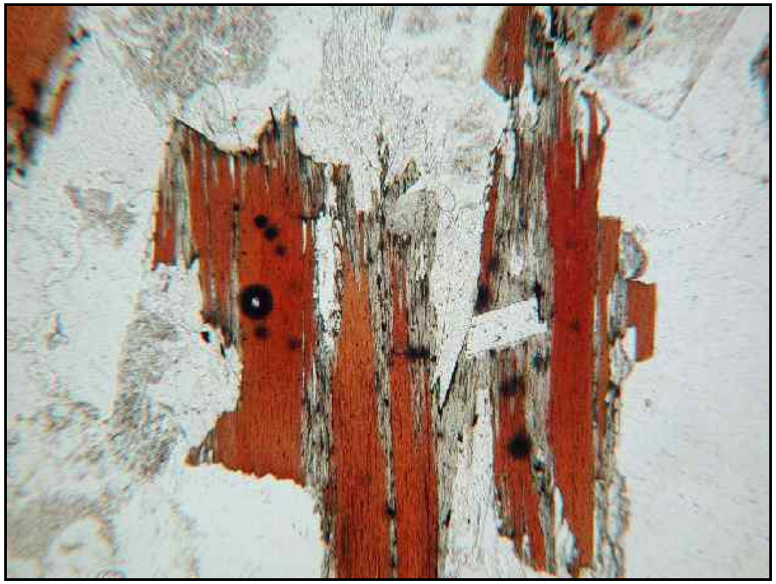


Father		Daughter	Nb. α particles	Half-live (Ga)
^{238}U	->	^{206}Pb	+ 8 α	(4.4683)
^{235}U	->	^{207}Pb	+ 7 α	(0.7038)
^{232}Th	->	^{208}Pb	+ 6 α	(14.05)
^{147}Sm	->	^{143}Nd	+ 1 α	(106)

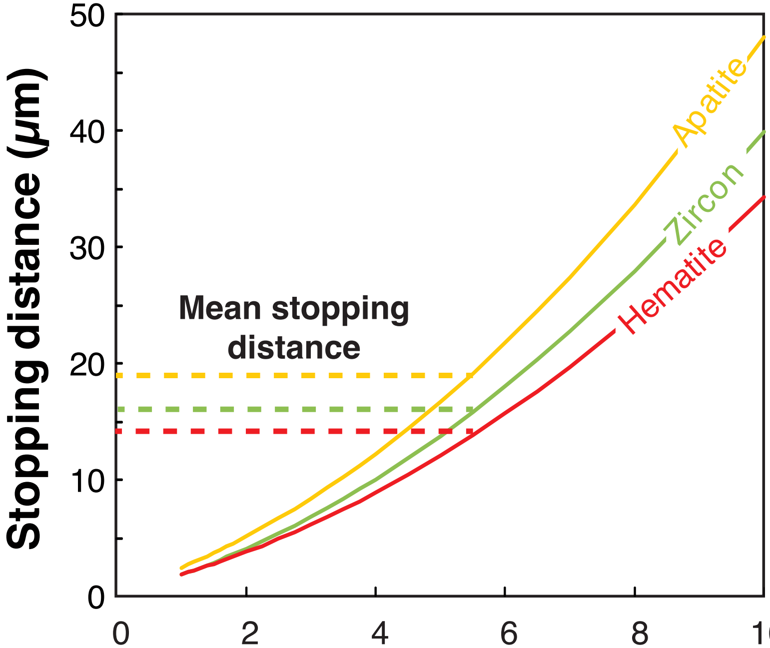
- Alpha particles production during U-Th-Sm alpha decay

II. Alpha particles production => high energies

SRIM; Ziegler (2008); Ketcham et al. (2011)



Alpha halo in biotite



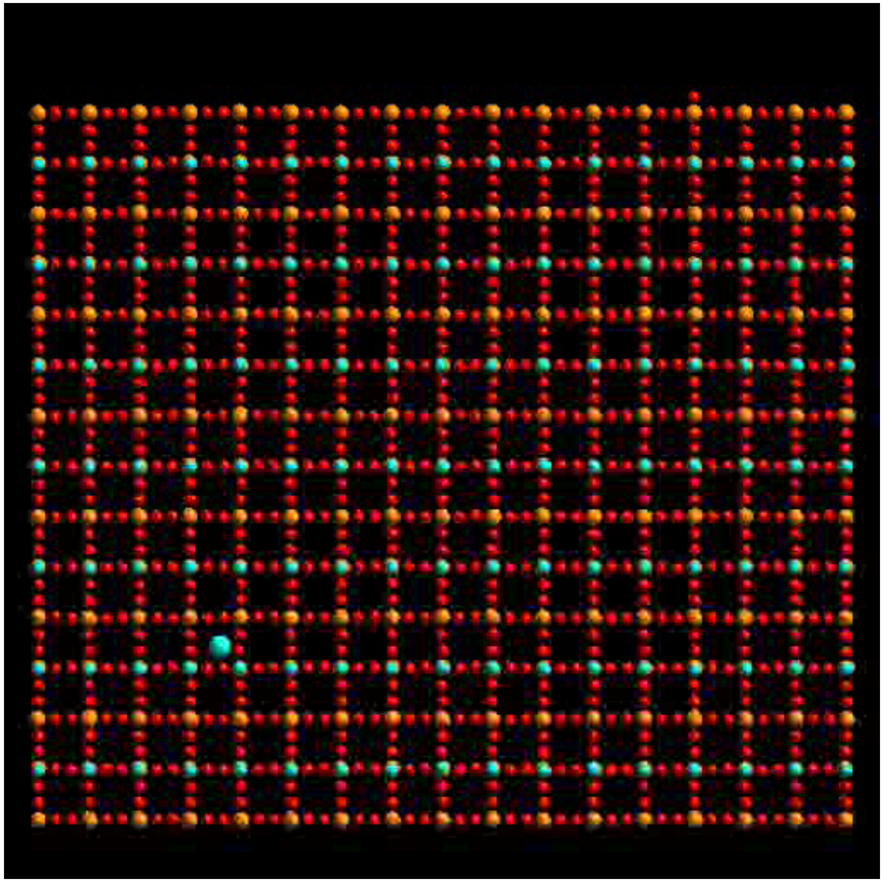
High kinetic energy of α particles,

α ------------> ^{4}He (after taking electrons)

He atoms will stop after some microns depending on initial energy, lattice density, chemistry and Th/U ratio **(See EXERCICE 1).**

II. Alpha particles energies = recoil damage

Trachenko, 2003



Associated to alpha decays, the "father" element will do a recoil.

- **Damage creation at nanometer scale**

II. ^{4}He production

$$[He] =$$

$$\left(8 \times \frac{137.88}{138.88}\left(e^{\lambda_{238}t} - 1\right) + 7 \times \frac{1}{138.88}\left(e^{\lambda_{235}t} - 1\right)\right) \times [U]$$

From ^{238}U and ^{235}U

$$+\left(6 \times \left(e^{\lambda_{232}t} - 1\right)\right) \times [Th]$$

From ^{232}Th

$$+\left(1 \times 0.1499 \times \left(e^{\lambda_{147}t} - 1\right)\right) \times [Sm]$$

From ^{147}Sm

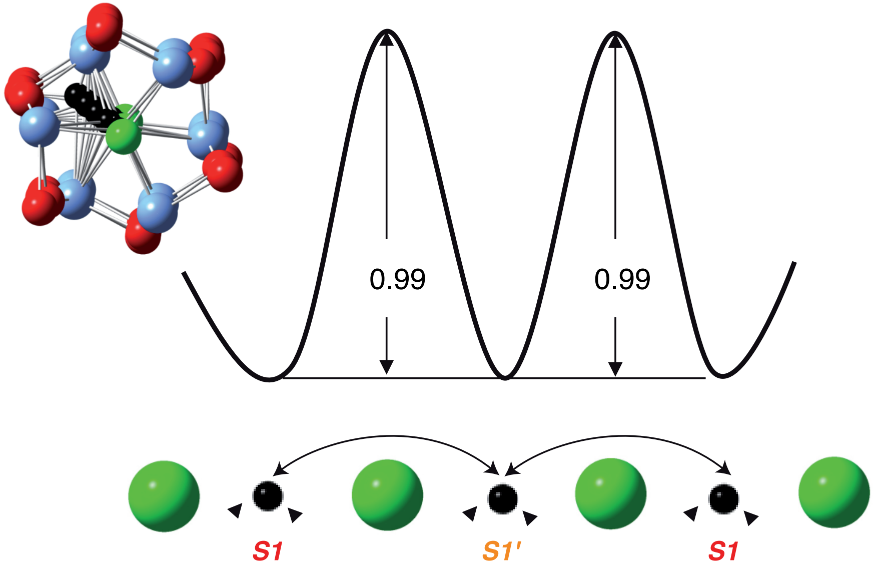
- **eU (effective Uranium) = U + 0.24 Th + 0.0005 Sm**

II. Diffusion in minerals : microscopic or macroscopic point of view

Diffusion is a microscopic (atomic) process that can be seen :

Microscopic level :

1D

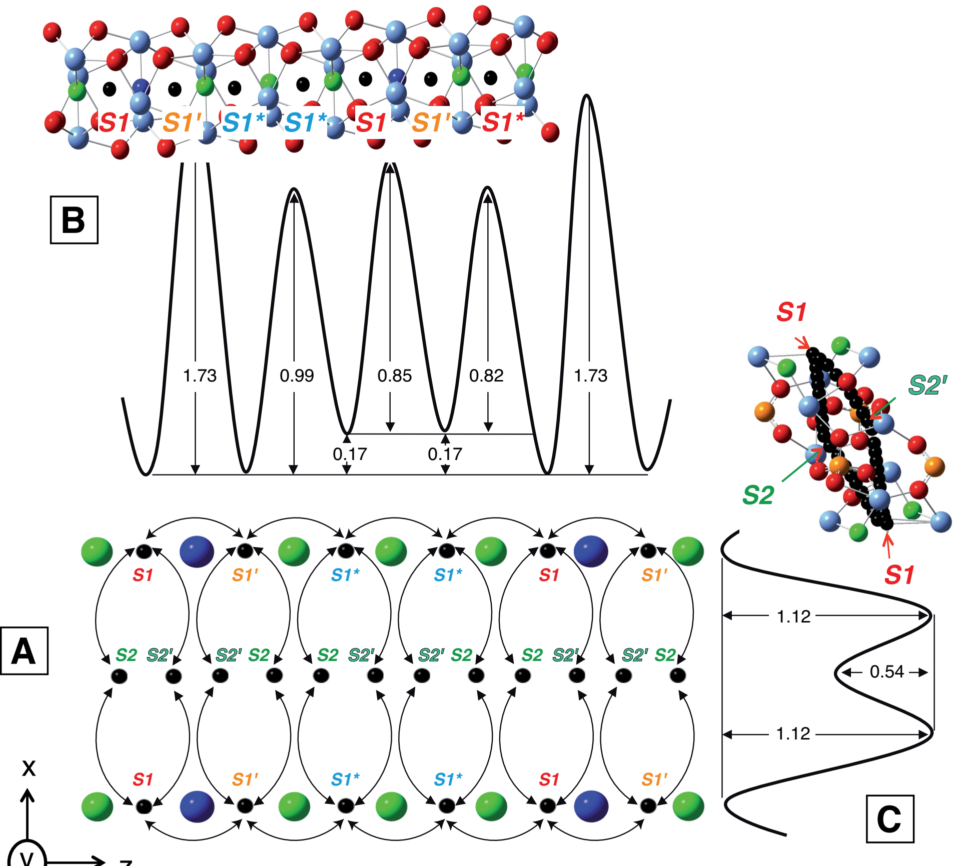


Djimbi et al. (2015)

Diffusion is a microscopic (atomic) process that can be seen :

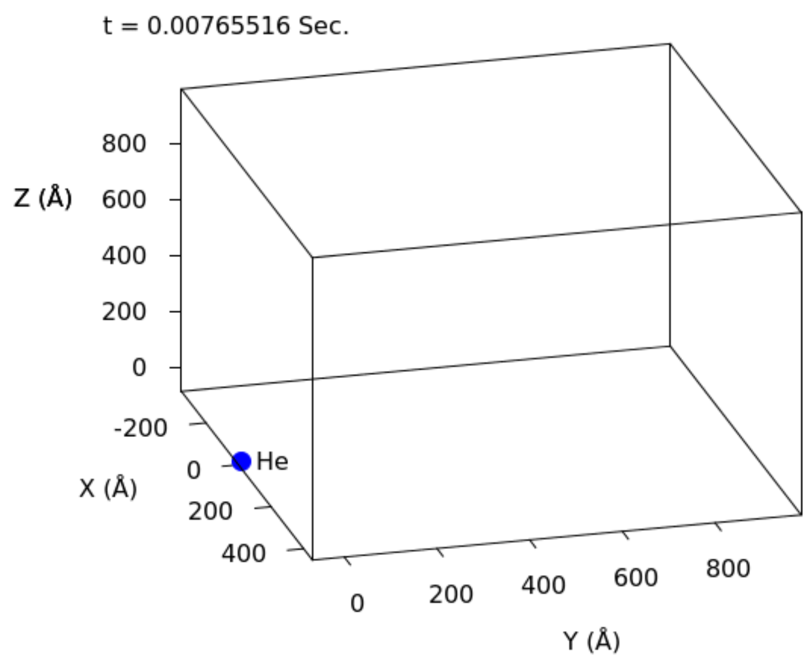
Microscopic level :

2D



Djimbi et al. (2015)

3D



Balout et al. (2017)

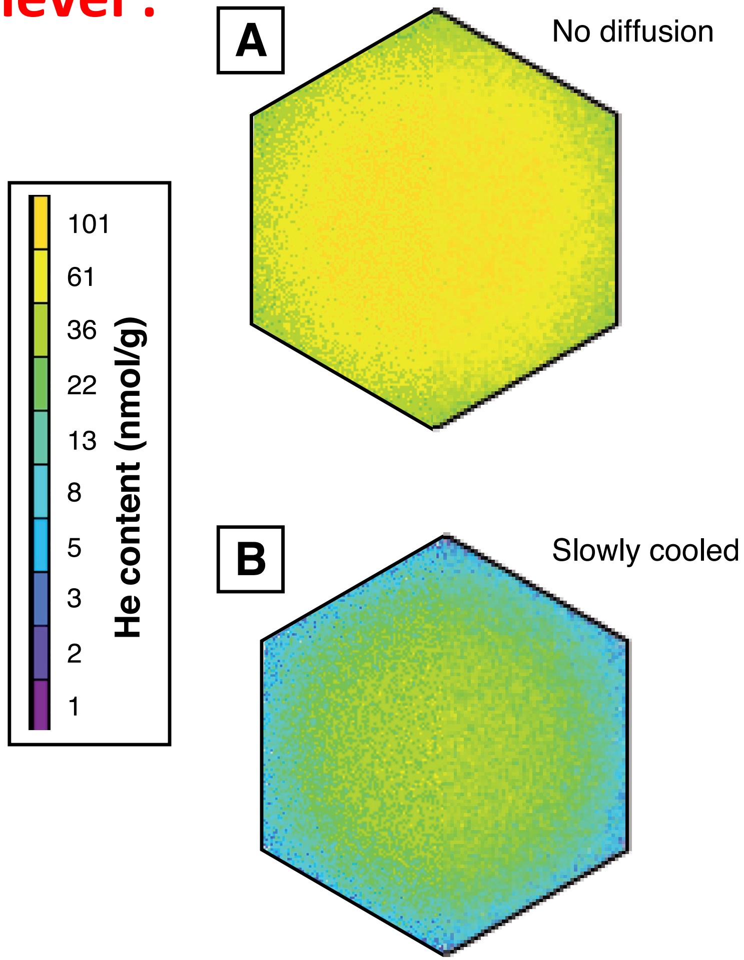
II. Diffusion in minerals : microscopic or macroscopic point of view

Diffusion is a microscopic (atomic) process that can be seen :

Macroscopic level :

✧ Random diffusion can be described at macroscopic level using Fick's law:

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial C^2}{\partial x^2} + \frac{\partial C^2}{\partial y^2} + \frac{\partial C^2}{\partial z^2}\right)$$



Gautheron et al. (2012)

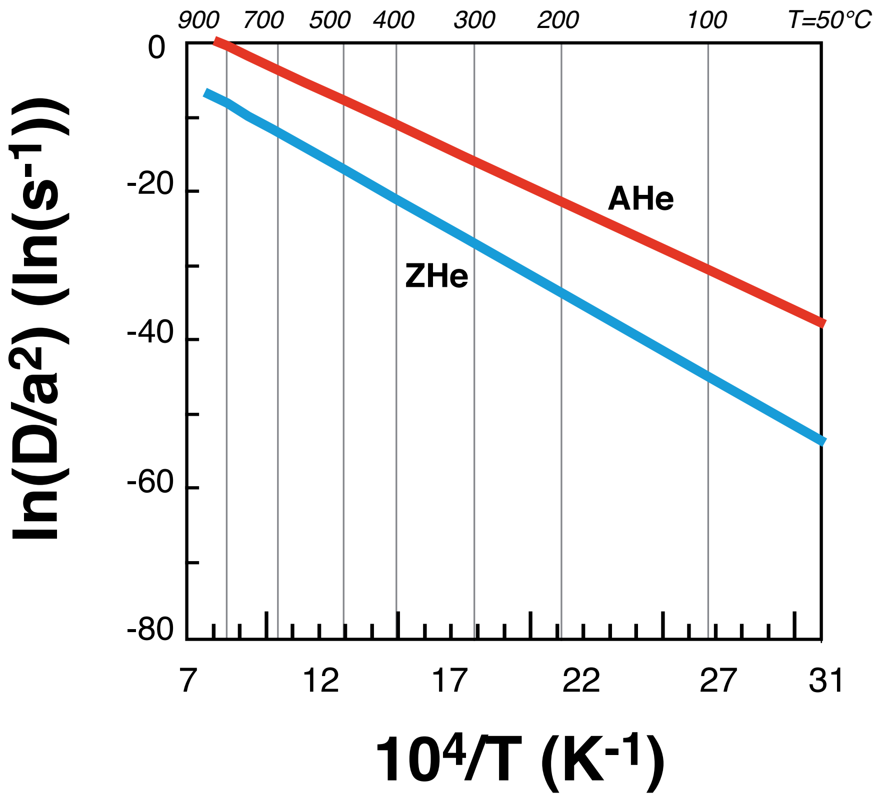
II. Diffusion coefficient in minerals

At first order, diffusion coefficient, D, follows the Arrhenius law:

One unique D_0 and E_a

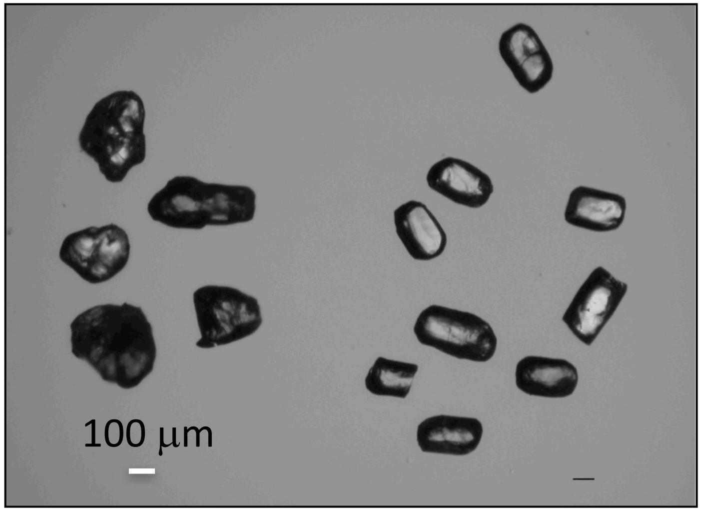
$$\frac{D}{a^2} = \frac{D_0}{a^2} \exp\left(\frac{-E_a}{RT}\right)$$

Different size (a) domains



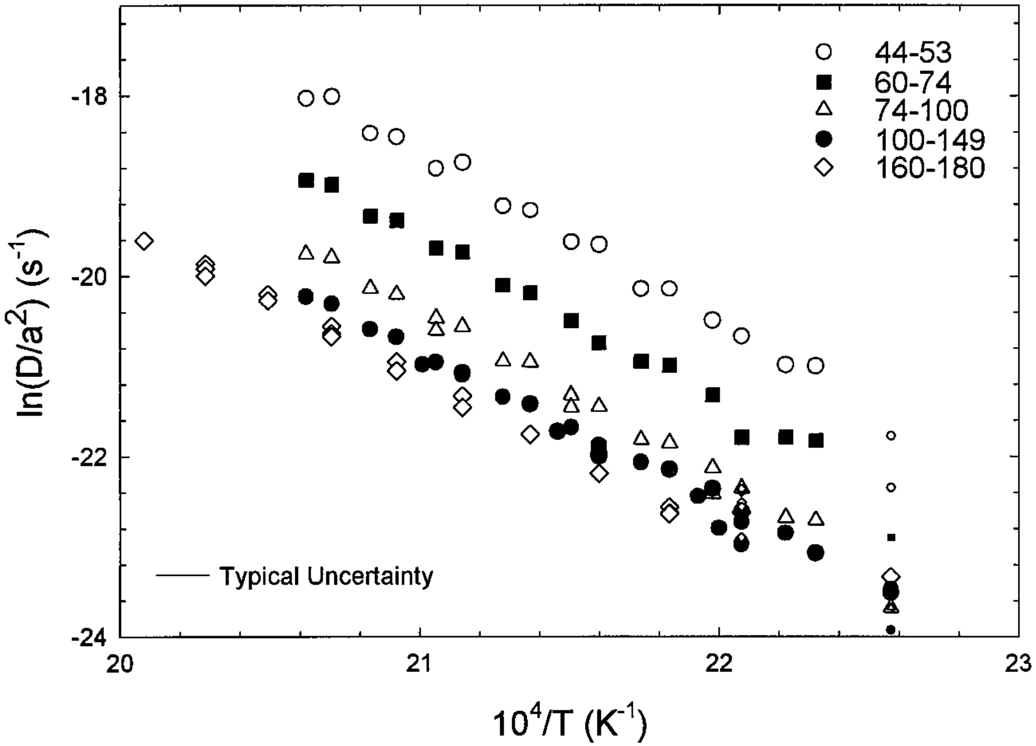
Reiners (2009)

II. Diffusion in a simple system : one crystal



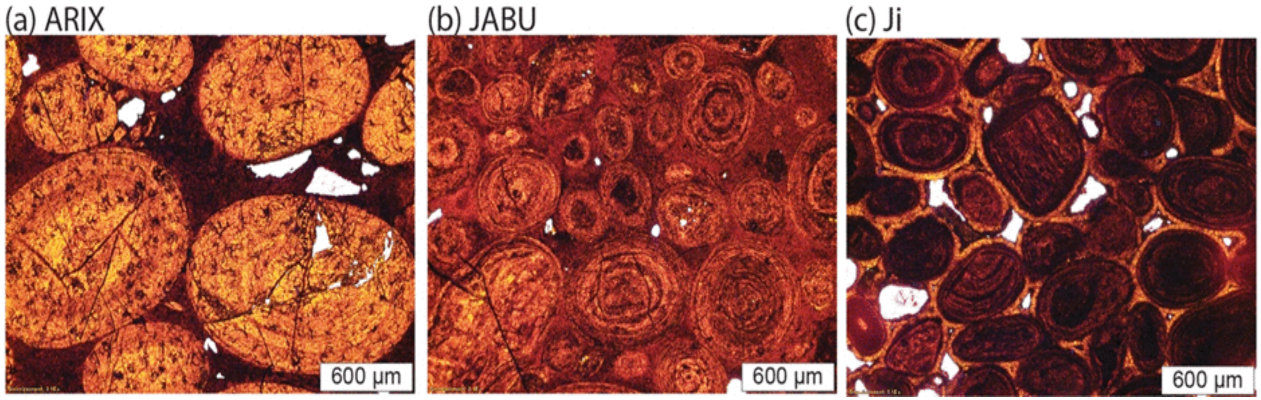
Ehlers and Farley (2003)

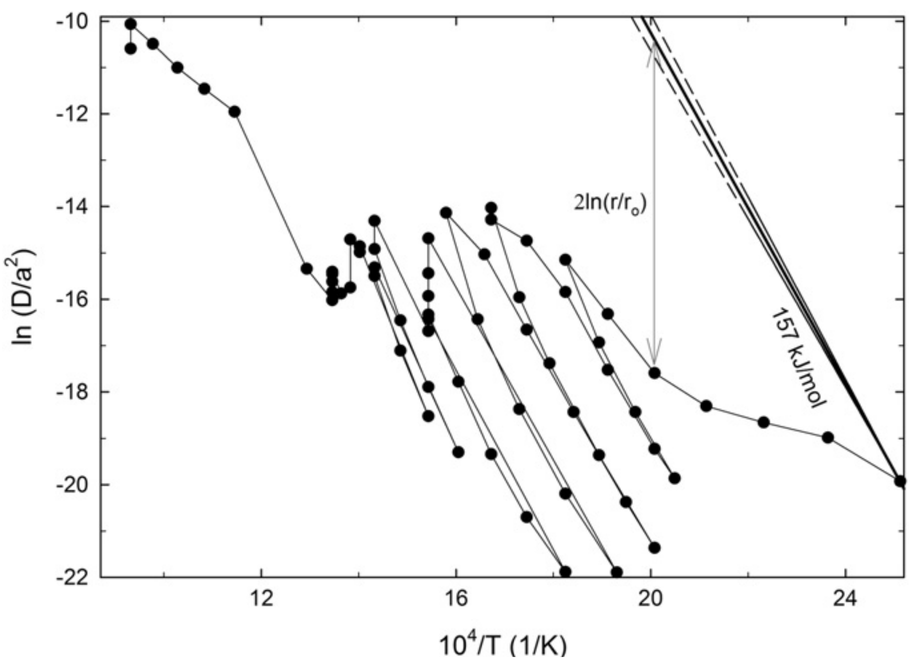
Farley (2000)



- The grain volume is the diffusion domain
- One crystal size (a)
- **Similar D_0 and E_a for all the grain size**

II. Diffusion in a complex system : polycrystalline structure

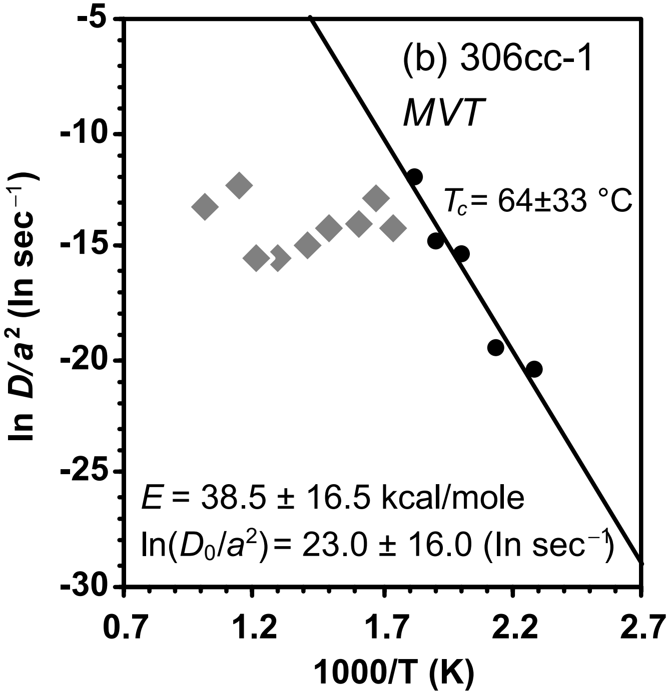


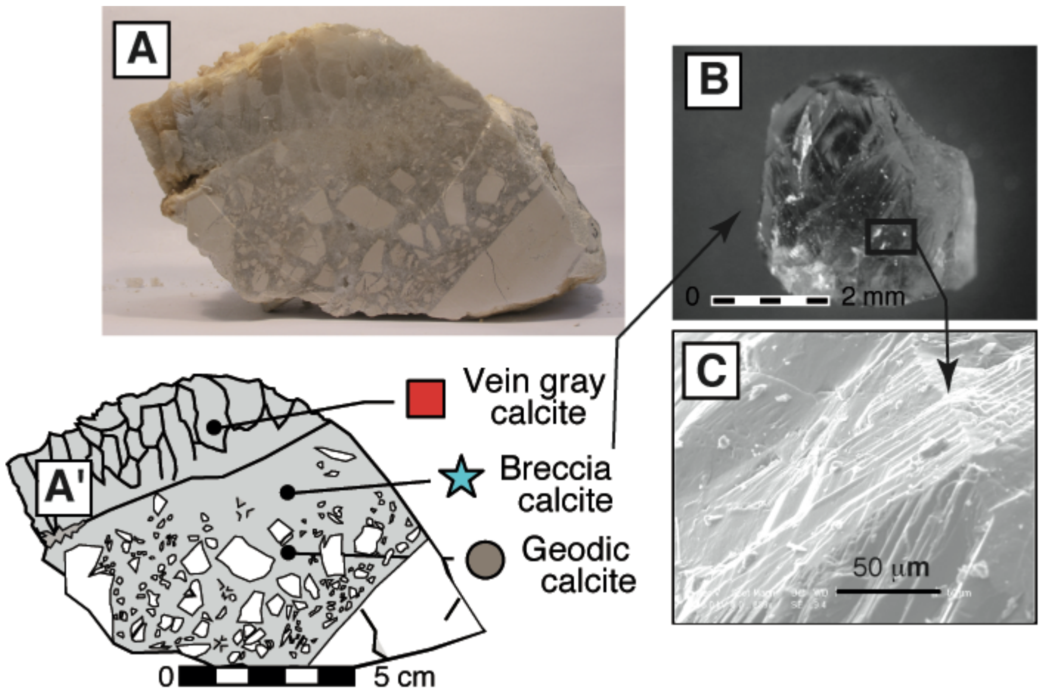


- Polycrystalline structure in iron oxide crystals (hematite and goethite)
- Different crystal sizes (a)
- **Difficulty to determine D_0 and E_a**

Farley and Flowers (2012)
Allard et al. (Submitted)

II. Diffusion in a complex system : fast paths

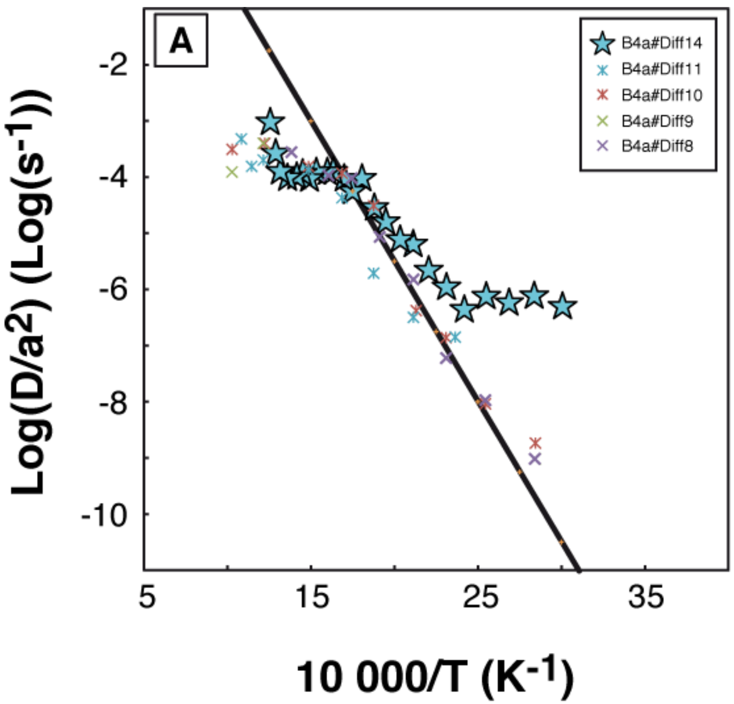


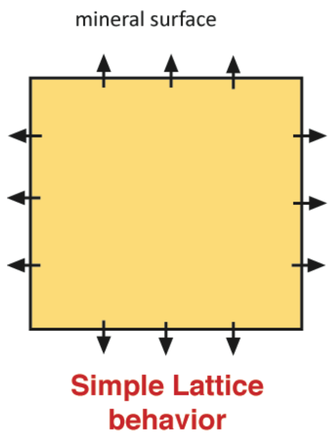


Breccia and fault filling calcite samples from the **Eocene/Oligocene Gondrecourt graben**.

Copeland et al. (2007);
Lovera et al. (1989, 1991); Cros et al. (2014)

II. Diffusion in a complex system : use of a MDD model.

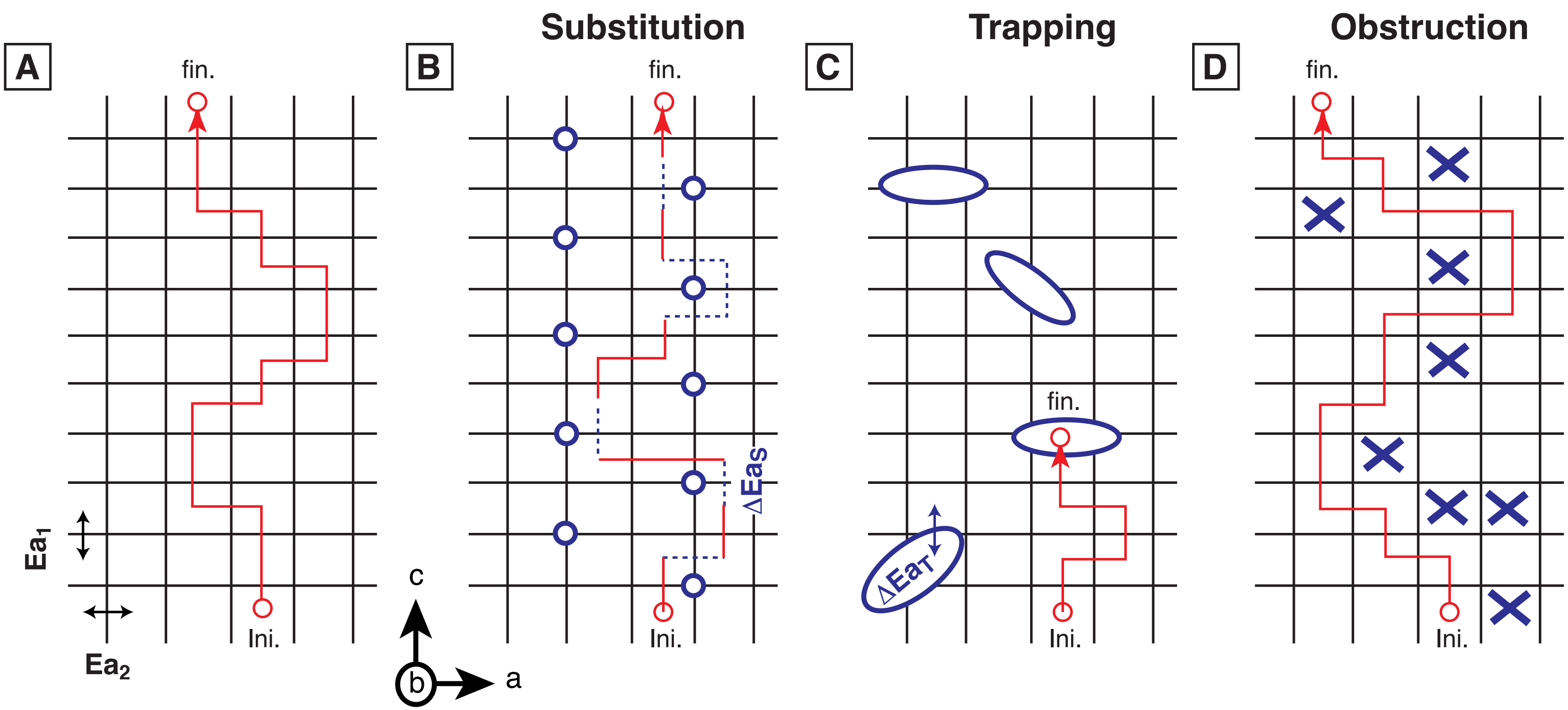




Lovera et al. (1989; 1991); Gautheron and Tassan-Got (2010); Cros et al. (2014)

II. Diffusion in a complex system: some hypotheses

- Different parameters can influence diffusivity in a crystal:



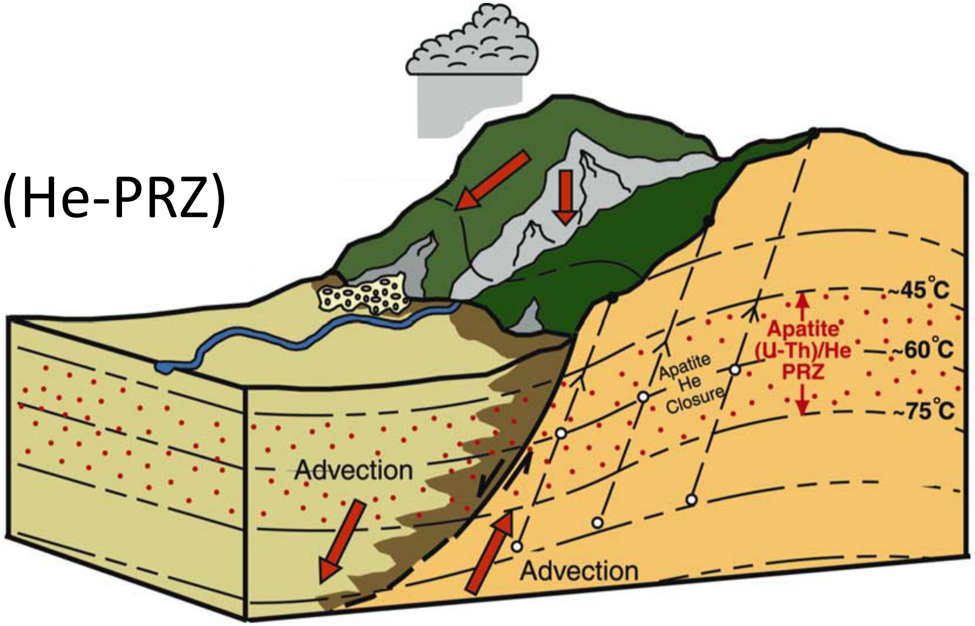
Gautheron et al. (in prep.)

- **He retention in crystal depends on:**

  1. Grain size (a)
  2. Diffusion coefficient (D_0, E_a)
  3. Thermal history (T-t)

- **Need to get useable values such as of:**

  1. Closure temperature (Tc)
  2. He Partial Retention Zone (He-PRZ)



Ehlers and Farley (2003)

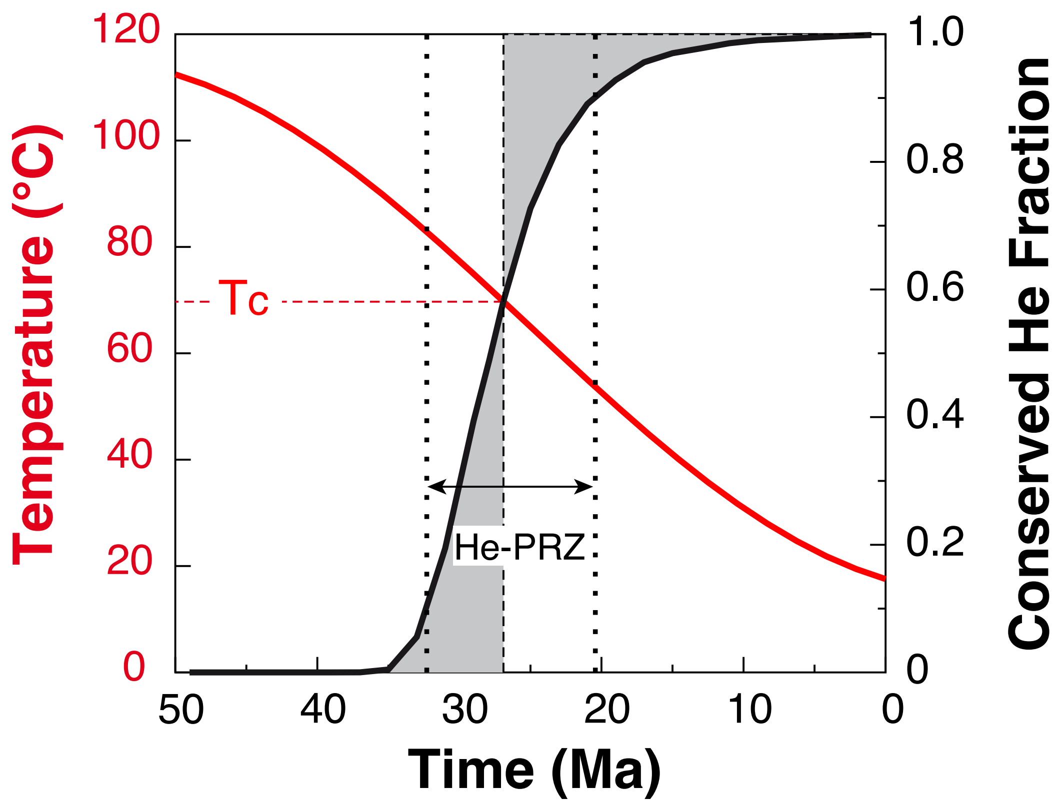
II. Closure temperature and He-PRZ

- **Tc:** when 50% of produced He atoms is retained in the crystal
- **He-PRZ:** between 10 to 90% of the retained He

$$T_c = \frac{E_a}{R\ln\left(A\tau\frac{D_0}{a^2}\right)}$$

$$\tau = \frac{RT_c^2}{E_aT}$$

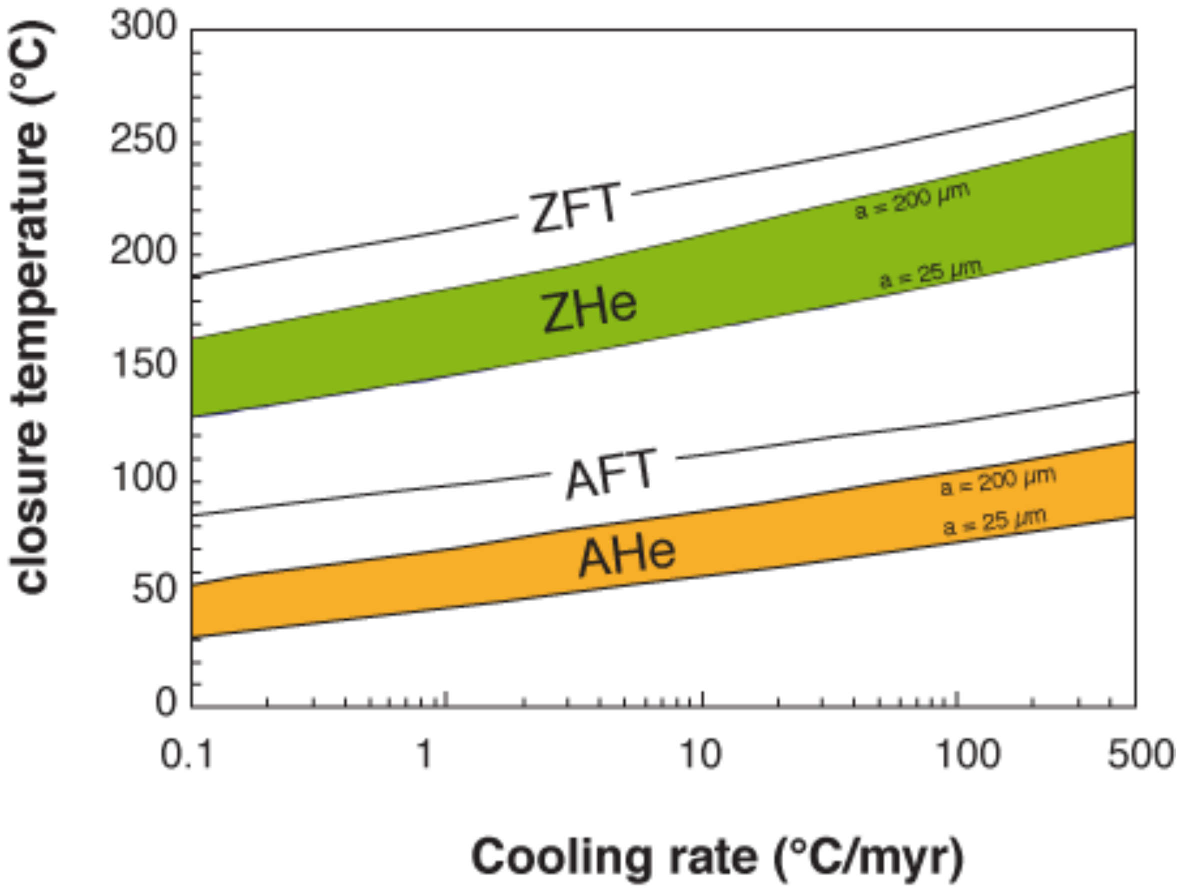
Dodson (1973)



- **See EXERCICE 1**

Using Gautheron and Tassan-Got (2010) code

II. Closure temperature example



Modified from Reiners (2005)

- **Tc = f(D_0, E_a, cooling rate, grain size)**

TAKE HOME MESSAGE:

- (U-Th-Sm)/He age is **not the time** when rock crosses the closure temperature (Tc) or very rarely
- **Diffusion domain** and diffusion **coefficient** strongly influence thermochronometric age

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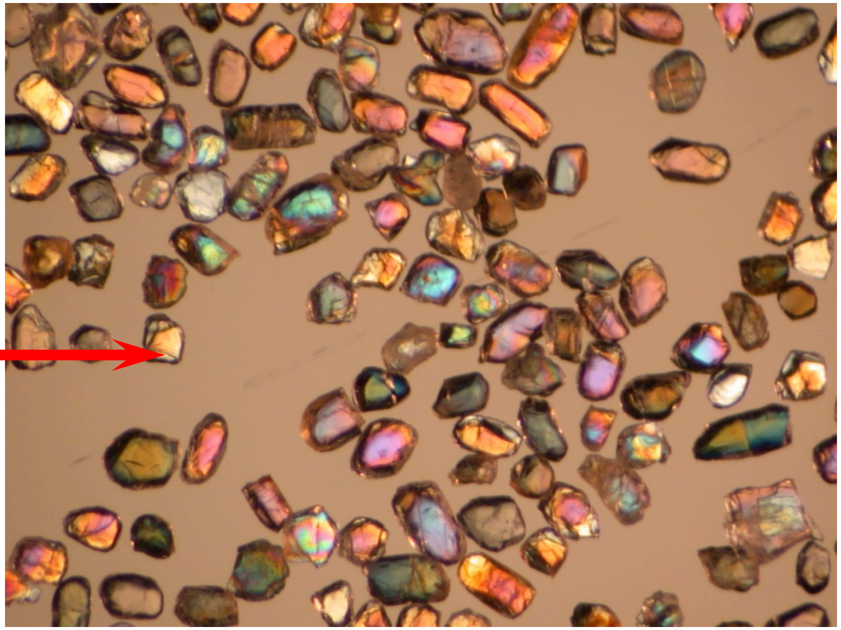
IV. Other applications (zircon, iron oxides,…)

(4) Exercises (Tc, ejection, weight, Rs), thermal modeling

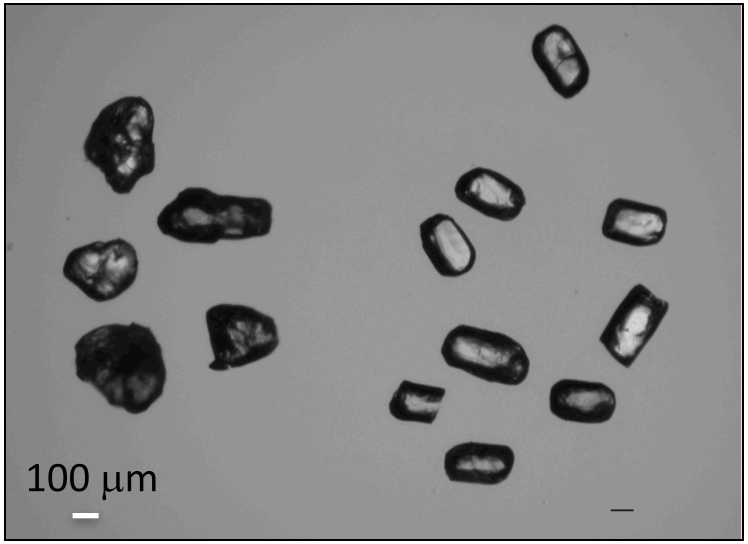
(2) From sample to grain separation



Crushing, sieving, cleaning...

Need of 1 to 10 kg of rock to obtain enough “datable” apatite grains

(2) Grain selection



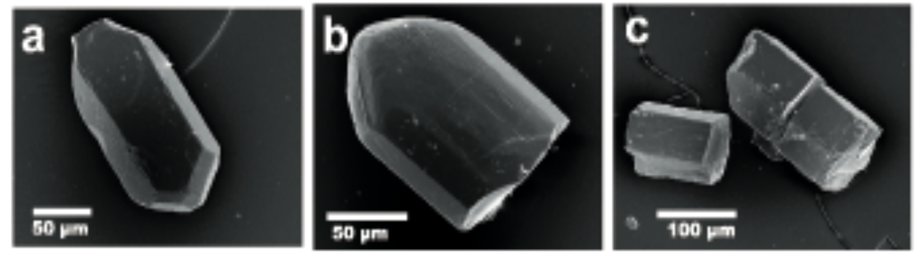
Ehlers and Farley (2003)

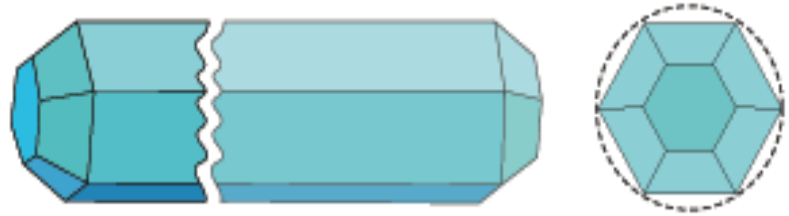
Drastic apatite selection criterion, grain size measurement + geometries (pyramids, broken faces)

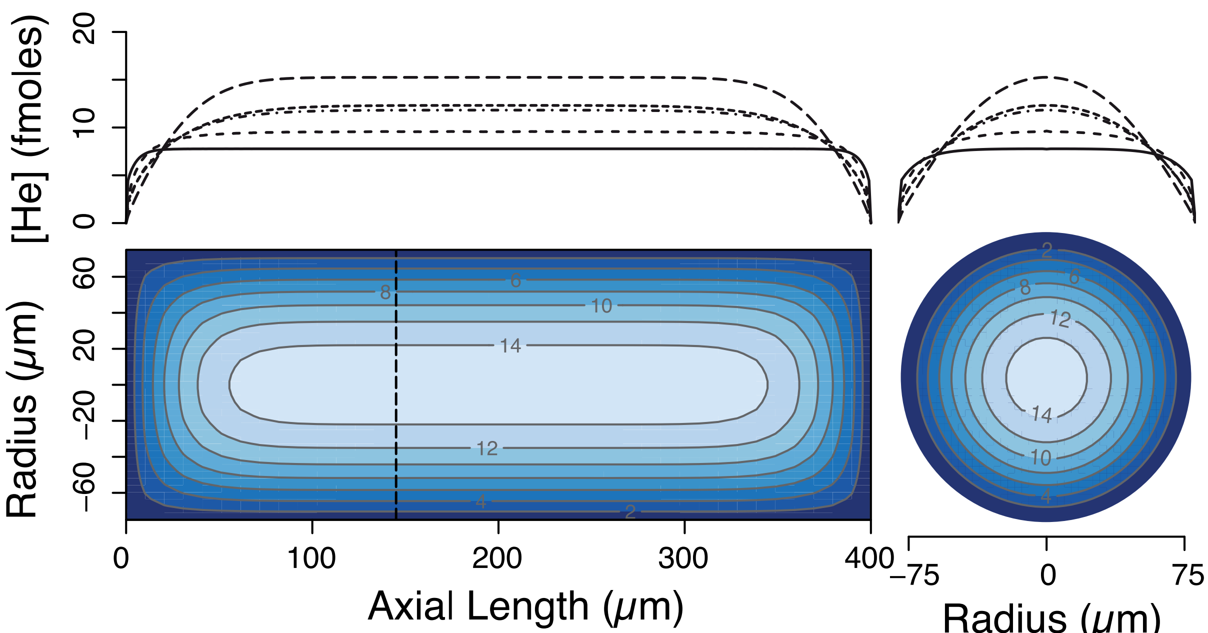
(2) Grain morphology impact on AHe age interpretation

AHe age will be impacted by:

1. Crystal size (L, H, W),
2. Grain morphology,
3. Broken faces

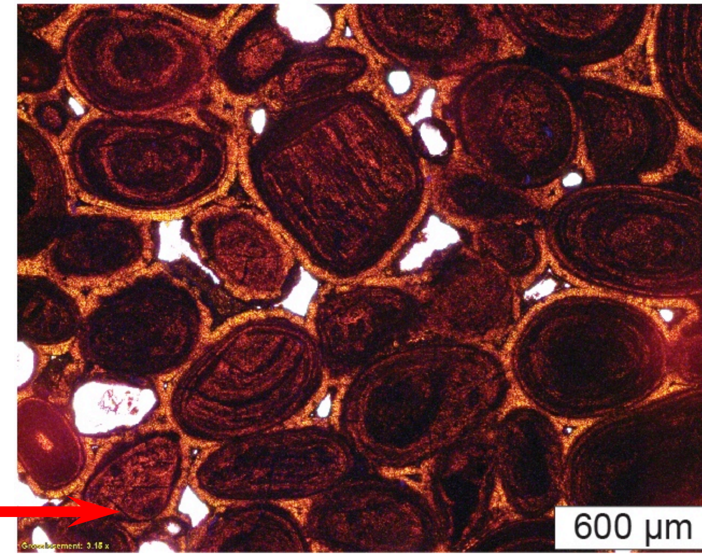


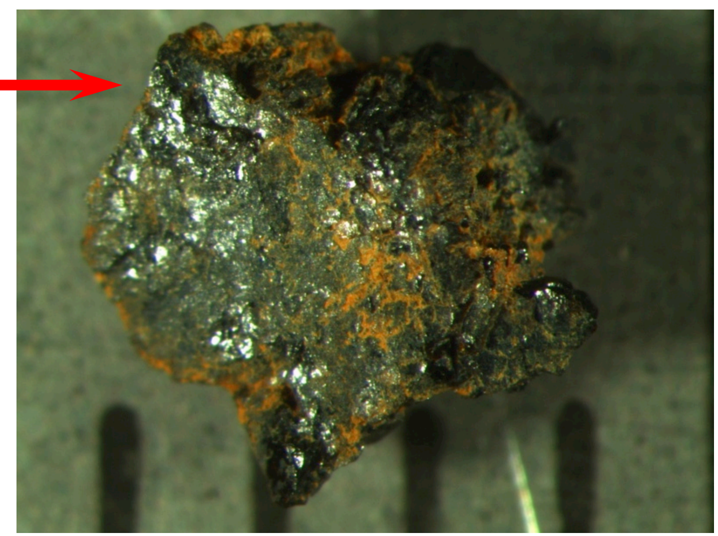




Beucher et al. (2013); Brown et al. (2013)

(2) From sample to grain separation



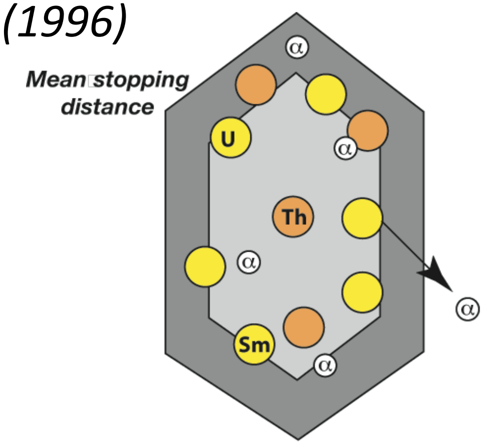


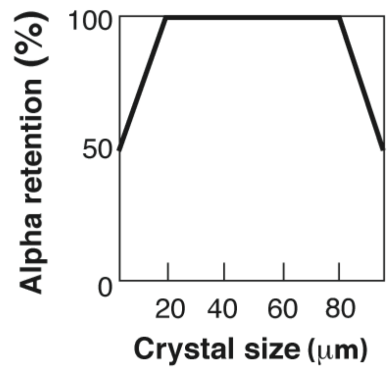
Iron oxide duricrusts or pisoliths

(crystallographic characterization)

(2) Alpha ejection correction factor (F_T)

Farley et al. (1996)





Alpha ejection correction factor F_T:

- *sphere with homogeneous U-Th-Sm repartition*

$$F_T = 1 - \frac{1}{4}\frac{SR}{V} = 1 - \frac{3}{4}\frac{R}{R_s}$$

For realistic geometries (2 approaches):

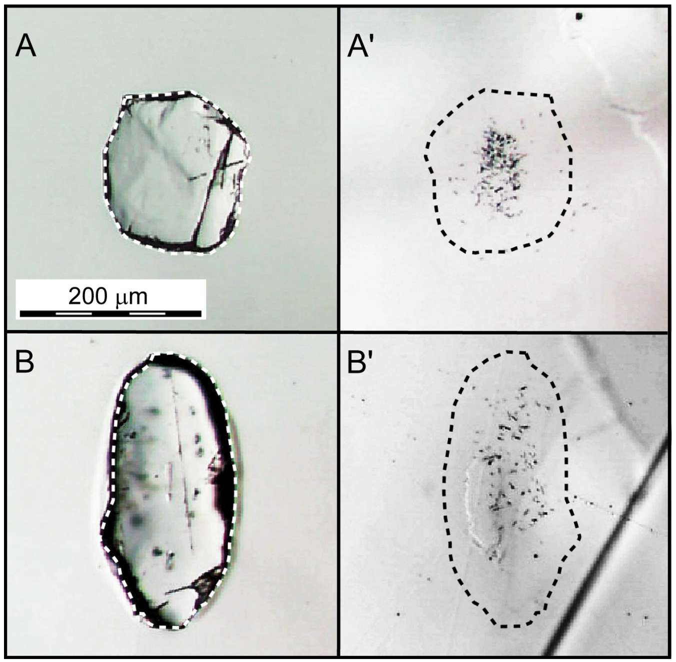
- *Hexagonal ± pyramids, for homogeneous U-Th-Sm*

$$F_T = 1 - \frac{3}{4}\frac{R}{R_s}\left[\left(0.2093 - 0.0465 N_p\right)\left(W + \frac{L}{\sqrt{3}}\right) + \left(0.1062 + \frac{0.2334 R}{R + 6\left(W\sqrt{3} - L\right)}\right)\left(H - N_p \frac{W\sqrt{3/2} + L}{4}\right)\right]\frac{R^2}{V}$$

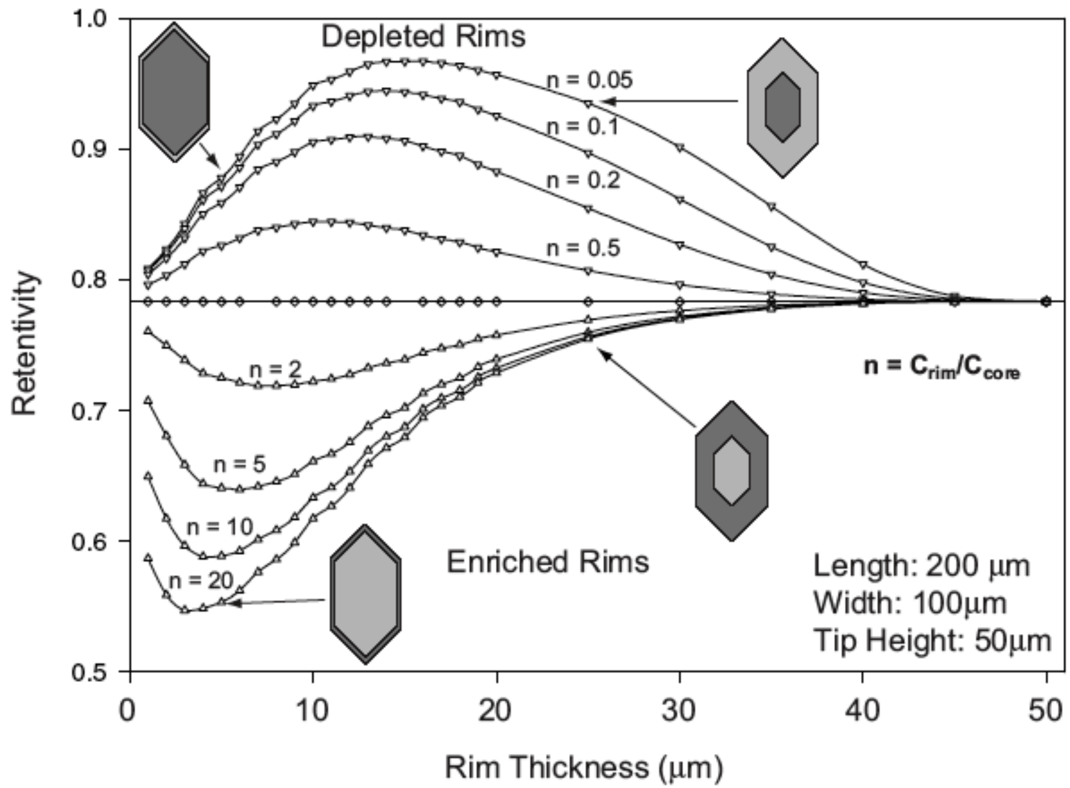
Ketcham et al. (2011)

(2) Alpha ejection correction factor: zoned U-Th-Sm crystals (F_{ZAC})

For crystals zoned in U-Th-Sm, F_{ZAC} factor can be determined analytically or using a Monte Carlo simulation



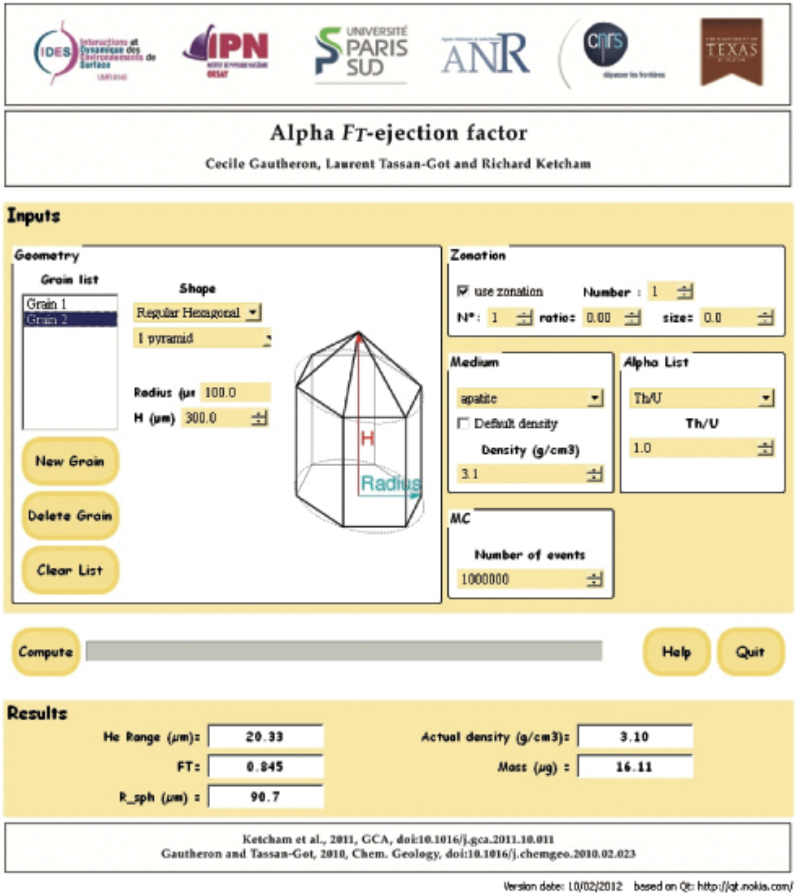
Vernon et al. (2009)



Hourigan et al. (2005)

Calculation using a Monte Carlo model of:

- **Grain weight** (µg)
- **F_T, F_{ZAC}** alpha ejection correction (0 to 1)
- **Rs** sphere equivalent radius (µm) for isotropic or anisotropic diffusion domain
  - Hexagonal (apatite)
  - Tetragonal (zircon)
  - ± pyramids, broken faces
  - …



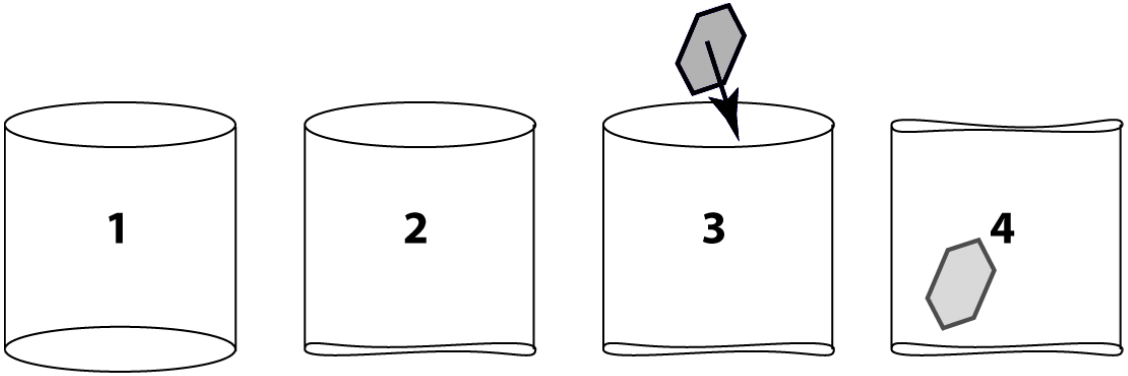
Need of a F_T > 0.65 and Rs > 40 µm…

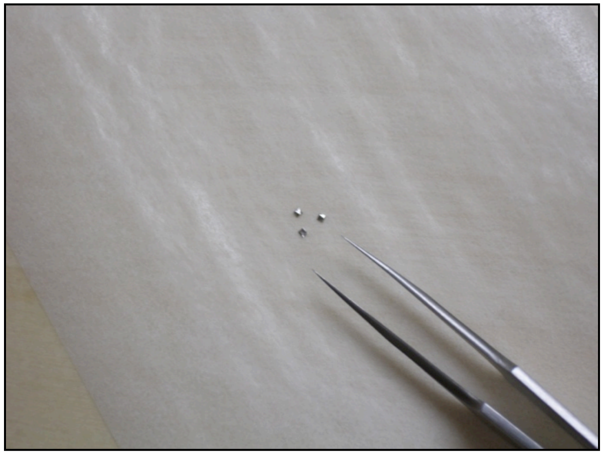
Ketcham et al. (2011); Gautheron et al. (2012)

http://hebergement.u-psud.fr/flojt/

(2) Crystals packing: apatite , zircon, titanite… examples

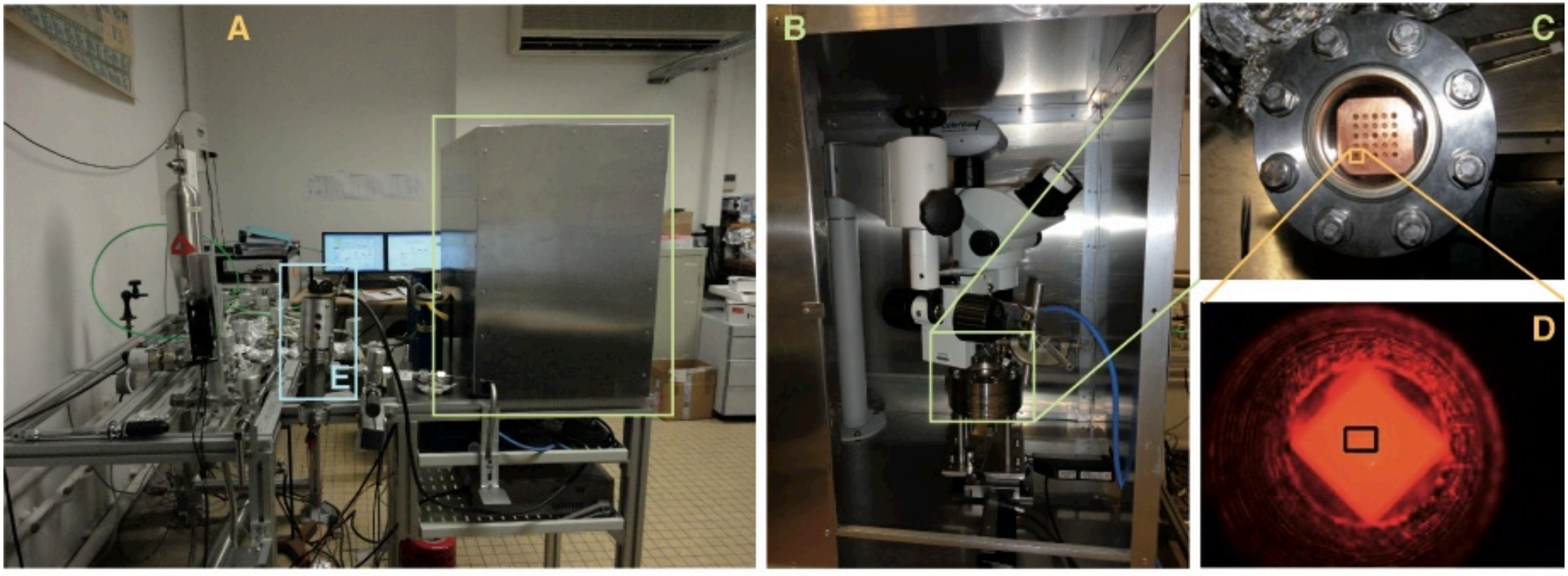
Platinum tube (apatite), **niobium** tube (zircon, titanite) or **niobium** foil (iron oxides, calcite…)





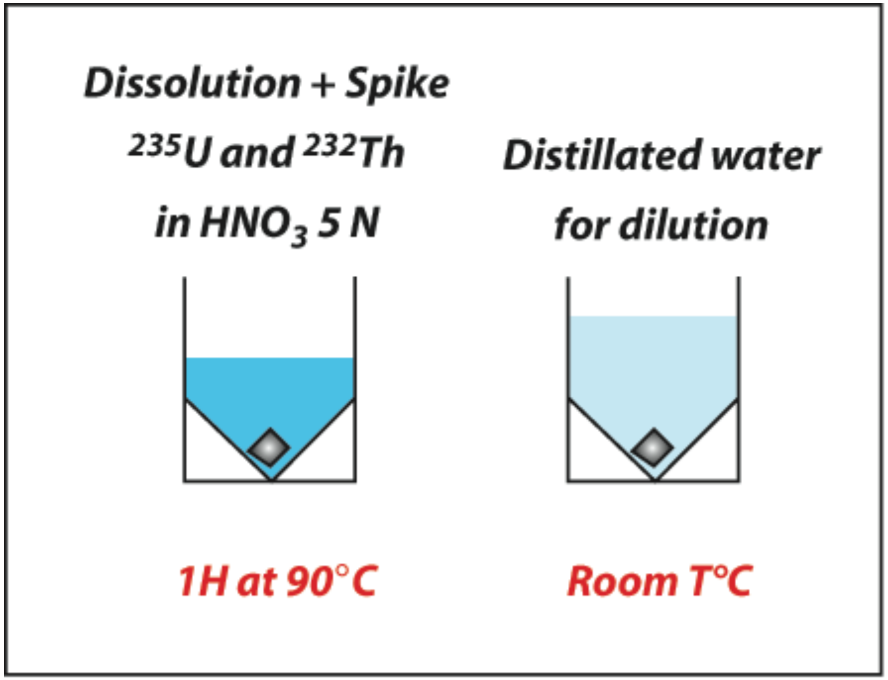
Capsule is used to transport the grain(s) and to ensure He degassing (laser light absorption).

(2) ^{4}He analysis



- Extraction, purification and analysis line for ^{4}He content determination at ~2%
- Special gas purification for iron oxides (i.e. goethite) and calcite because of large H_2O and CO_2 degassing

(2) U-Th-Sm analysis



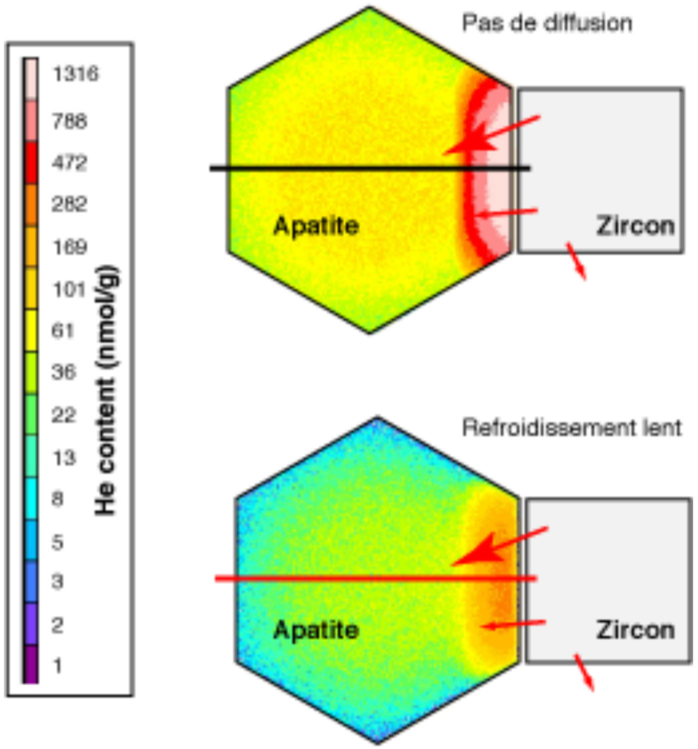
- Addition of pure selected isotopes (example: ^{235}U, ^{230}Th, ^{149}Sm) spikes during dissolution.

(2) U-Th-Sm analyses by ICPMS

- ^{238}U, ^{232}Th and ^{147}Sm determination by isotopic dilution method (see Evans et al., 2005 for details)

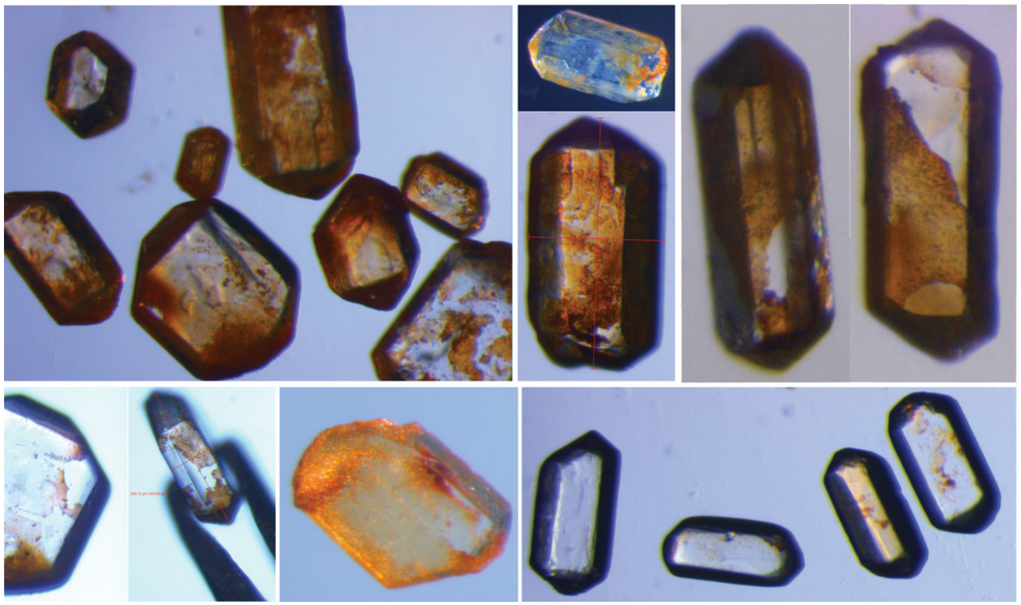
(2) Base hypothesis

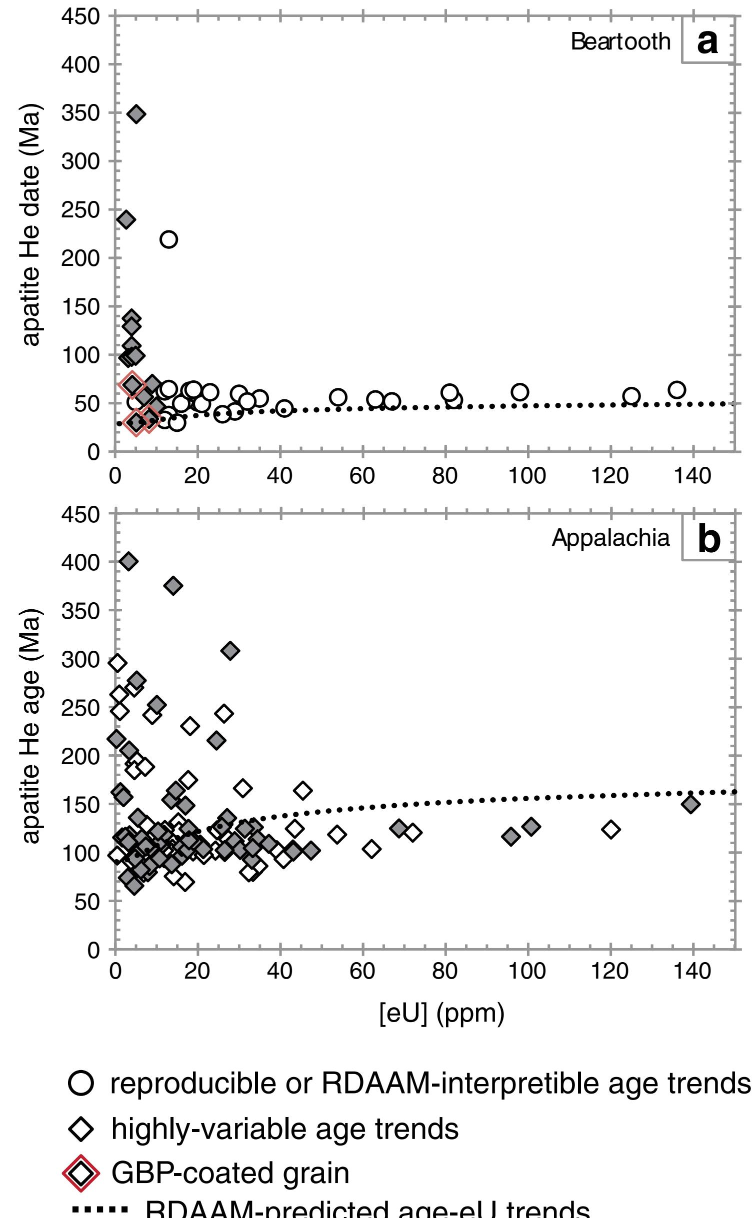
- U-Th decay series are on secular equilibrium (t>1Ma)
- No U-Th-Sm loss
- No common helium,
  or ^{4}He, $^{21}Ne_c$ << ^{4}He* (radiogenic)
- No ^{4}He implantation
  from neighbor minerals



Gautheron et al. (2012)

(2) Impact of He implantation on AHe age





From Murray et al. (2014);

See also Spiegel et al. (2009); Janowski et al. (2017)

(2) (U-Th-Sm)/He age calculation

1. **(U-Th-Sm)/He age:** $$Raw\ age = \frac{\left[{}^{4}He\right]}{P^{*}\left(He\ production\right)}$$

2. **He instantaneous production (P* / per year):**

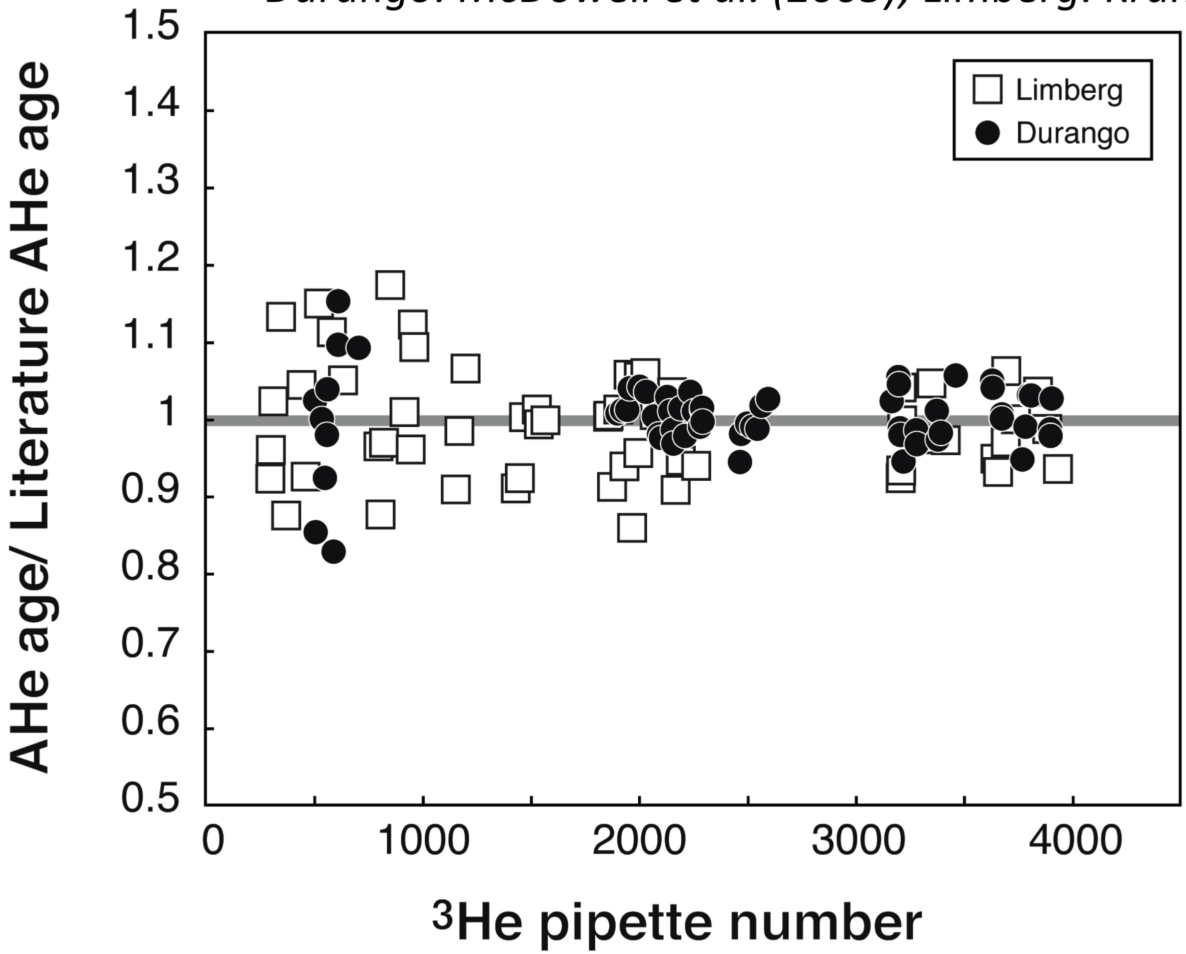
$$P^{*} = \left(8 \times \frac{137.88}{138.88}\left(e^{\lambda_{238}\times 1} - 1\right) + 7 \times \frac{1}{138.88}\left(e^{\lambda_{235}\times 1} - 1\right)\right) \times [U]$$

$$+\left(6 \times \left(e^{\lambda_{232}\times 1} - 1\right)\right) \times [Th] + \left(1 \times 0.1499 \times \left(e^{\lambda_{147}\times 1} - 1\right)\right) \times [Sm]$$

3. **Alpha ejection corrected age:** $$Corrected\ age = \frac{Raw\ age}{F_T}$$

(2) He age reproducibility

Durango: McDowell et al. (2005); Limberg: Kraml et al. (2006)

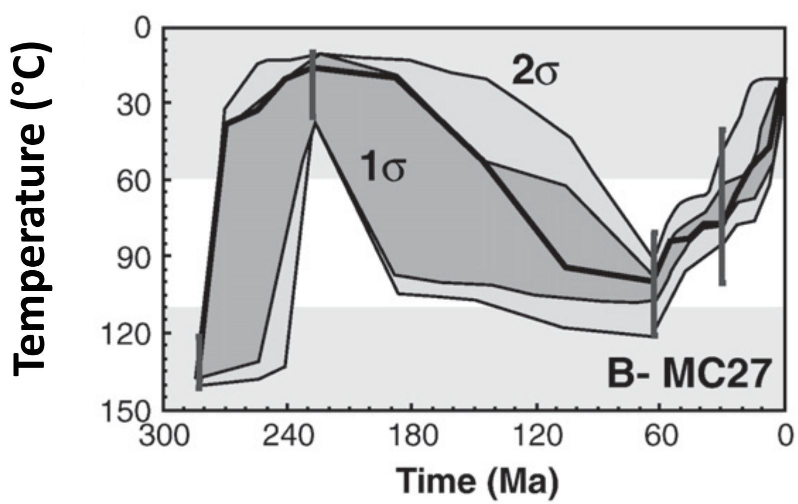


- **Analytical age: <4% =** <2% for He and <2% for U-Th-Sm measurements
- **Error on He age with ejection factor => 8-10%**

(2) Inversion of low temperature thermochronological data

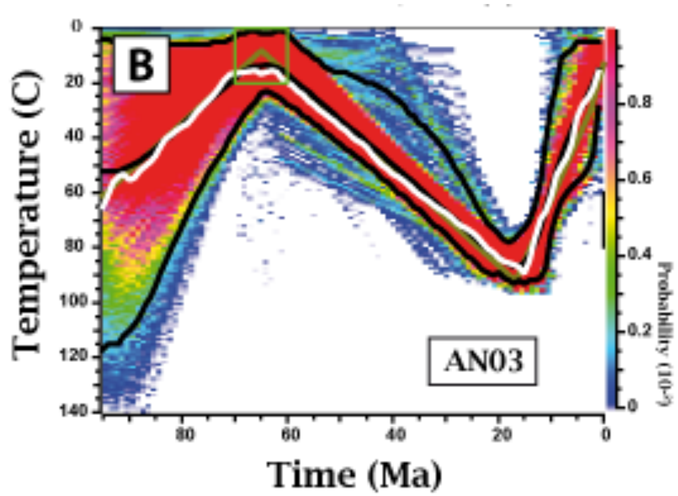
→ ***HeFTy :***

→Tt path modeling



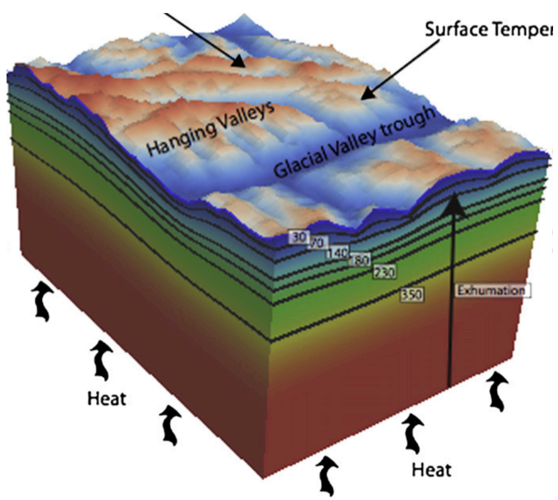
→ ***QTQt :***

- Tt + pluri-samples (vertical profile) modeling



→ ***PECUBE :***

- 3D modeling + vertical profile + faults …



Ketcham (2005); Gallagher (2012): Braun (2003)

TAKE HOME MESSAGE:

- **Do not underestimate** the time to **prepare and** pick your grains (especially for apatite)
- Measure all grains **geometry** and report all data (L, H, W, geometries)
- Error on (U-Th)/He age will be **~10%**

(1) (U-Th)/He dating system

I. **Introduction, generalities**

II. **(U-Th)/He principles (chronometer vs thermochronometer)**

(2) How to get an (U-Th)/He age

(3) Applications

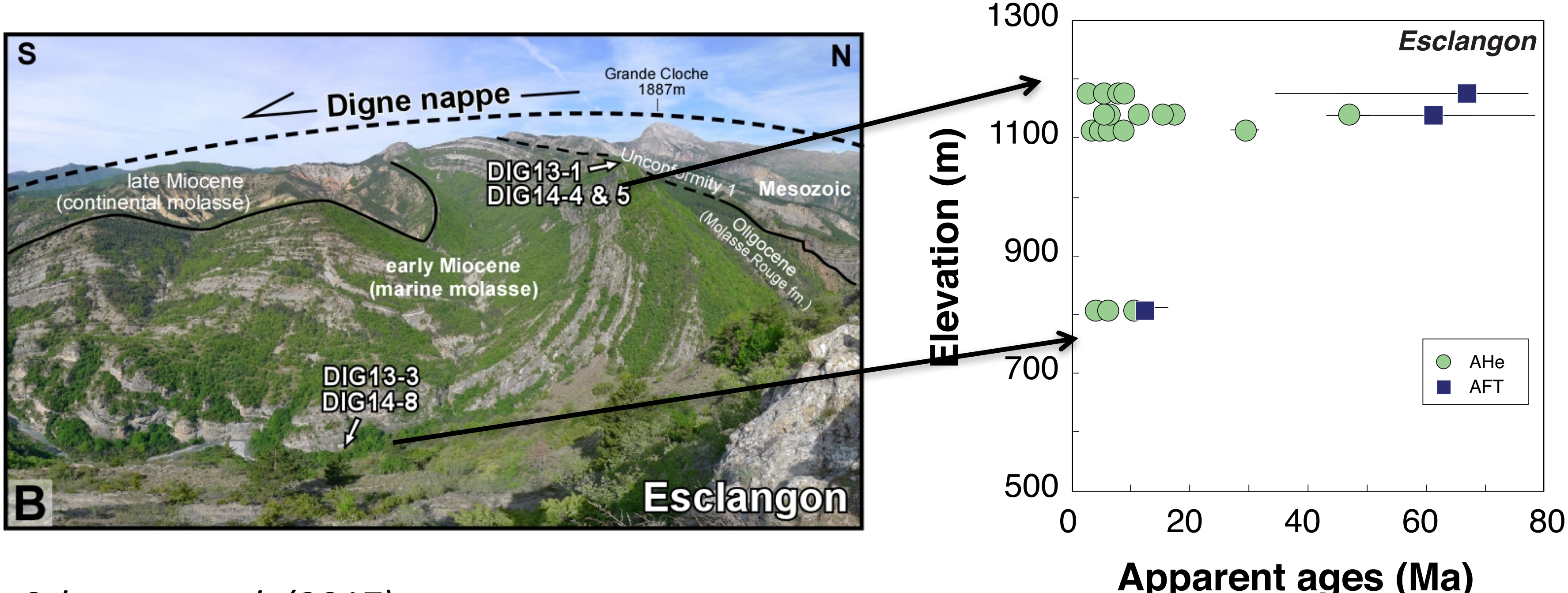
III. **Apatite (U-Th-Sm)/He (AHe) method**

IV. **Other applications (zircon, iron oxides,…)**

(4) Exercises (Tc, ejection, weight, Rs), thermal modeling

- AHe age dispersion is often higher than analytical error (~8%)

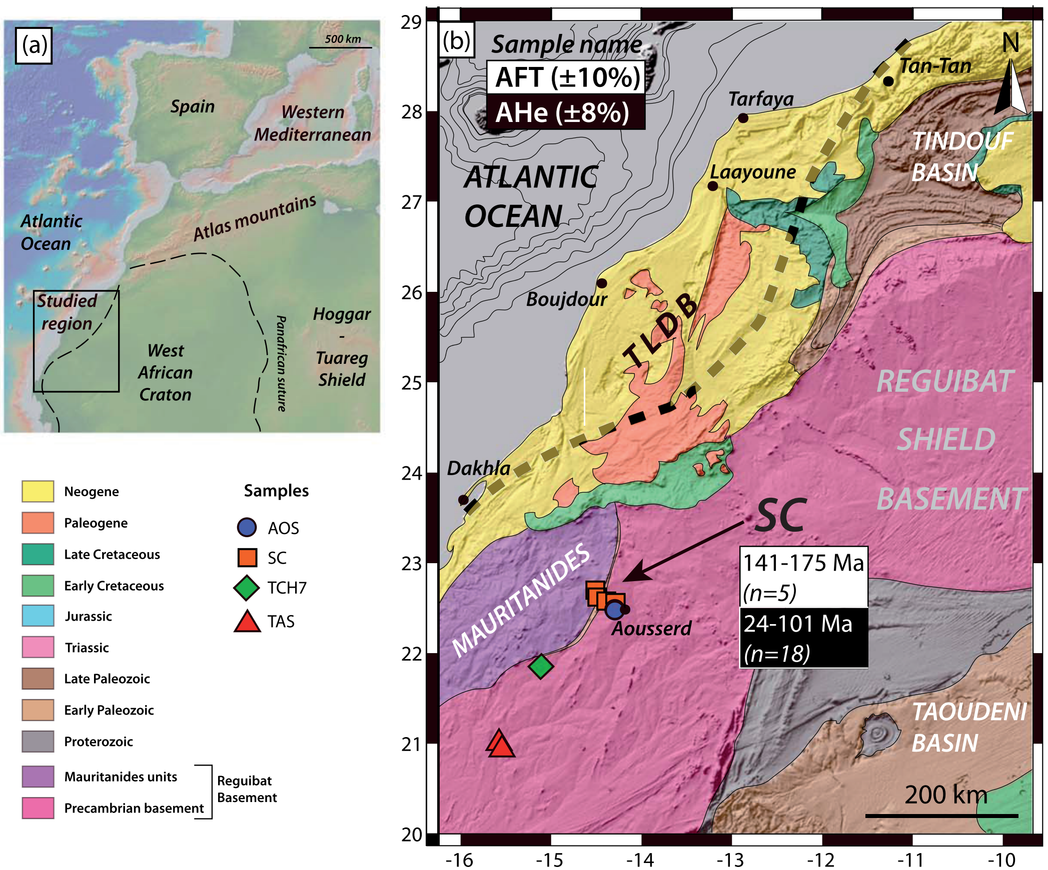
1. French foreland example (buried detrital apatite)

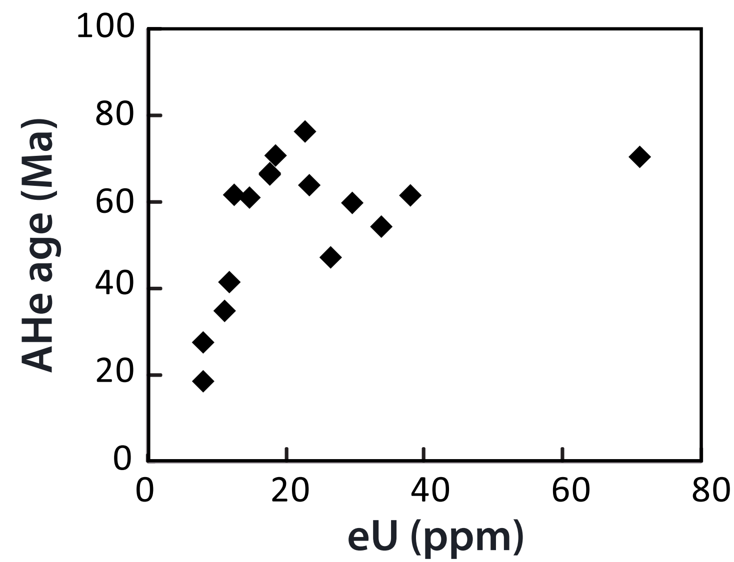


Schwartz et al. (2017)

Important dispersion for higher elevation sample **=> non total diffusion?**

2. Moroccan margin exhumed during Atlantic breakoff





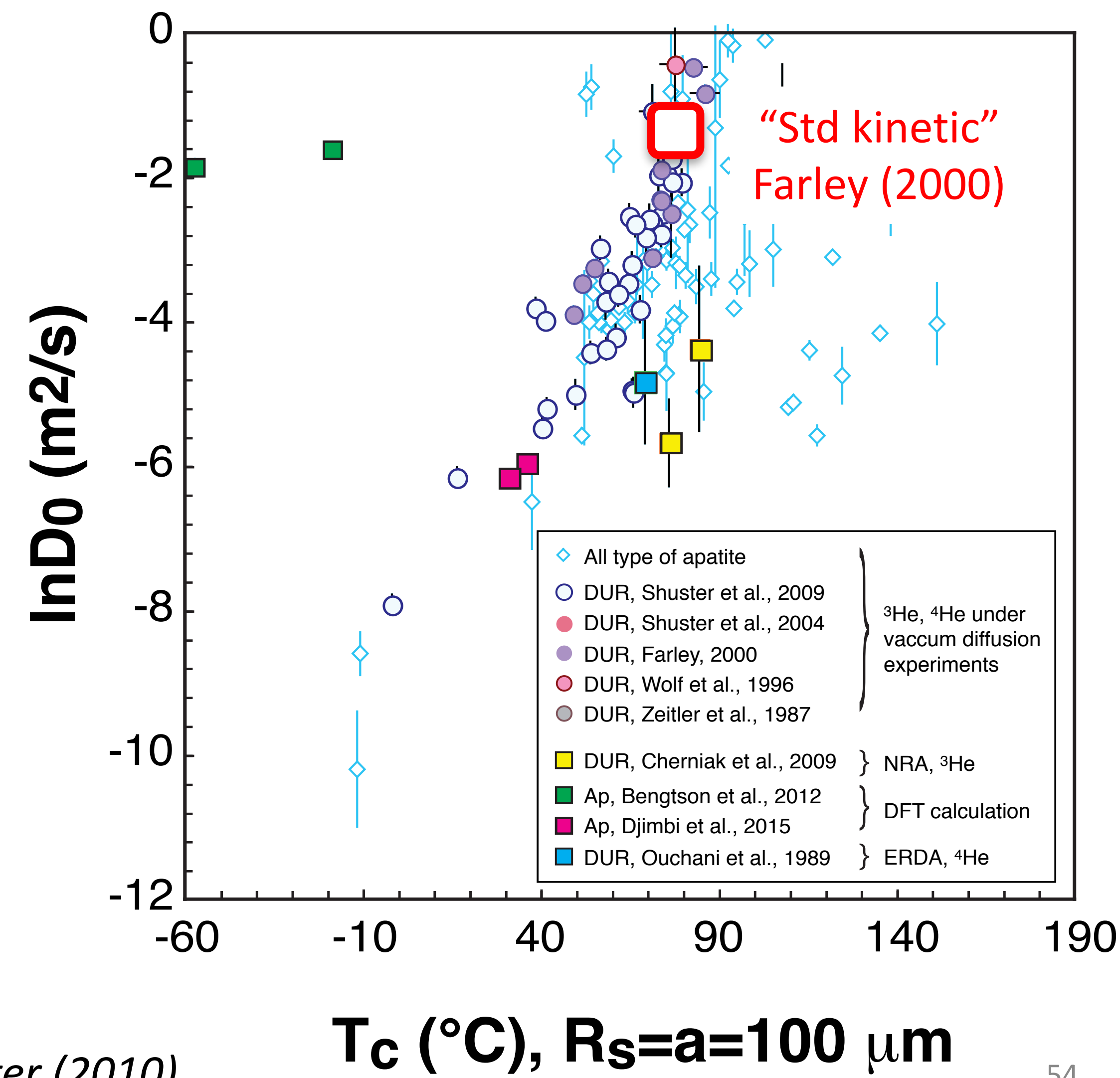
Leprêtre et al. (2015)

Important AHe age dispersion: **relation with eU content?**

III. Apatite He diffusion coefficient

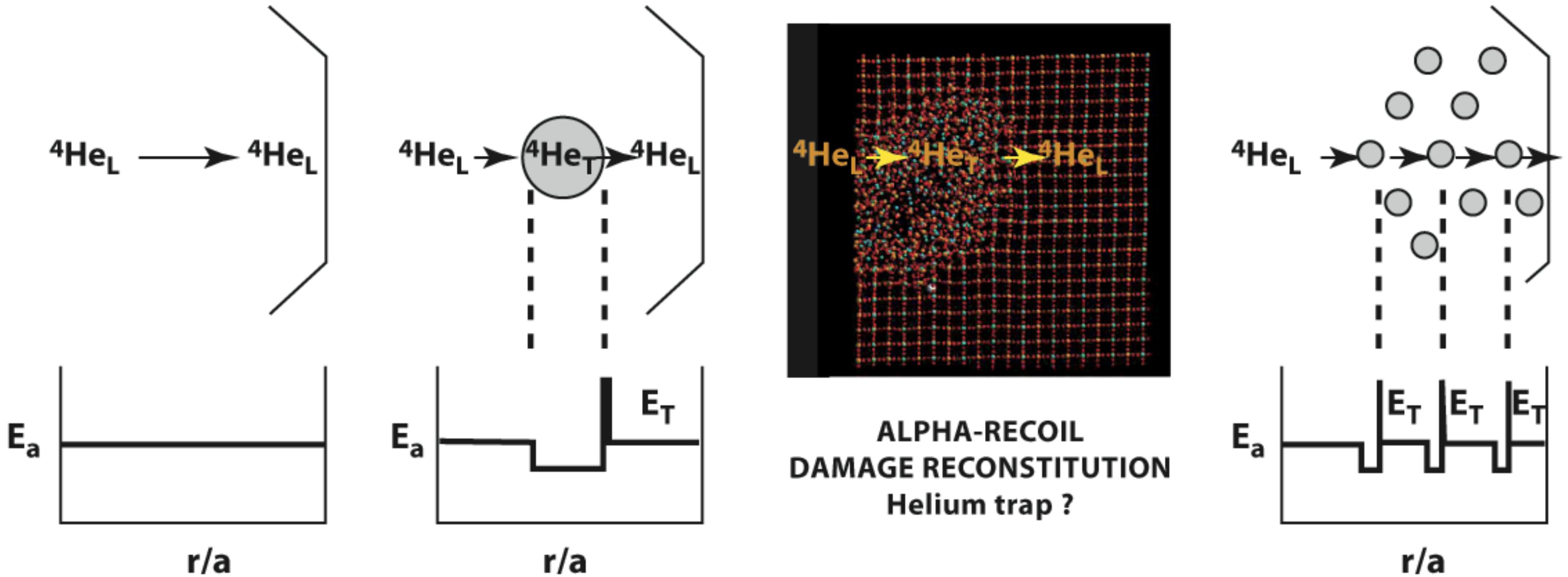
➢ Published He diffusion coefficient using different methods:

1. Under vacuum degassing experiments
2. Ion beam experiments
3. DFT calculation



Complied 1987-2010 data by Baxter (2010)

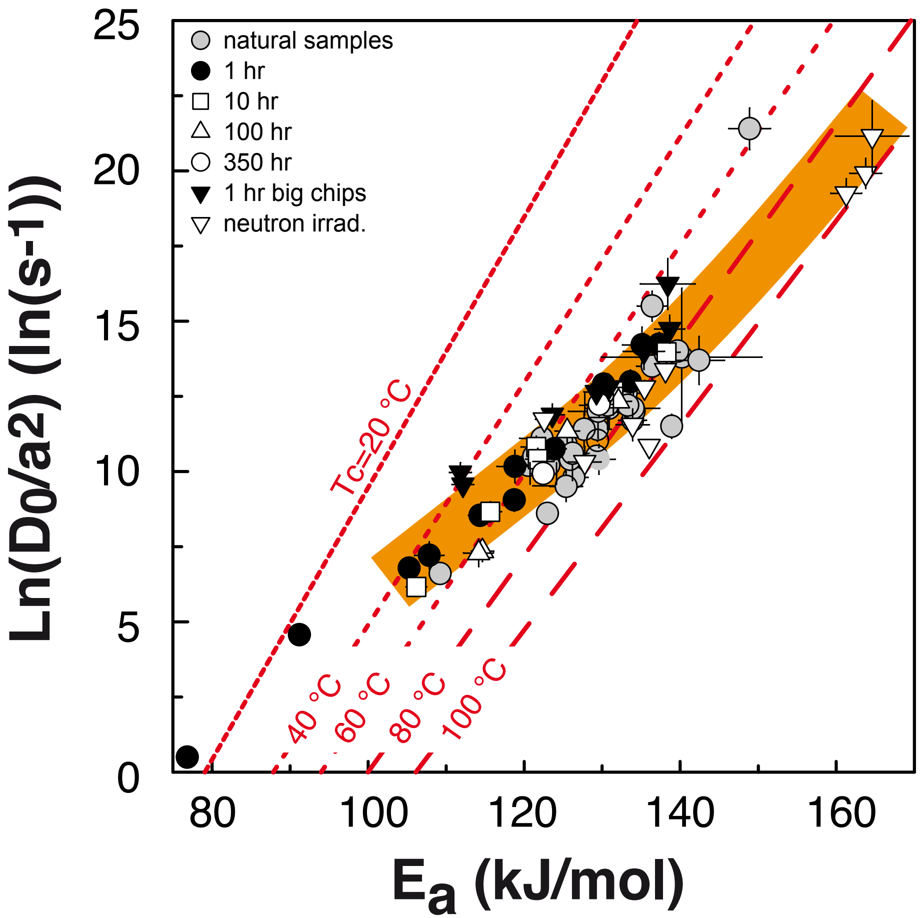
III. Relationship between eU and AHe age



Shuster et al. (2006); Trachenko (2003);
See Green et al. (2006) for similar observation

- Model where He atoms are trapped into damage zone => increase of He retention in apatite crystal and Tc value

III. Relationship between damage and diffusion coefficient



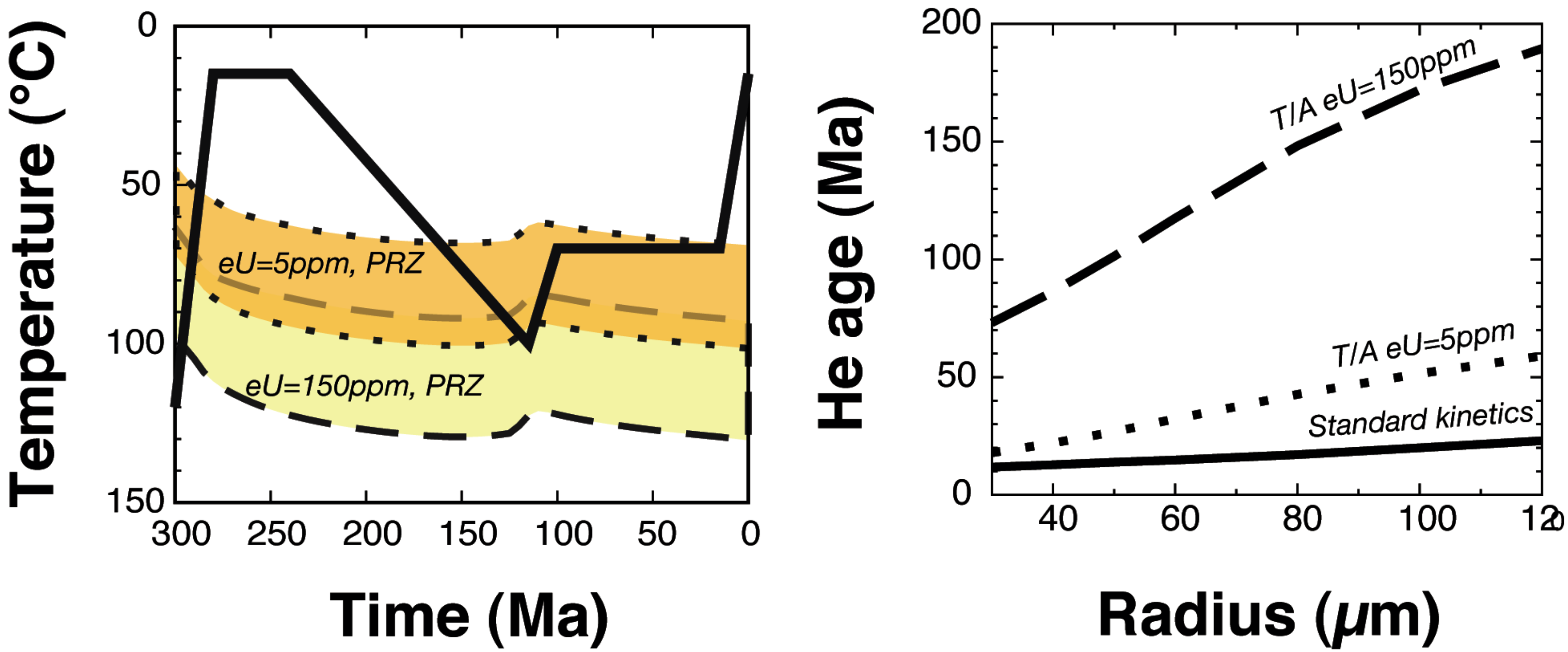
Shuster et al. (2006); Shuster and Farley (2009)

- Empirical data showing the change of diffusion coefficient with artificial damage content

=> Tc ranges from 40 to > 100°C

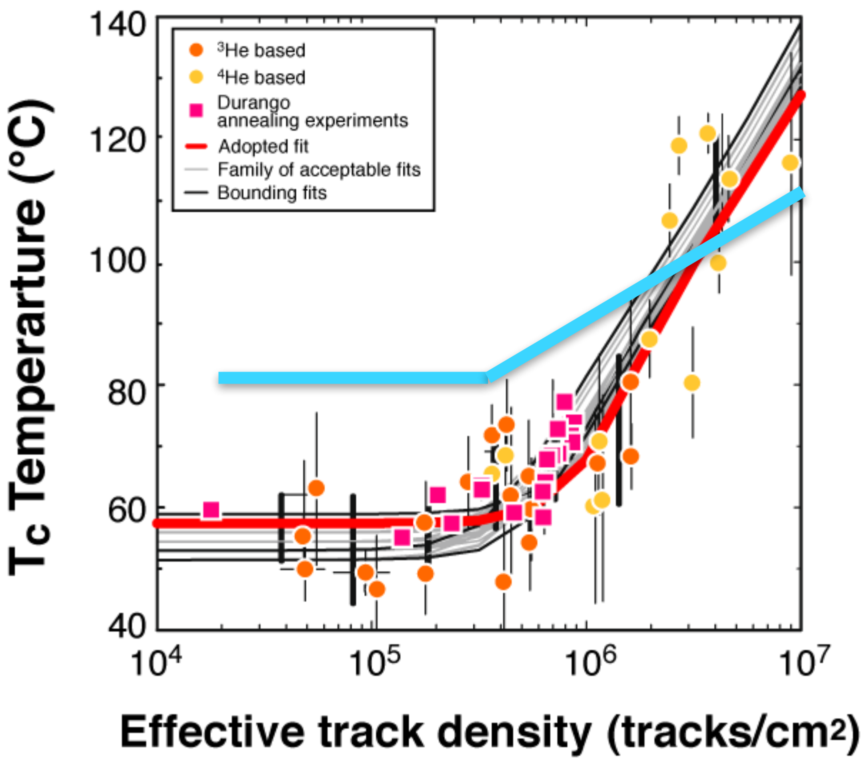
III. Implication of damage content on He-PRZ

Gautheron et al. (2009)



- Damage production and change of He diffusion, will change the Tc and He-PRZ through time

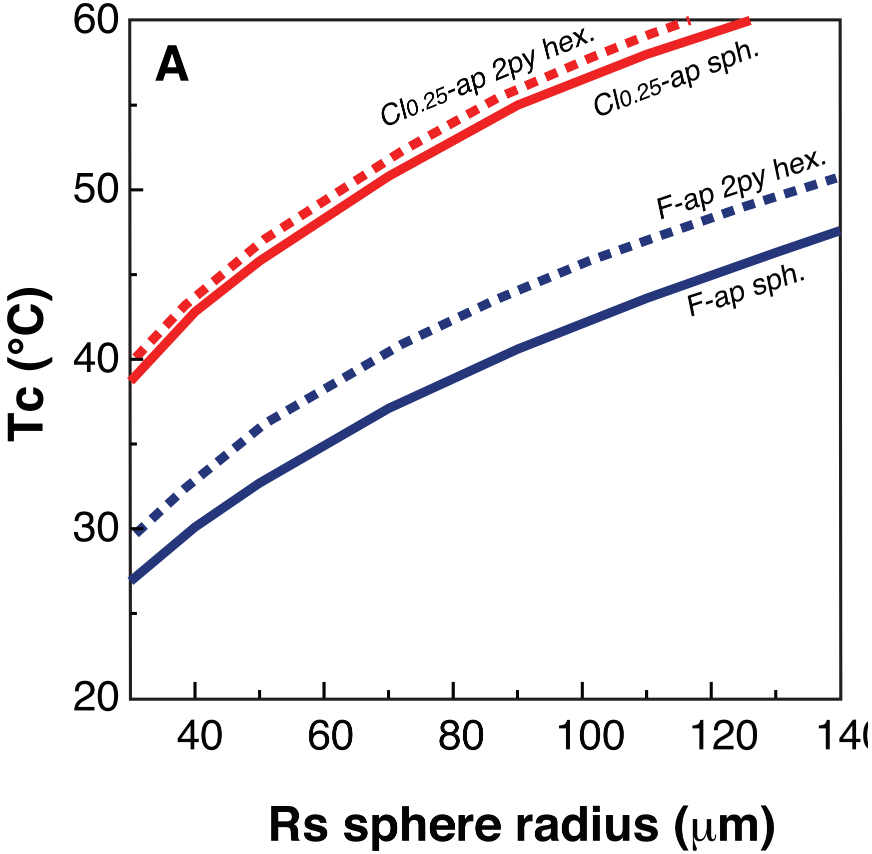
III. Diffusion in complex system: damage trapping + annealing model



Two damage + annealing models are used :

- Flowers et al. (2009): calibrated on natural + irradiated samples
- Gautheron et al. (2009): calibrated on “old” natural AHe ages

III. Chemical impact on diffusion

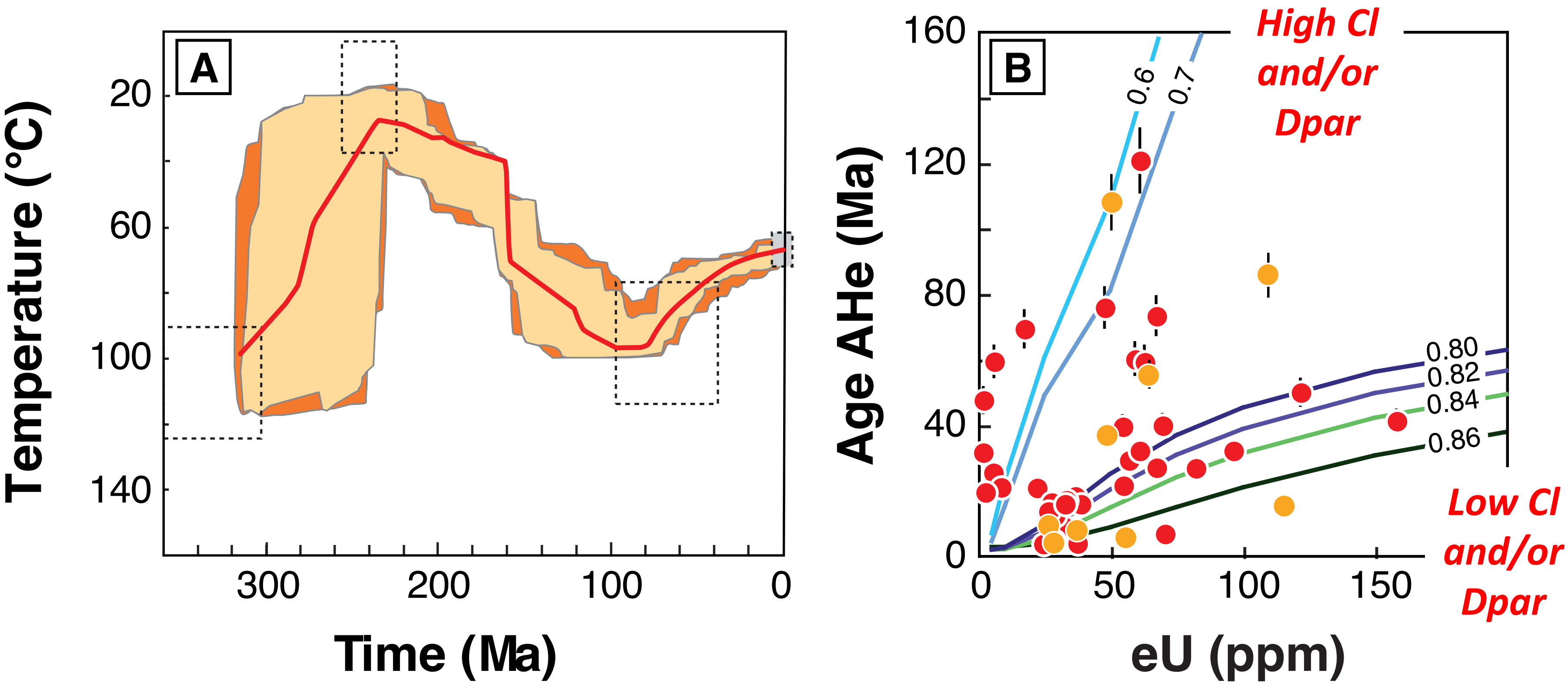


Djimbi et al. (2015)

- Chemical impact on He diffusion
- Lower Tc for undamaged apatite Tc=30-40°C

III. Chemical impact on diffusion

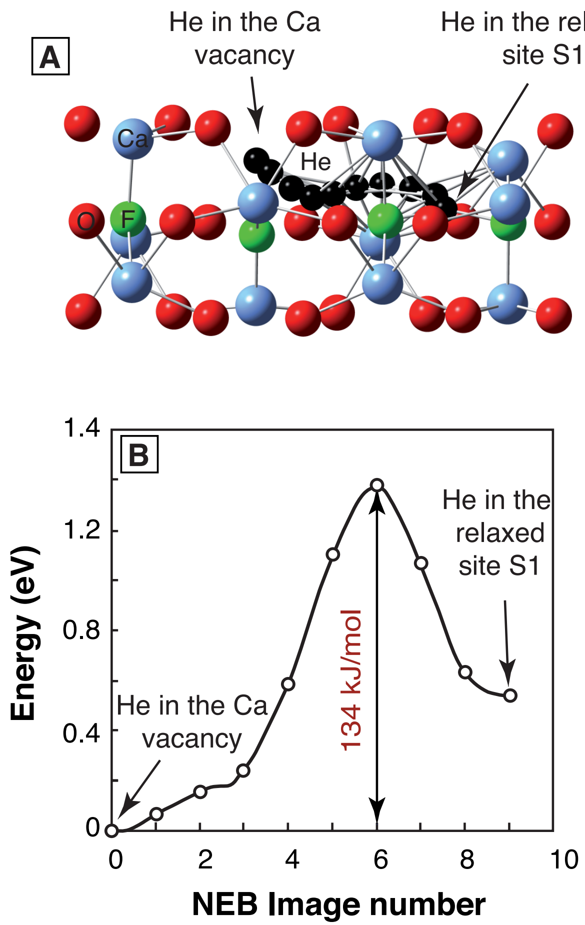
➢ Apatite chemistry play a role on damage annealing rate (such as for apatite fission tracks)

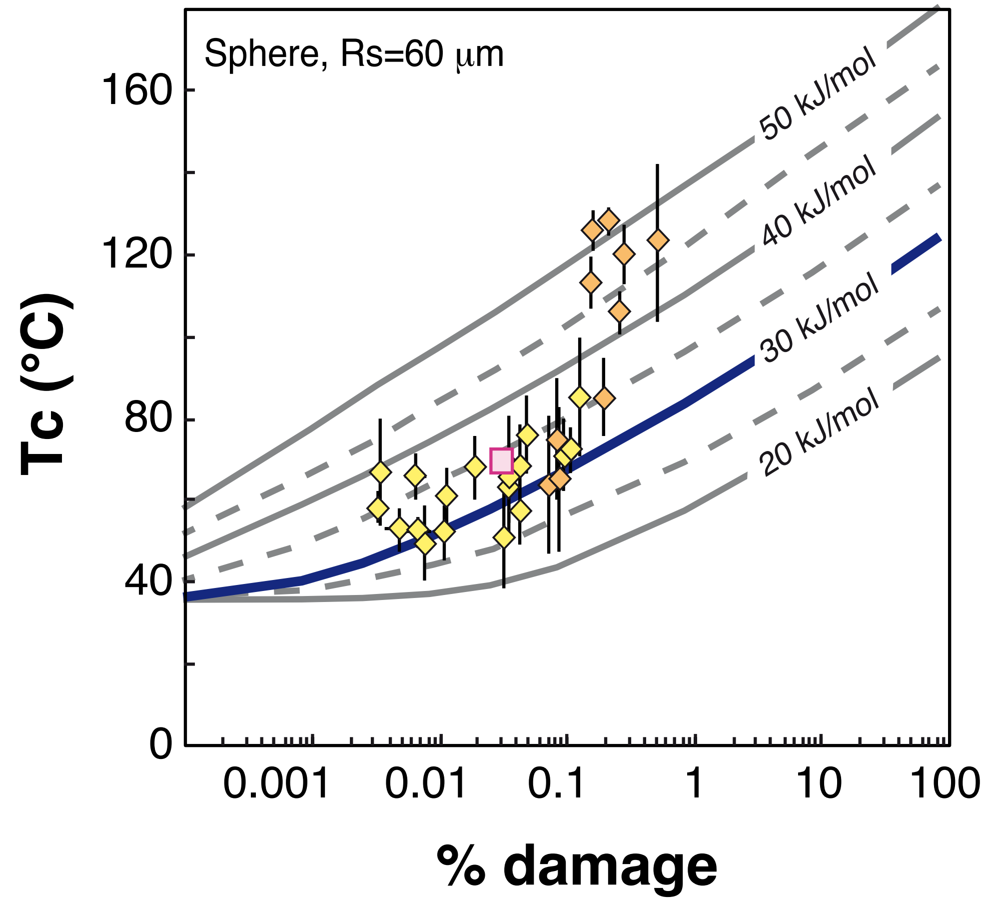


Modified from Gautheron et al. (2013);
Modeling: HeFTy Ketcham (2005) + Flowers et al. (2009)

(See EXERCICE 3)

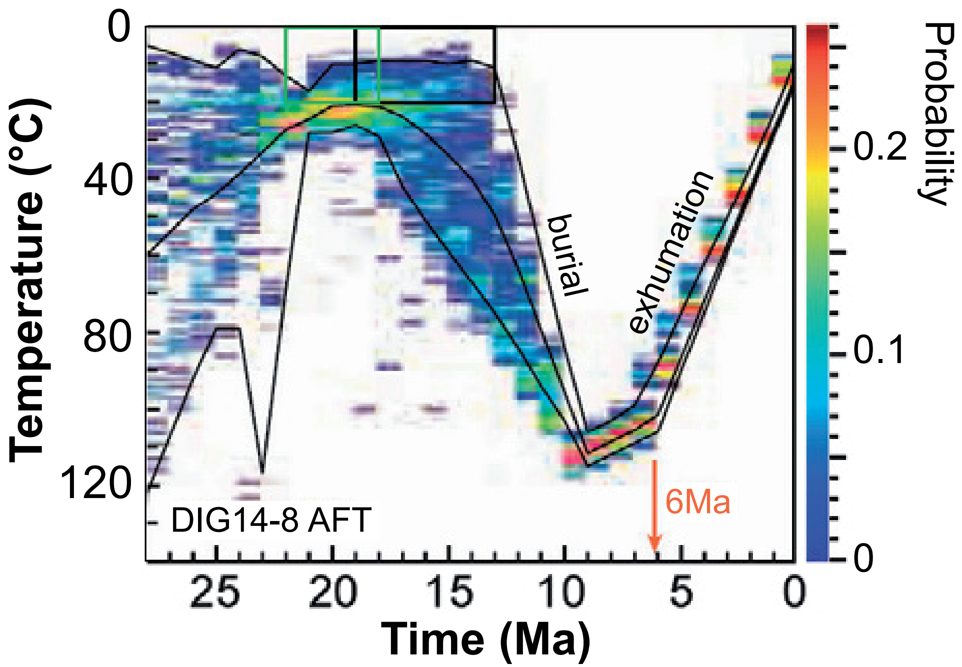
III. Damage impact on diffusion

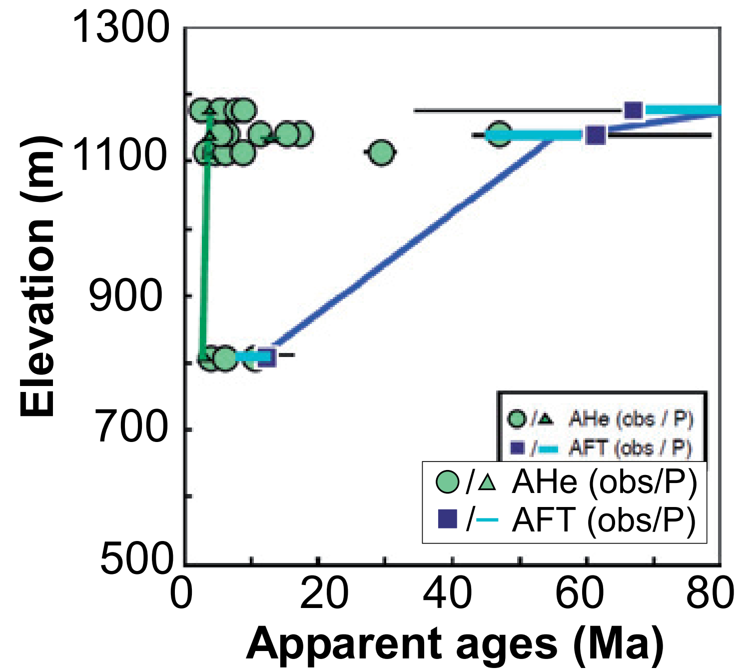




Gerin et al. (2017)

- We are currently calibrating the new He damage model
- New code will be implemented into QTQt and HeFTy in 2018

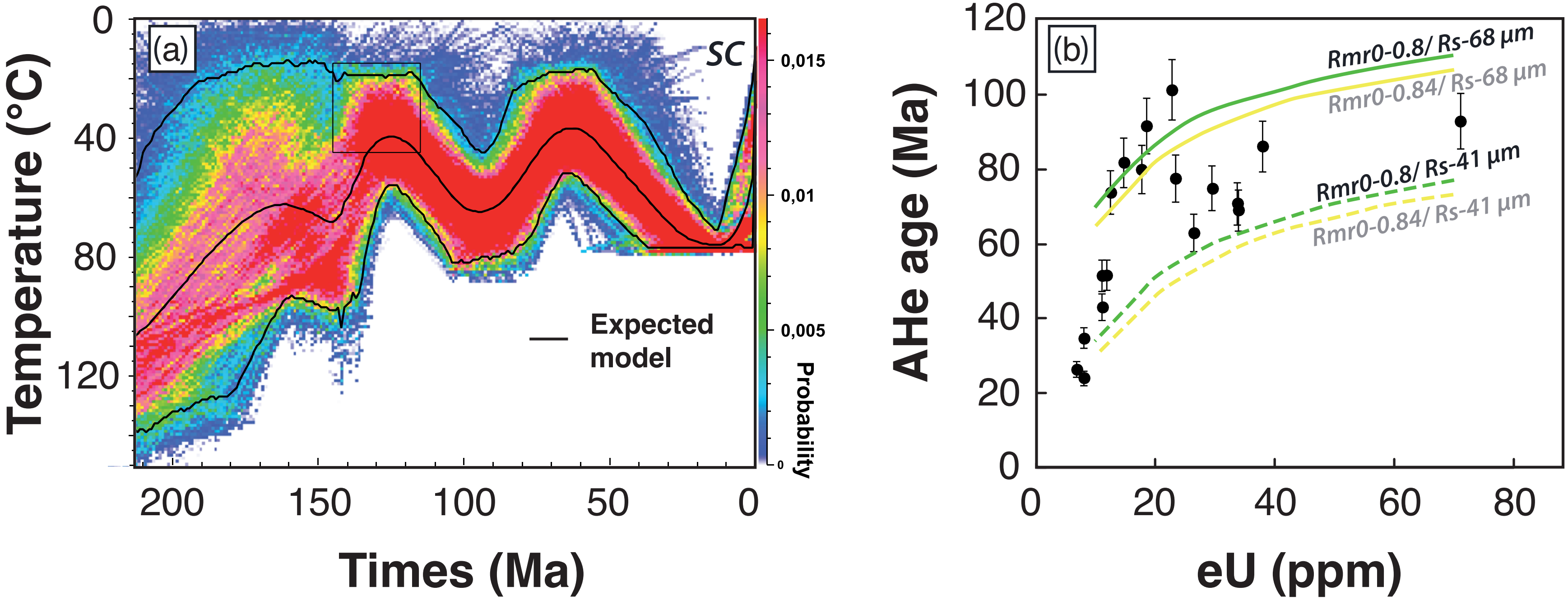




Schwartz et al. (2017)
Simulation QTQt (Gallagher, 2012), with Flowers et al. (2009) code

- AHe age dispersion is useful to refine not only the burial time and temperature

III. Impact of chemistry and grain size on AHe age dispersion



Leprêtre et al. (2015);
QTQt simulation using AHe and AFT data (Gallagher (2012)

- ➢ Need to consider grain chemistry variation in addition to grain size and damage model

TAKE HOME MESSAGE:

- A **geological meaning is associated with AHe age dispersion** as the age reflects the impact of:
  1. Grain size (diffusion domain)
  2. Damage content (eU + time + annealing via chemistry)
  3. Thermal history

- **Adapt the number of analyzed grains** as a function of thermal history (3 to > 10 apatite crystals)

(1) (U-Th)/He dating system

I. **Introduction, generalities**

II. **(U-Th)/He principles (chronometer vs thermochronometer)**

(2) How to get an (U-Th)/He age

(3) Applications

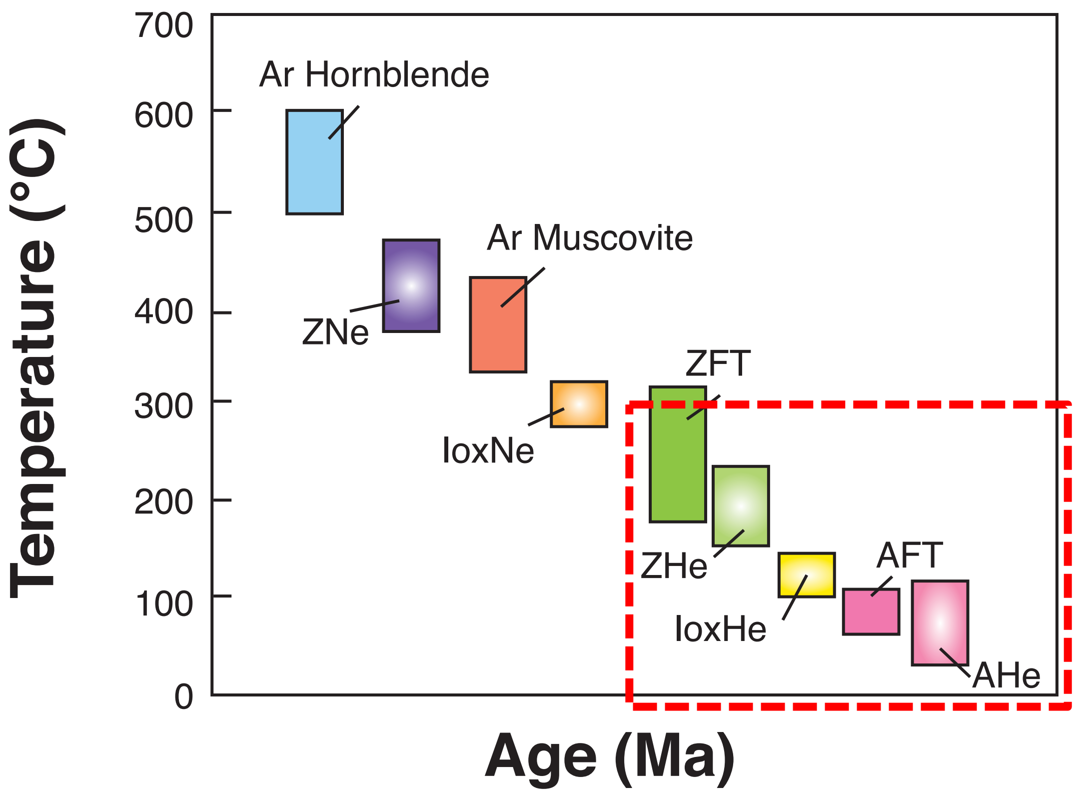
III. **Apatite (U-Th-Sm)/He (AHe) method**

IV. **Other applications (zircon, iron oxides,…)**

(4) Exercises (Tc, ejection, weight, Rs), thermal modeling

IV. Others applications

- (U-Th)/He system can be applied to a large range of minerals



Which geological application ?

1. **Higher temperature information than apatite** => zircon, titanite
2. **Ore deposit, laterite dating** => goethite, hematite, magnetite

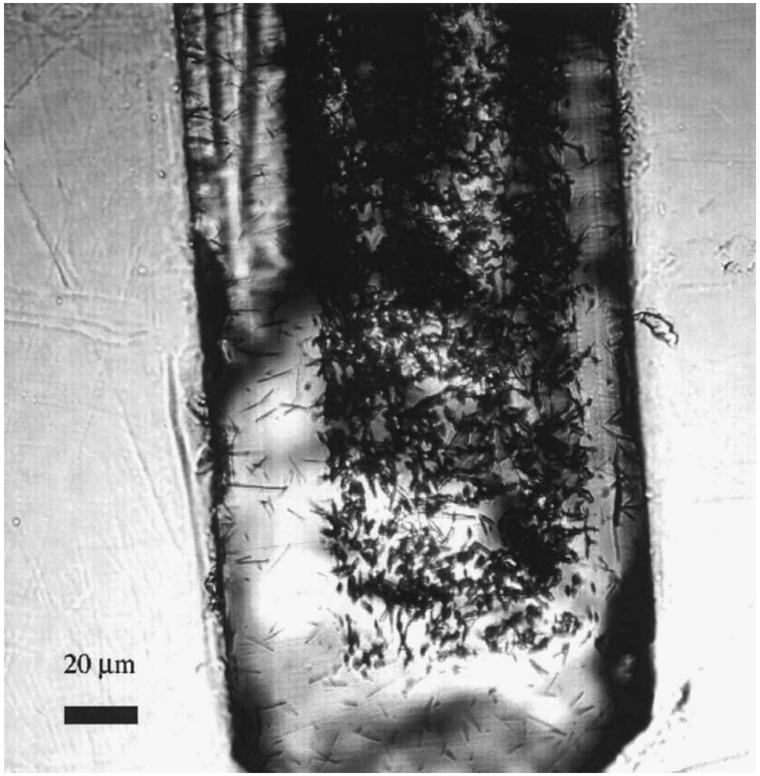
IV. Zircon (U-Th)/He (ZHe) method

- Zircon crystal can be found in a large variety of rocks (plutonic, volcanic and sedimentary)

1. Rich U-Th content: eU= 100 to 3000 ppm (He production from Sm is "null")

2. U-Th zoned crystal

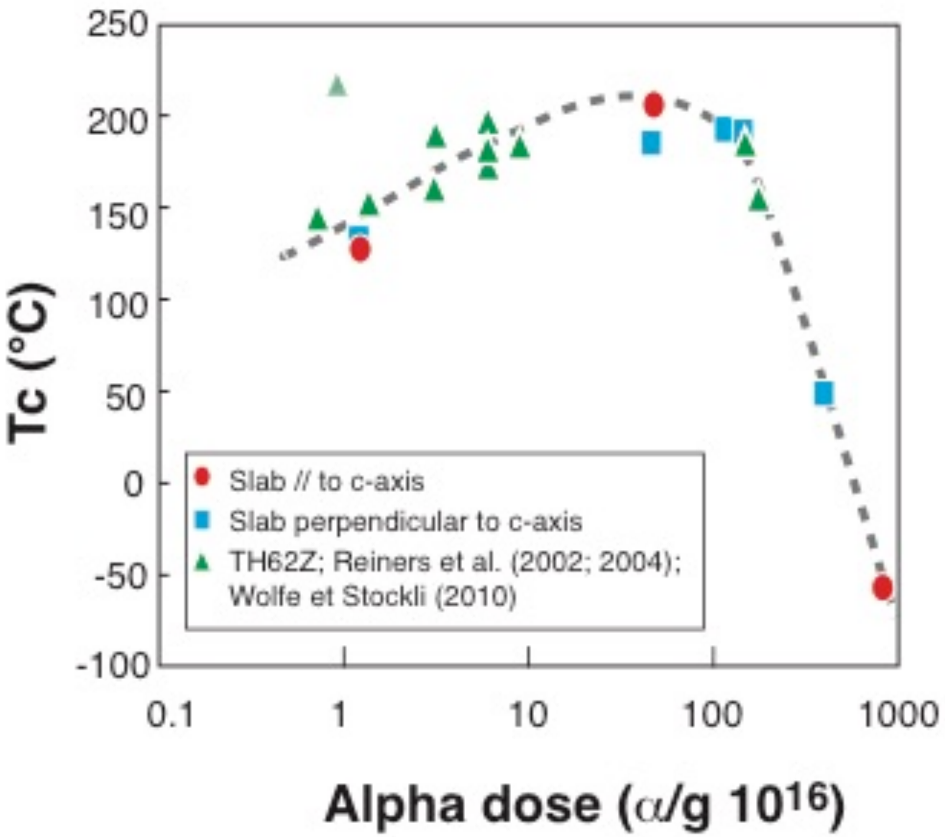
3. Lower stopping distance



Tagami et al. (2003)

- **Tc= 140-200°C (>AHe)**

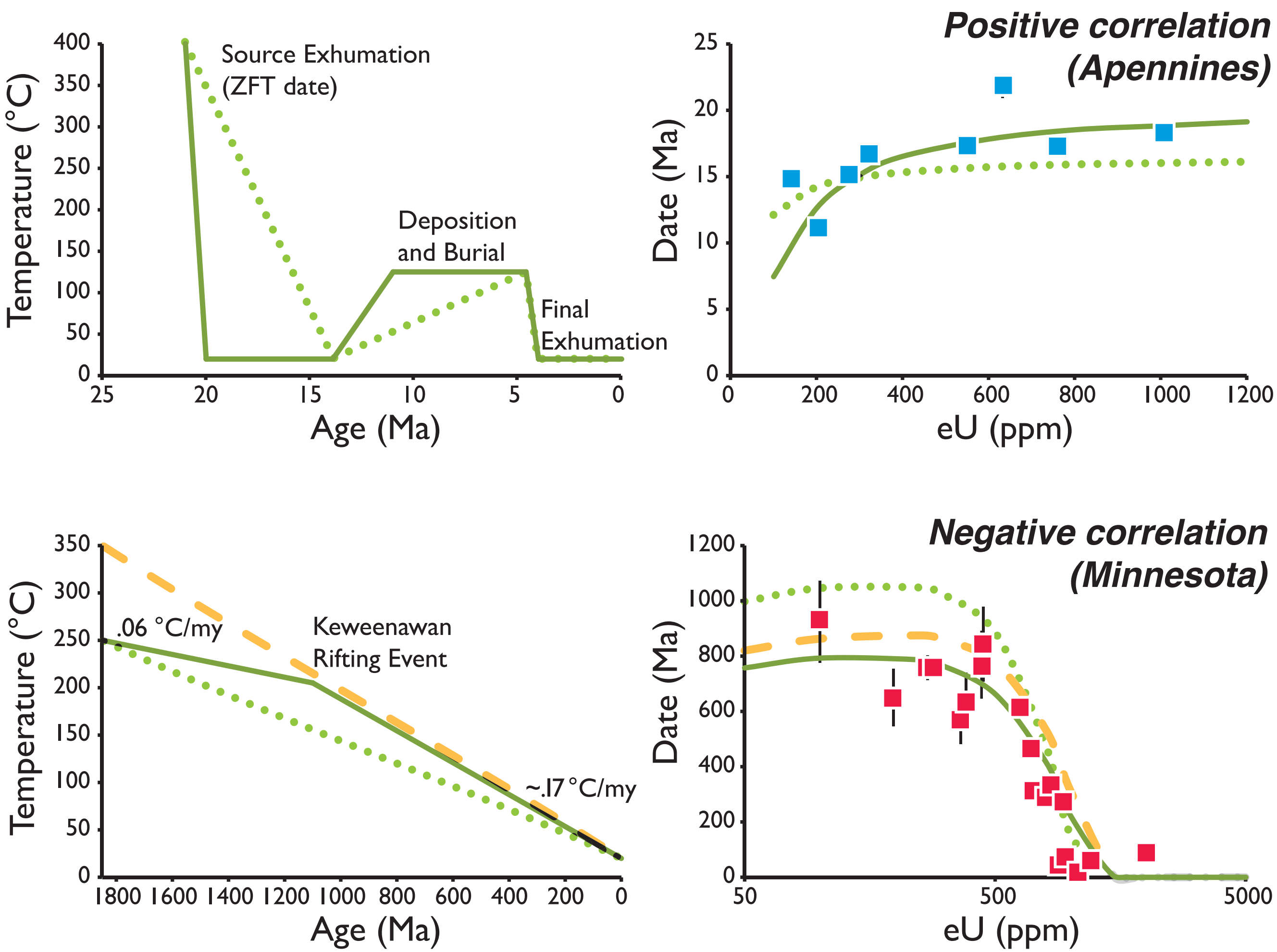
1. Strong modification of diffusion coefficient by recoil damage,
2. Damage clustering and interconnection
3. Lattice amorphisation at high dose



Guenthner et al. (2013)

IV. Interpretation of ZHe data

Guenthner et al. (2013)



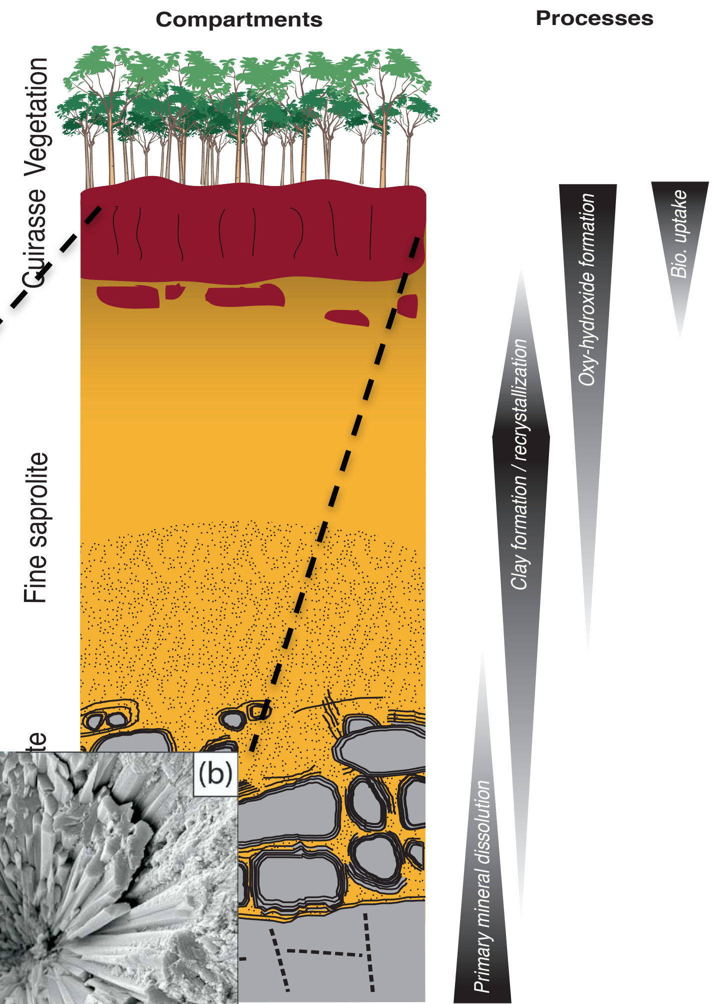
- ➢ Used of ZHe data dispersion to determine a precise thermal history, similarly to AHe

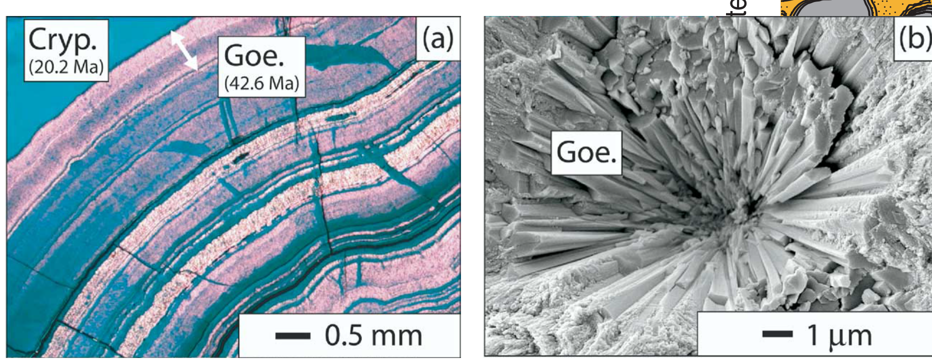
IV. Laterite, ore deposit dating

Laterite surface development reflects intense weathering phases

Crystallization of supergene mineralogical phases:

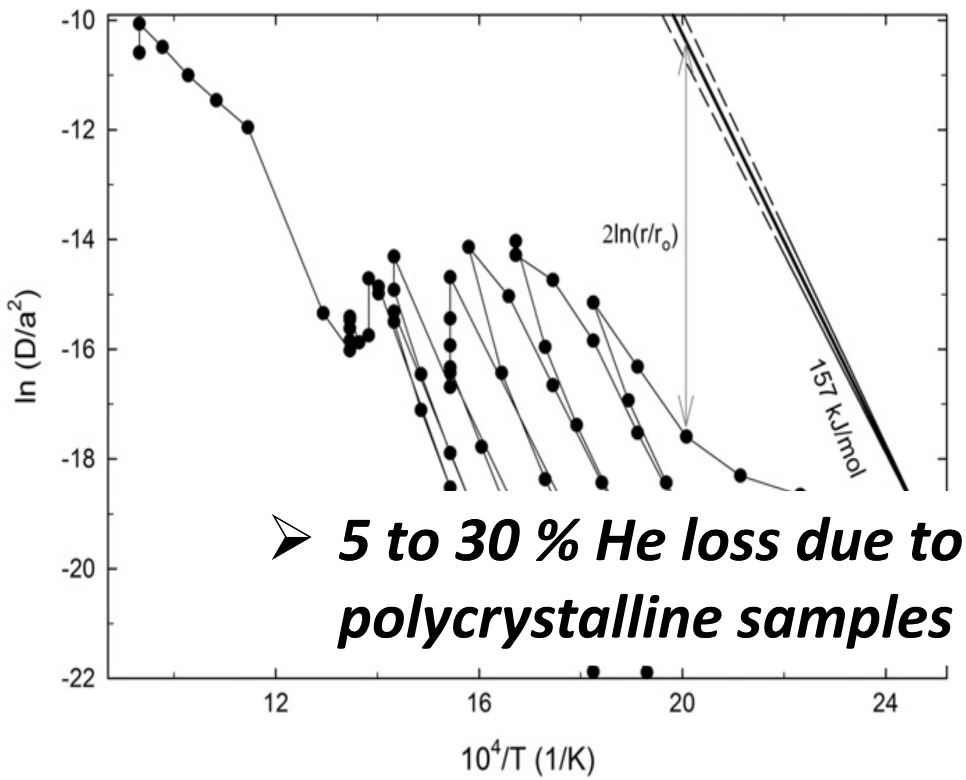
- Iron oxides (H – G)
- K-Mn oxides
- Kaolinites

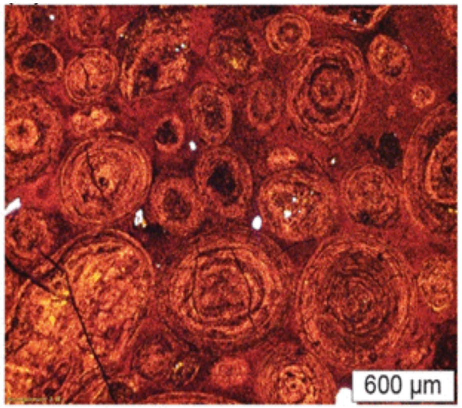


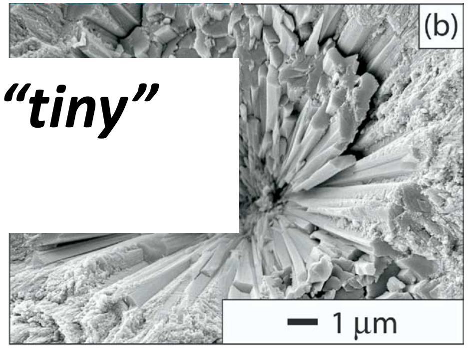


Shuster et al. (2005); Vasconcelos et al. (205)

- **He diffusion behavior in hematite and goethite**







- ***5 to 30 % He loss due to "tiny" polycrystalline samples***

- **Crystals of 0.1 µm**

Hematite

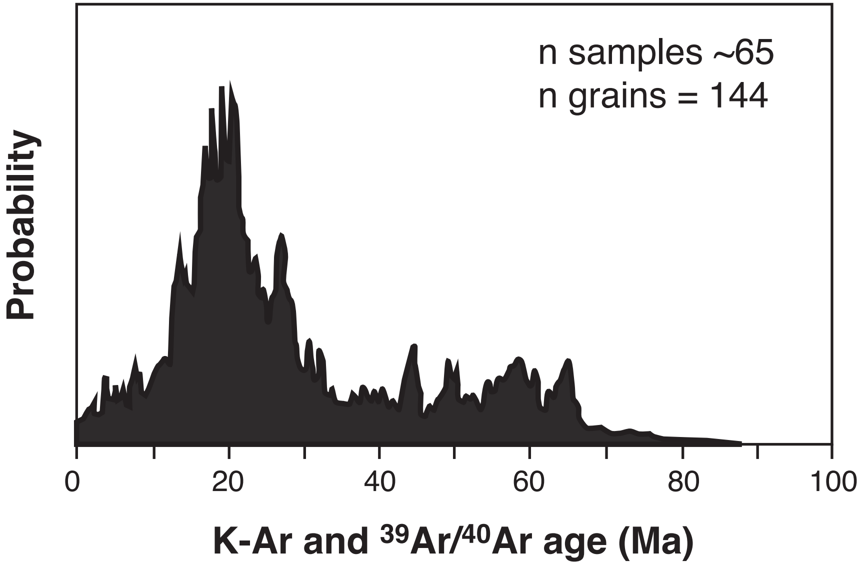
- *T_c* (He)= 56°C

Goethite

- *T_c* (He)~ 49°C

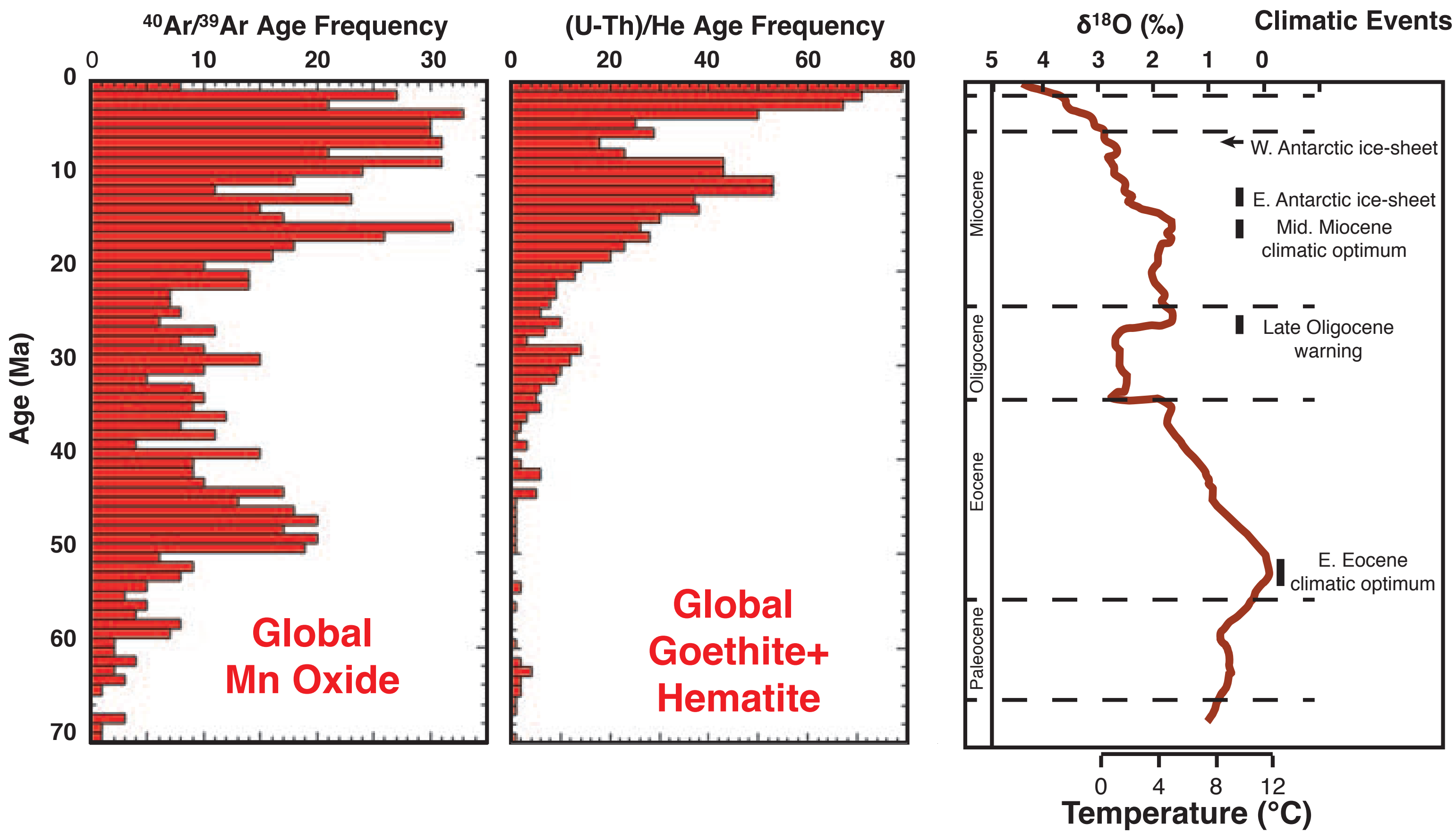
Shuster et al. (2005); Farley and Flowers (2012); Balout et al. (2017); Allard et al. (Submitted)

➢ Ore-deposit formation : Carajas Mountains (Brazil)



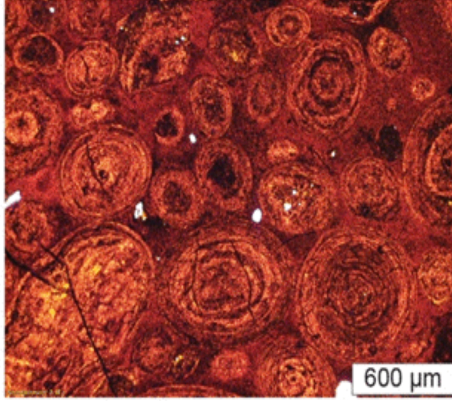
Vasconcelos et al. (2015) and references therein

➢ All Amazonian and Australian laterites ages



Vasconcelos et al. (2015) and references therein

➢ Similar ages given by the K-Ar/Ar-Ar and (U-Th)/He systems



TAKE HOME MESSAGE :

(U-Th-Sm)/He dating can be applied to many systems if:

1. **Crystal contains U-Th-Sm AND**
2. **Produced He atoms are quantitatively retained in crystal lattice at surface temperatures** (because of diffusion ~Tc>40° C) **AND**
3. **Grain or sample (made of polycrystalline grains) size are > 100 µm** (because of significant alpha ejection) **AND**
4. **Possible strong damage impact on crystal lattice**

(1) (U-Th)/He dating system

I. Introduction, generalities

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(2) How to get an (U-Th)/He age

(3) Applications

III. Apatite (U-Th-Sm)/He (AHe) method

IV. Other applications (zircon, iron oxides,…)

(4) Exercises (Tc, ejection, weight, Rs), thermal modeling

(4) Exercices

Different exercises using diffusion coefficient (or Tc), and notions seen during lecture: ejection, diffusion domain, age calculation and dispersion

1. **Closure temperature calculation**

2. **Alpha ejection, Rs, weight determination (Qtflojt)**

3. **AHe age simulation using HeFty**

(4) Ex 1. closure temperature calculation

- With the given D_0 and E_a, **calculate the closure temperature Tc**, for a given cooling rate and grain size (a)

Ea (kJ/mol)	139.5
D_0 (m^2/s^{-1})	3.37×10^{-2}

$$T_c = \frac{E_a}{R \ln\left(A\tau \frac{D_0}{a^2}\right)} \qquad \tau = \frac{R T_c^2}{E_a T}$$

Dodson (1973)

- With R=8.31 J/mol/K; A=55 and T=273 K

(4) Ex 1. closure temperature calculation

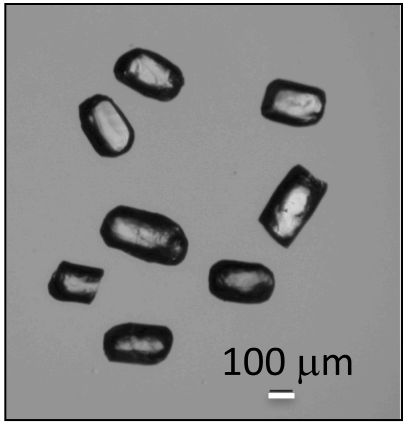
- Using an excel sheet, enter the need values need

	values	
Ea (J/mol)	139528,4	
D_0 (m^2/s^{-1})	3,37E-02	
a (m)	1,70E-04	
D_0/a^2	1,17E+06	**!! Values to change !!**
R	8,31	
A (sphère)	55	**T1 Temperature (°C)**
T (°K)	345,00	**72,00**
		Cooling rate (°C/Ma)
Cooling rate (°/s)	3,17E-13	**10**
tau	2,24E+13	
Tc (°K)	345	
Closure temp Tc (°C)	**71,66**	**When it's the same value of T1**

conversion 1 cal => 4.18 J/mol

(4) Ex 2. grain characteristics

1. You have carefully selected apatite crystals and reported all measurements. Using those values, calculate the:
    a. Apatite weight
    b. Rs (equivalent diffusion domain)
    c. F_T (ejection factor)



2. For one sample, you are not sure if the termination was 2 broken faces or no pyramids. Test the influence on the F_T factor.

3. Test the influence of **U-Th zonation** on the F_T factor.

4. Calculate the corrected AHe age and estimate the maximum age dispersion induced by the F_T factor (geometries, zoning)

(4) Ex 2. grain characteristics

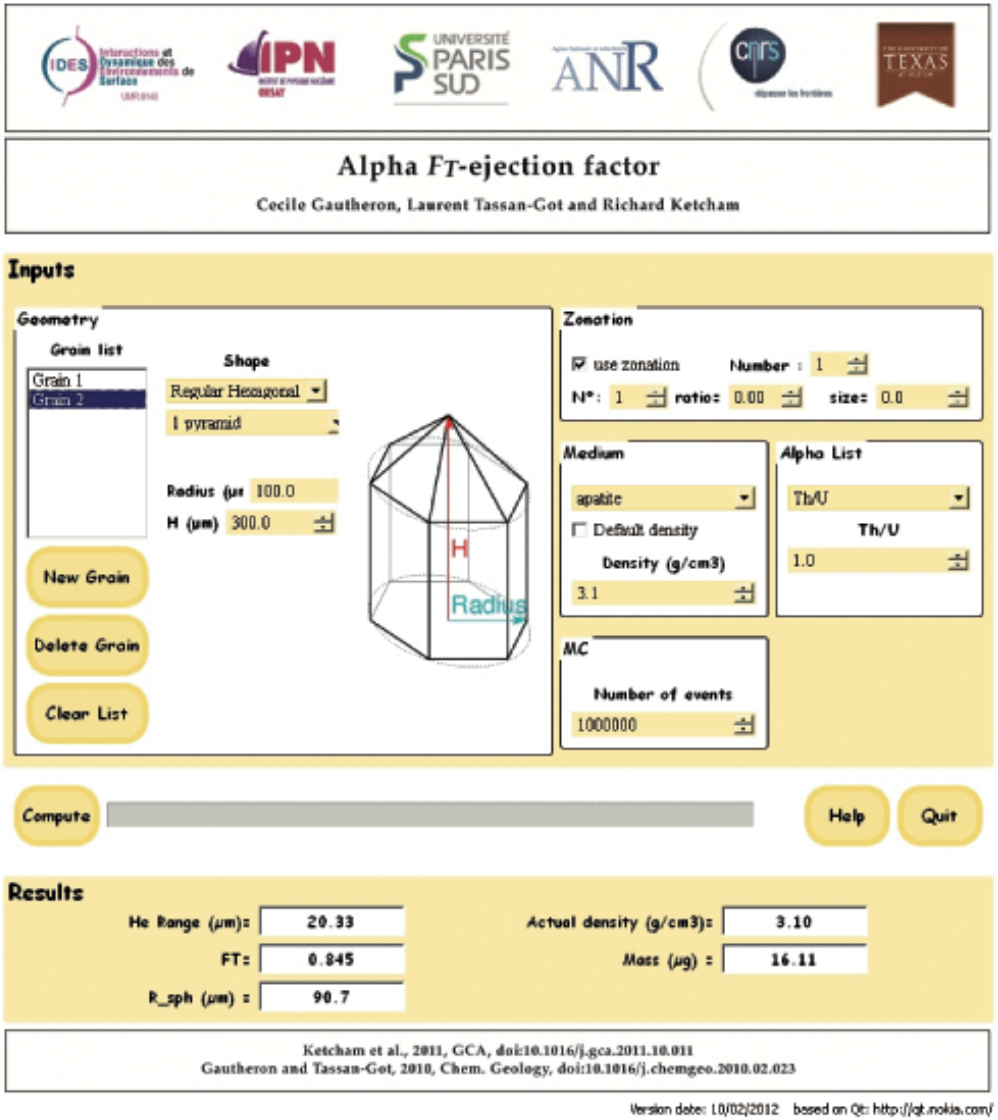
- For grain measurement, you get the following data:

Name	Geometry	H (µm)	W (µm)	T (µm)	Weights (µg)	FT	Rs (µm)
Hel_1	2bf	200	125	115	6.8	0.83	64.8
Hel_2	1+1	160	125	115	4.2	0.80	59.8
Hel_3	No py	200	145	140	9.4	0.81	73.5
Hel-4	2 bf	150	80	70			
With:							
2 bf=2 broken faces			1+1=1 pyramid + 1 bf				
No py=No pyramids							

(4) Ex 2. grain characteristics

1. Selected the grain shape
2. Grain geometry
3. Grain size
4. Use a Th/U value
5. For zonation, selected where the U-Th content is localized and normalized amount and size.

Ketcham et al. (2011); Gautheron et al. (2012)



http://hebergement.u-psud.fr/flojt/

(4) Ex 2. grain characteristics

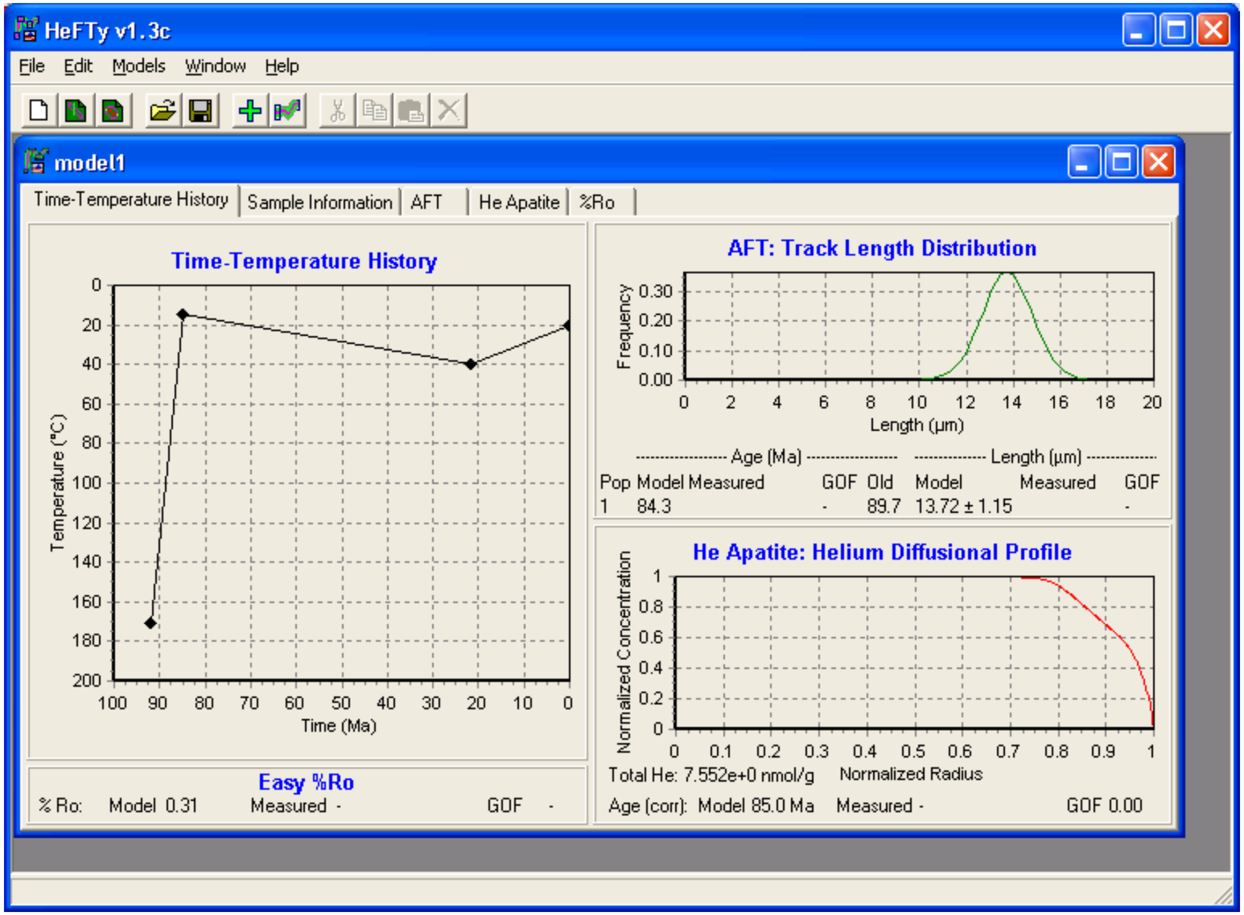
- With He, U, Th and Sm, you get the raw age for your sample.
  1. Calculate the alpha ejection corrected age

  1. Estimate the error on AHe age, by determining also the error associated with the determination of the F_T factor, knowing that the analytical error was at 4%.

Name	F_T	s	Rs	^{4}He	U	Th	Sm	eU	Th/U	Raw age	Cor age	σ
			(µm)	(nmol/g)	(ppm)					(Ma)		
Hel_1	0.83	4%	64.8	2,21	17	61	296	31	3,7	12,2	**14.7**	8%
Hel_2	0.80	4%	59.8	34,19	103	265	383	167	2,6	37,4	**46.7**	8%
Hel_3	0.81	4%	73.5	0,11	1	4	275	2	4,8	4,8	**5.9**	8%

(4) Ex 3. AHe age simulation

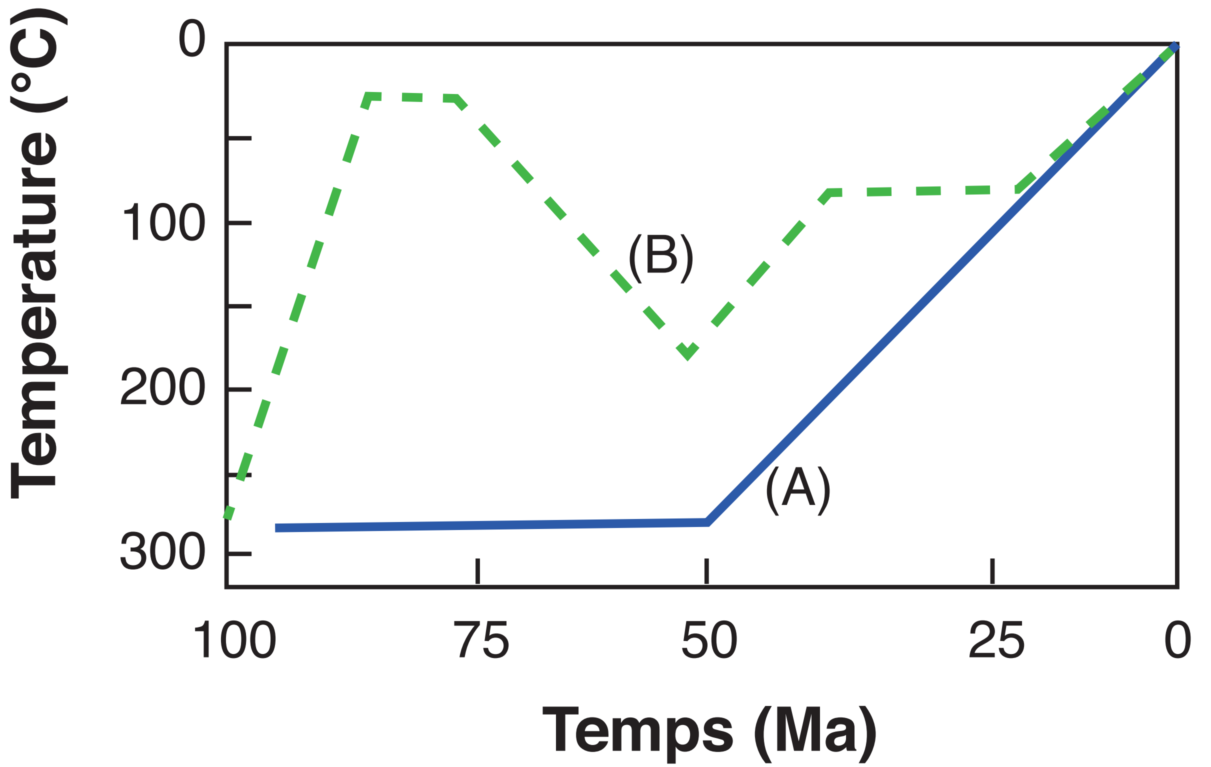
1. Using HeFTy, we will simulate AHe, ZHe and AFT age distribution



Ketcham (2005)

(4) Ex 3. AHe age simulation

1. Test on AHe and ZHe age for two different thermal histories (A and B), the impact of:
   a. Grain size,
   b. eU content
   c. grain chemistry (for apatite via the rmr_0)



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