$^{40}Ar/^{39}Ar$ Thermochronology: Practical applications (where theory and practise collide)

Clare Warren

Helsinki

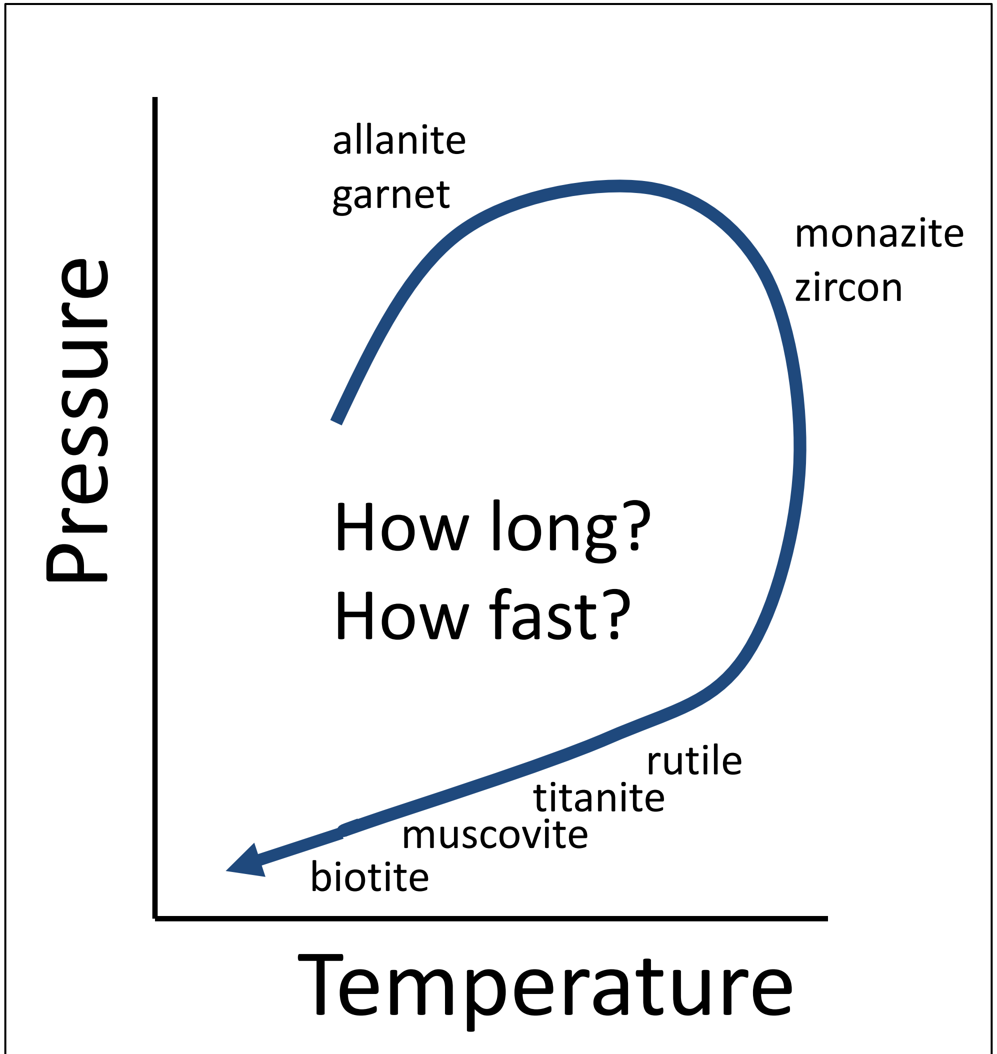
24 October 2017

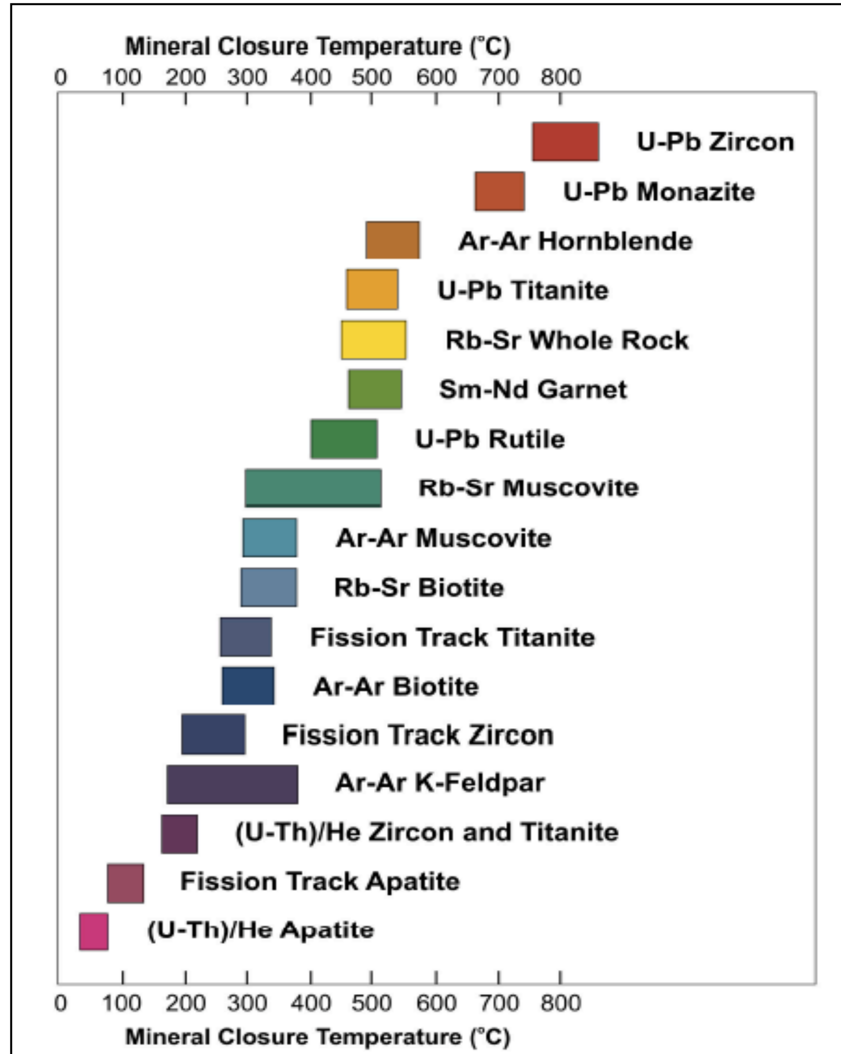
The Open University

Learning Outcomes

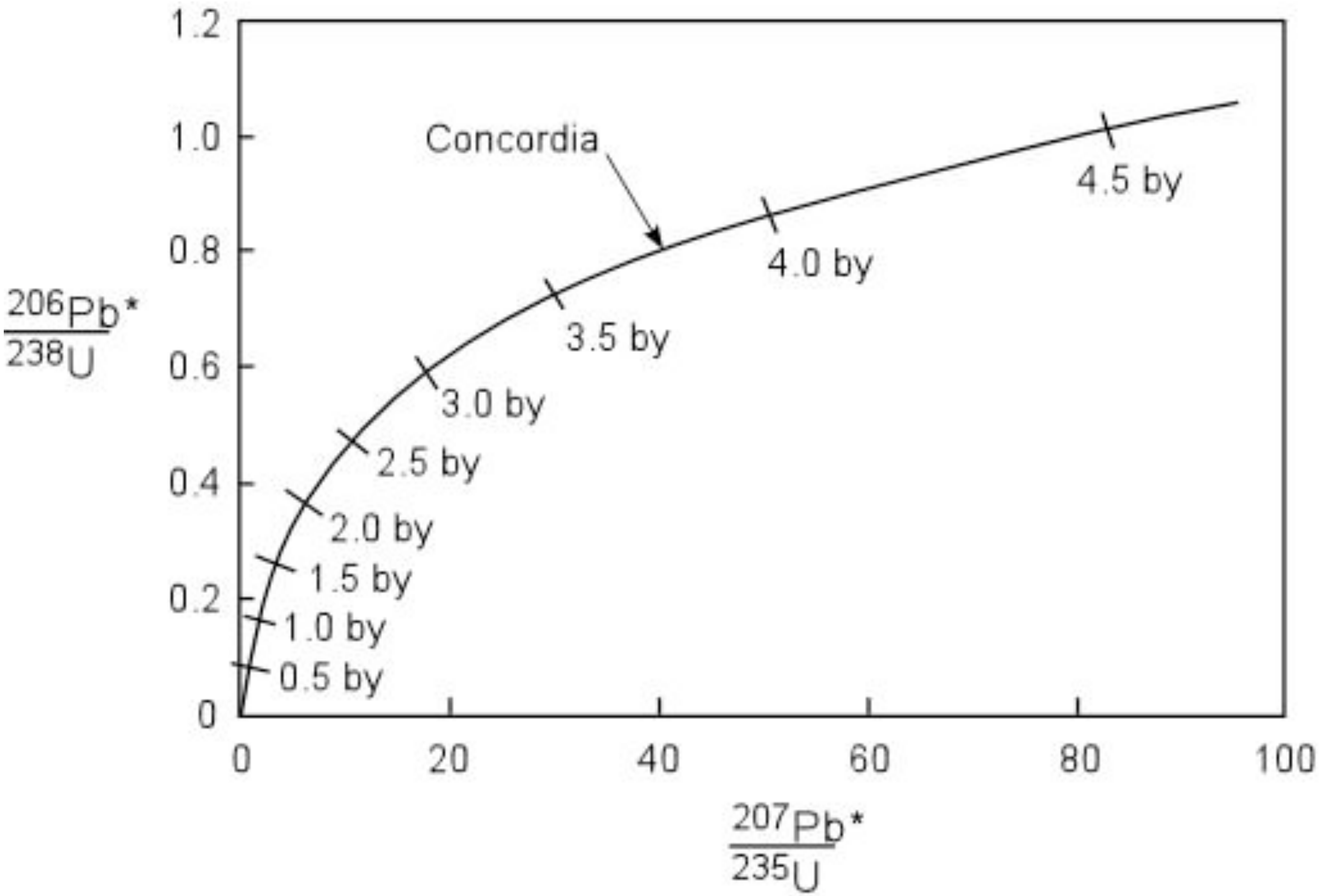
- You will become familiar with:
  - Thinking about assumptions underpinning diffusion theory
  - Assessing data against models
- You will be able to:
  - Carry out simple calculations using DiffArg
  - Plot up and think about data

The ideal


allanite
garnet
monazite
zircon
Pressure
How long?
How fast?
rutile
titanite
muscovite
biotite
Temperature


Mineral Closure Temperature (°C)
0 100 200 300 400 500 600 700 800
U-Pb Zircon
U-Pb Monazite
Ar-Ar Hornblende
U-Pb Titanite
Rb-Sr Whole Rock
Sm-Nd Garnet
U-Pb Rutile
Rb-Sr Muscovite
Ar-Ar Muscovite
Rb-Sr Biotite
Fission Track Titanite
Ar-Ar Biotite
Fission Track Zircon
Ar-Ar K-Feldpar
(U-Th)/He Zircon and Titanite
Fission Track Apatite
(U-Th)/He Apatite
0 100 200 300 400 500 600 700 800
Mineral Closure Temperature (°C)

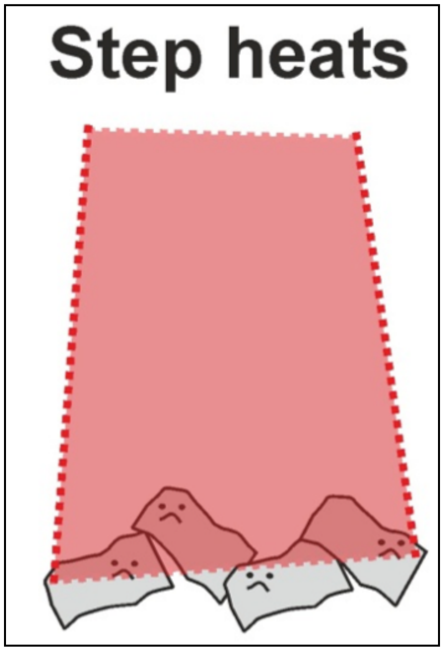
But no internal consistency check!



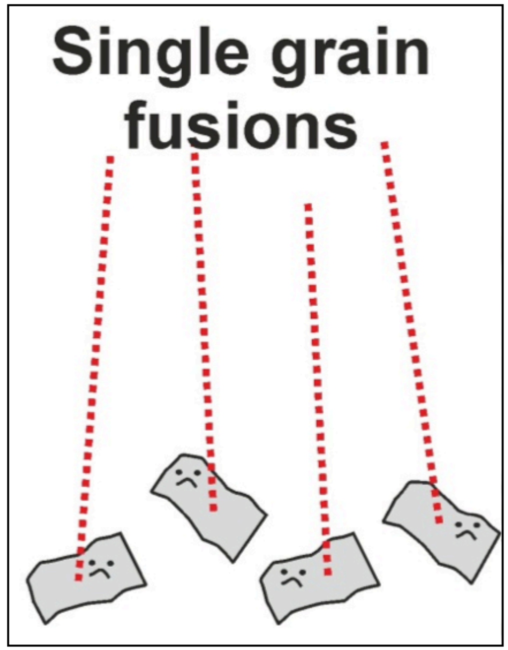
Only 1 isotope of Ar is radiogenic

Image: www.tulane.edu

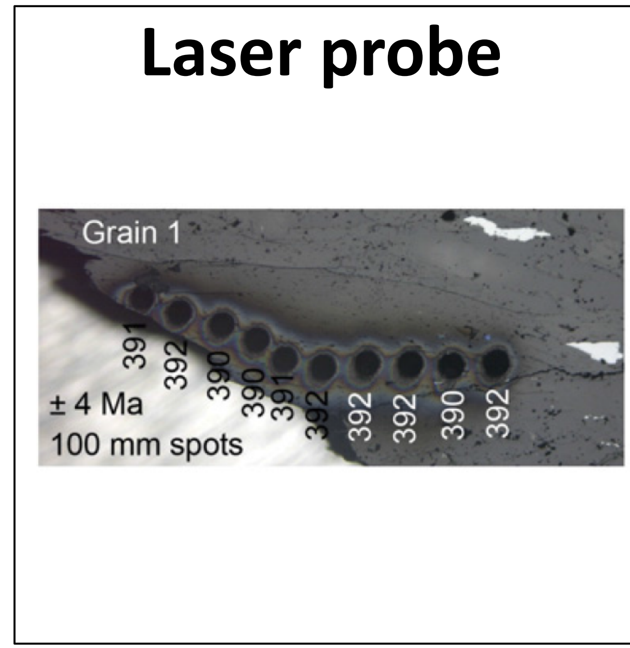
Analytical Evolution



Multi-grain;
Single grain



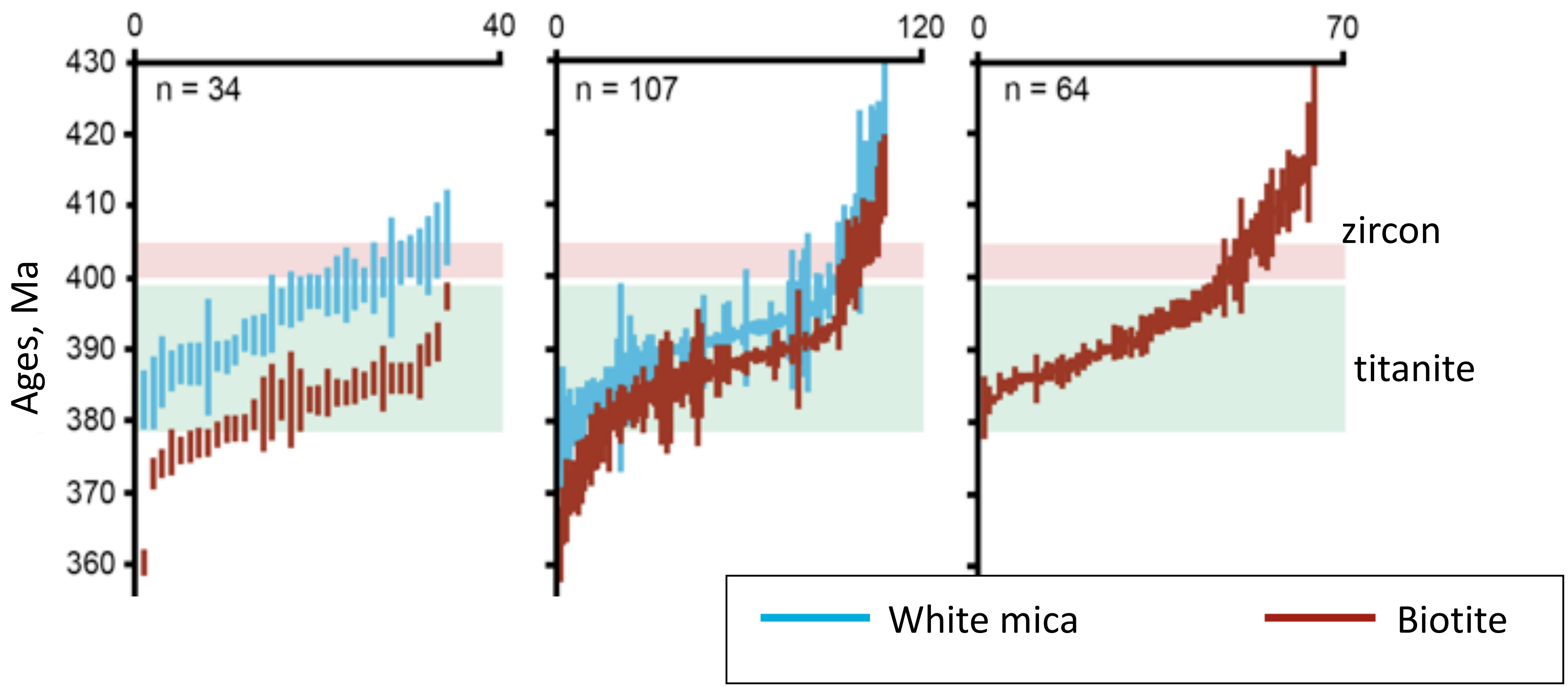
Single grain



Single spot

Images: Catherine Mottram; Chris McDonald

Dispersion in $^{40}Ar/^{39}Ar$ data

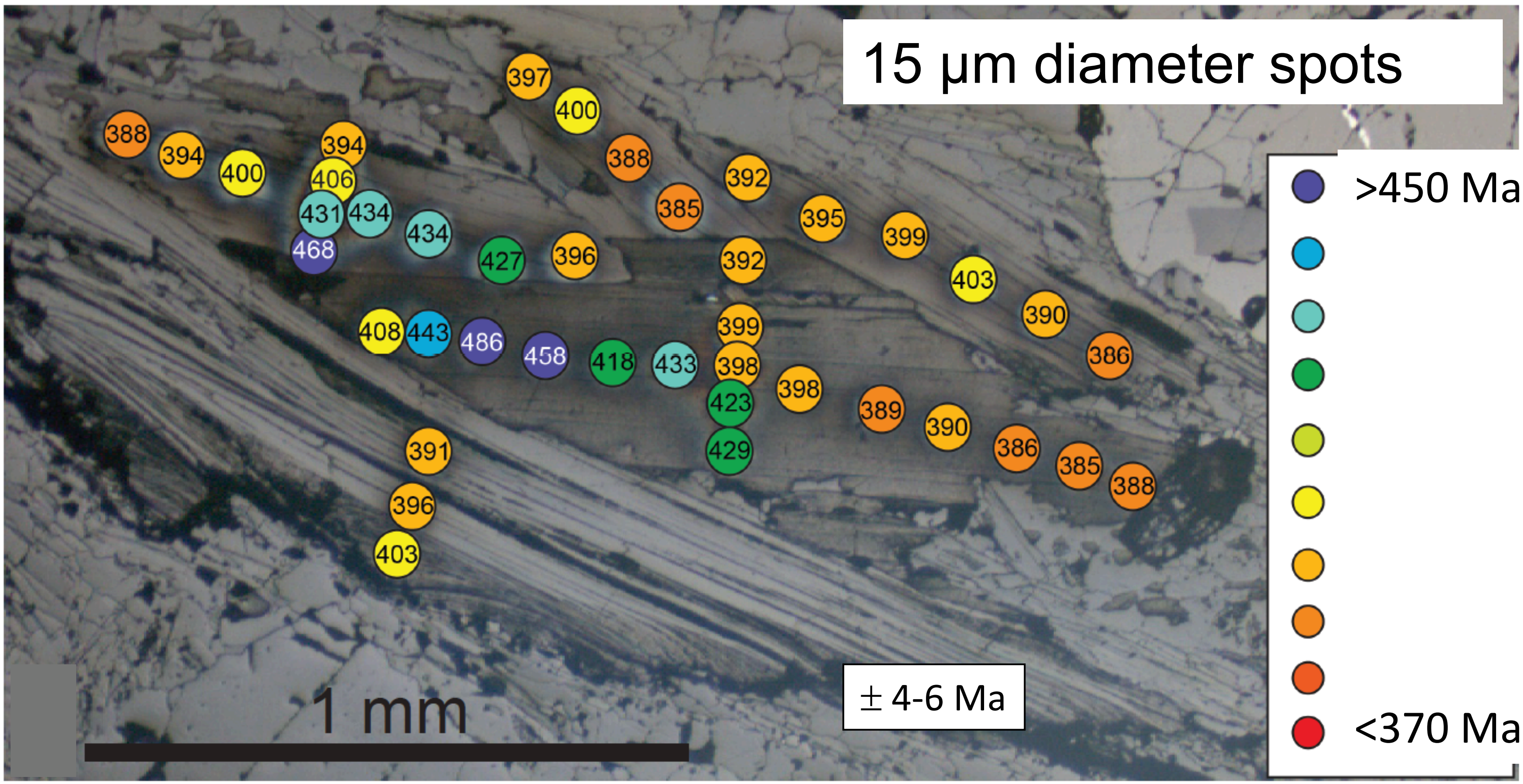


Single grain fusion, 1mm diameter grains

Caledonides: ~400 Ma. Argon 'ages' from 420-360 Ma

Ar: Chris McDonald PhD data; Zir: Hacker et al.; Titanite: Kylander-Clark et al.

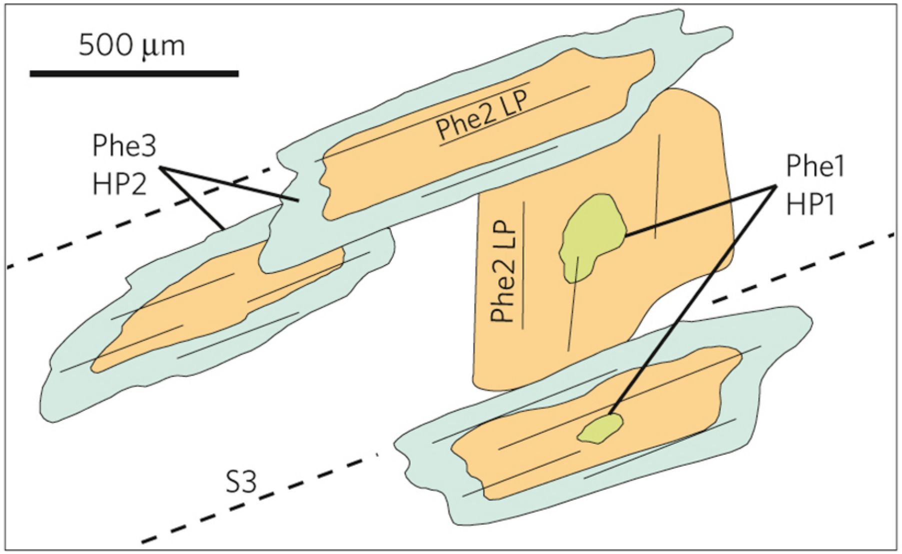
Within-grain variability

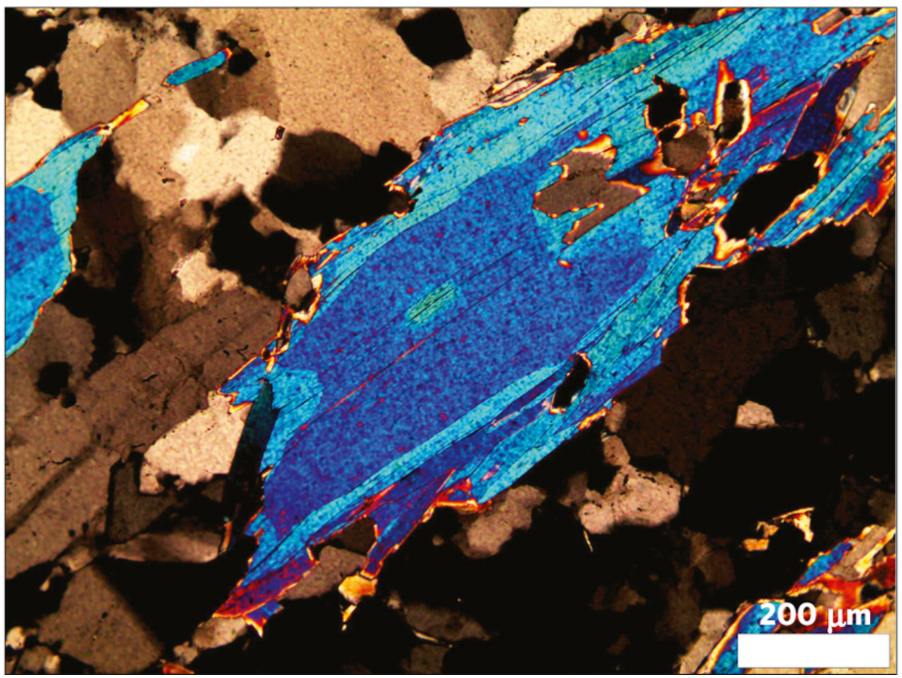


Same spread within grains as between grains

Chris McDonald PhD data

Mineral zoning?





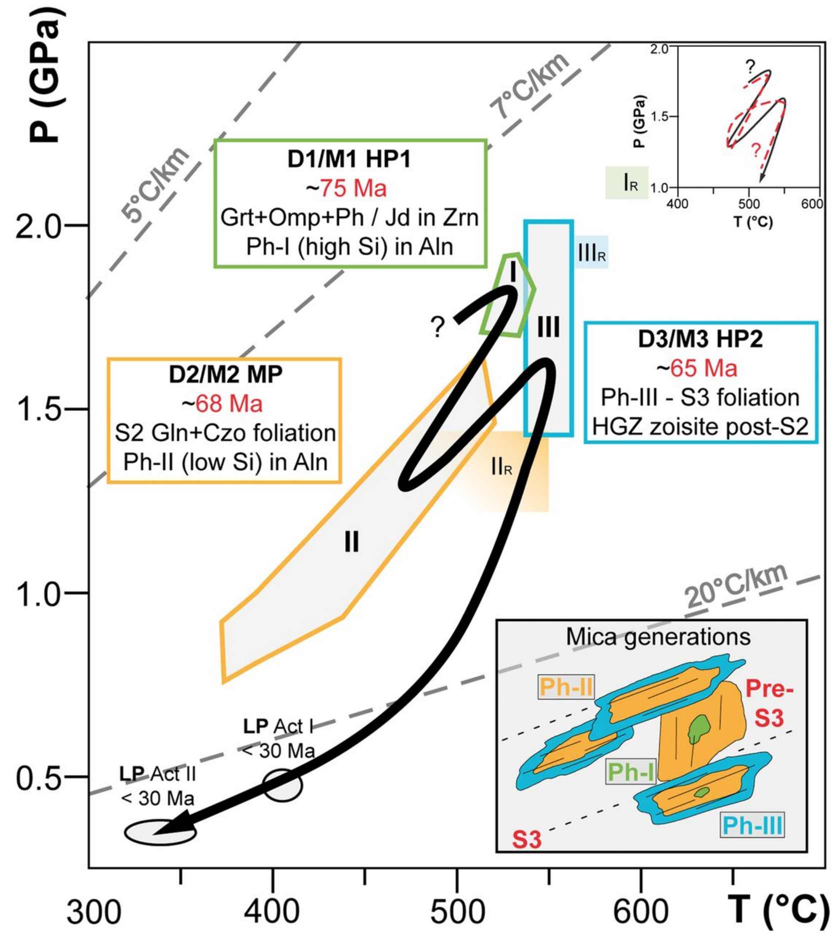
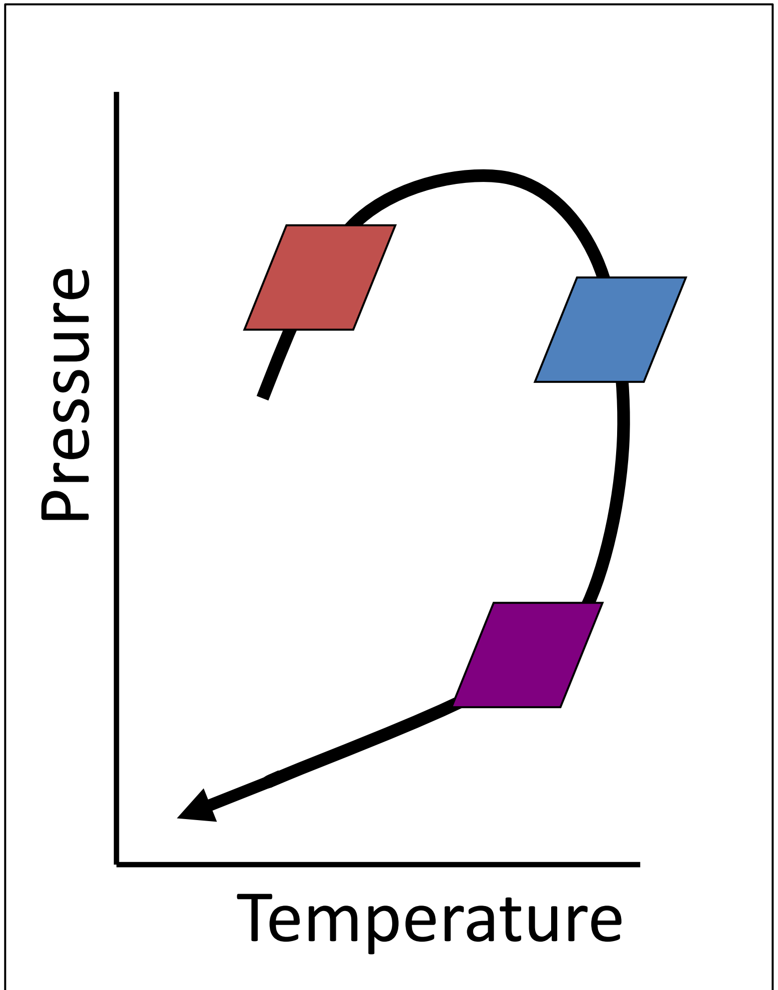


Image: Rubatto et al., 2011

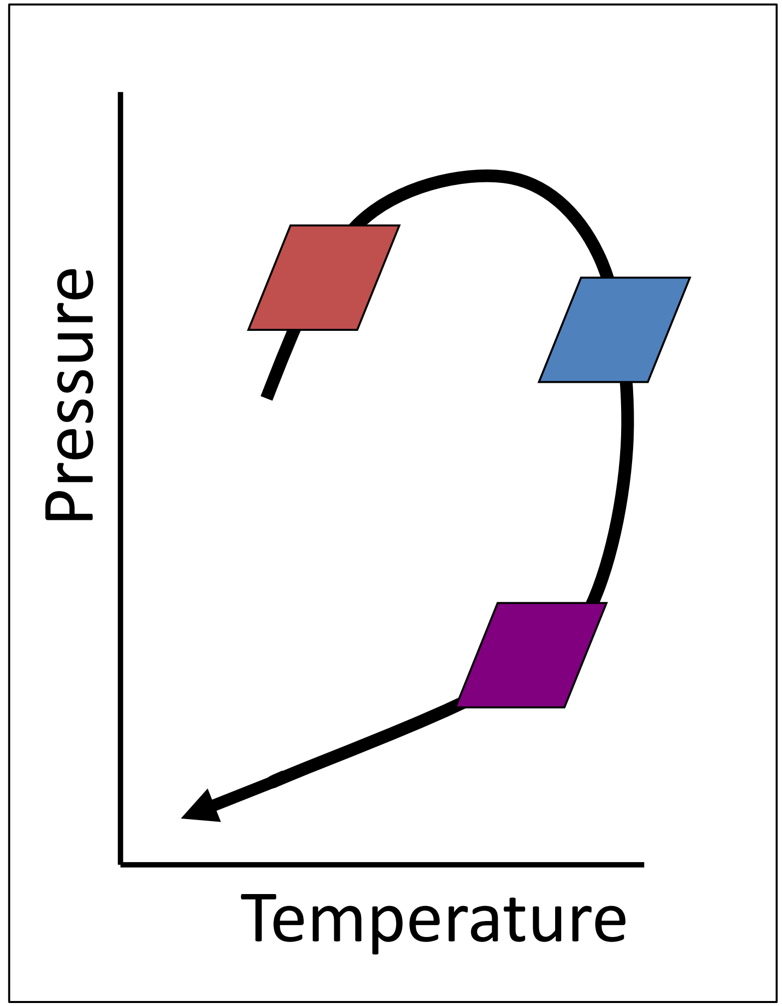
What do metamorphic Ar/Ar ‘ages’ mean?

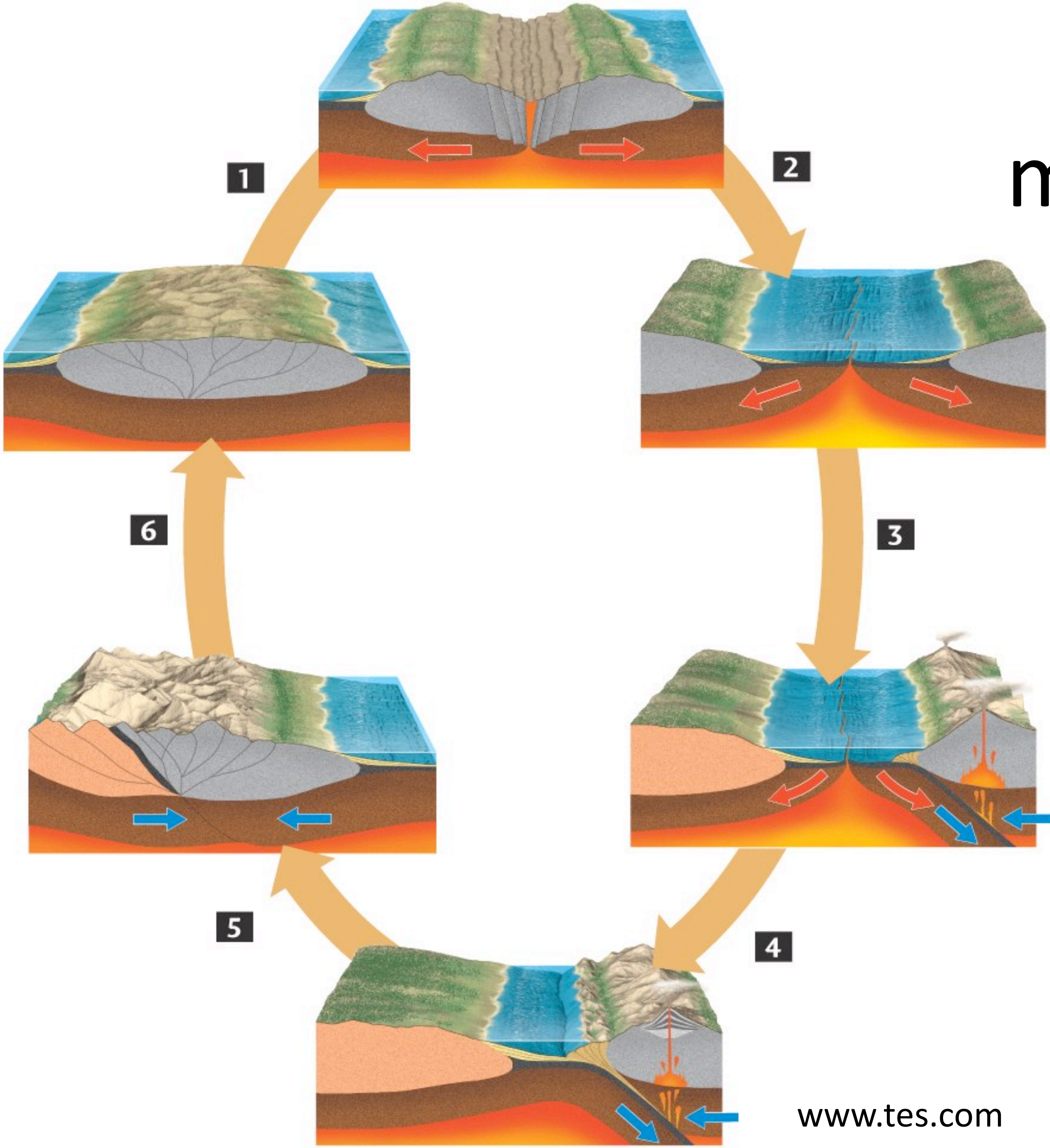


Difference between a date and an age?

What do metamorphic Ar/Ar ‘ages’ mean?

- Crystallisation?
- Cooling?
- Contamination?
- Effect of geologic process(es)?
- Combination?





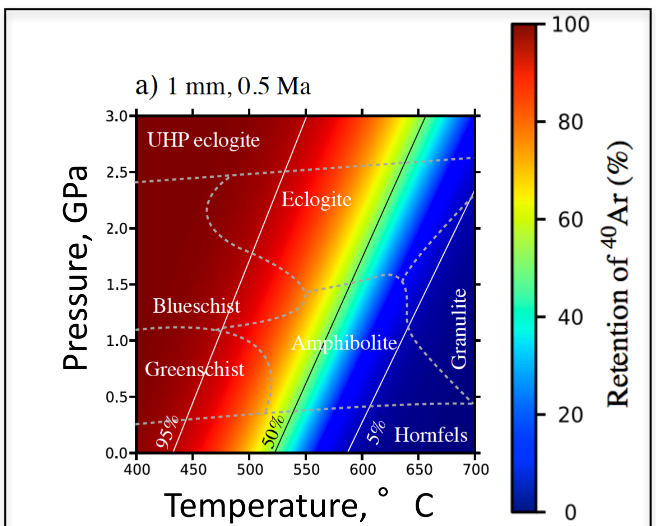
Two main metamorphic scenarios

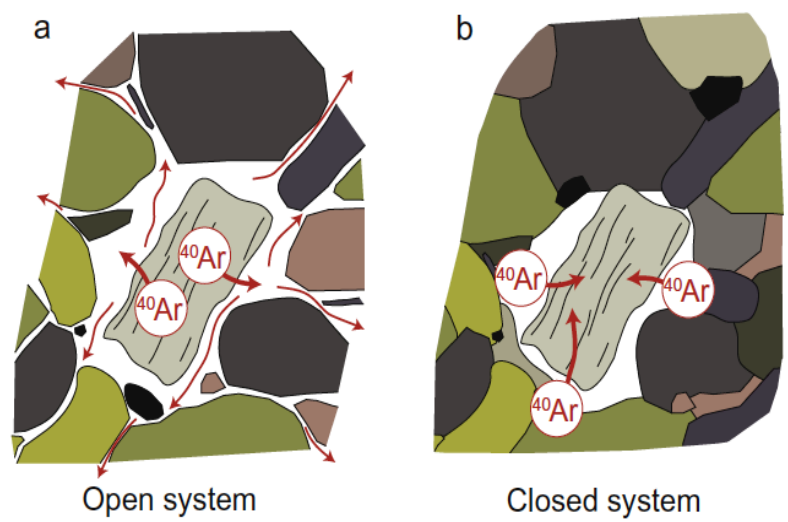
- Subduction zones
- Continental collision

www.tes.com

Thermochronometer considerations

- Temperature high enough for long enough for efficient diffusion?
- Efficient removal via grain boundary network?





How might you test/check for these approximations?

activity TIME

- No initial Ar in grain
- Thermally-activated volume diffusion
- Infinite grain boundary reservoir (open system)
- $T_{crystallisation} >> T_{closure}$

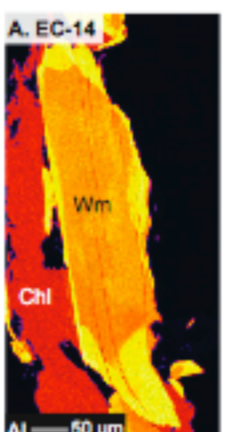
- Dependence of grain size with age
- Inverse isochrons
- Other age framework?
- Geological “sense”?

The metamorphic $^{40}Ar/^{39}Ar$ recipe book

1. Mineral history
2. Diffusion efficient?
3. Collect $^{40}Ar/^{39}Ar$ data
4. Compare data with models
5. Interpret the results

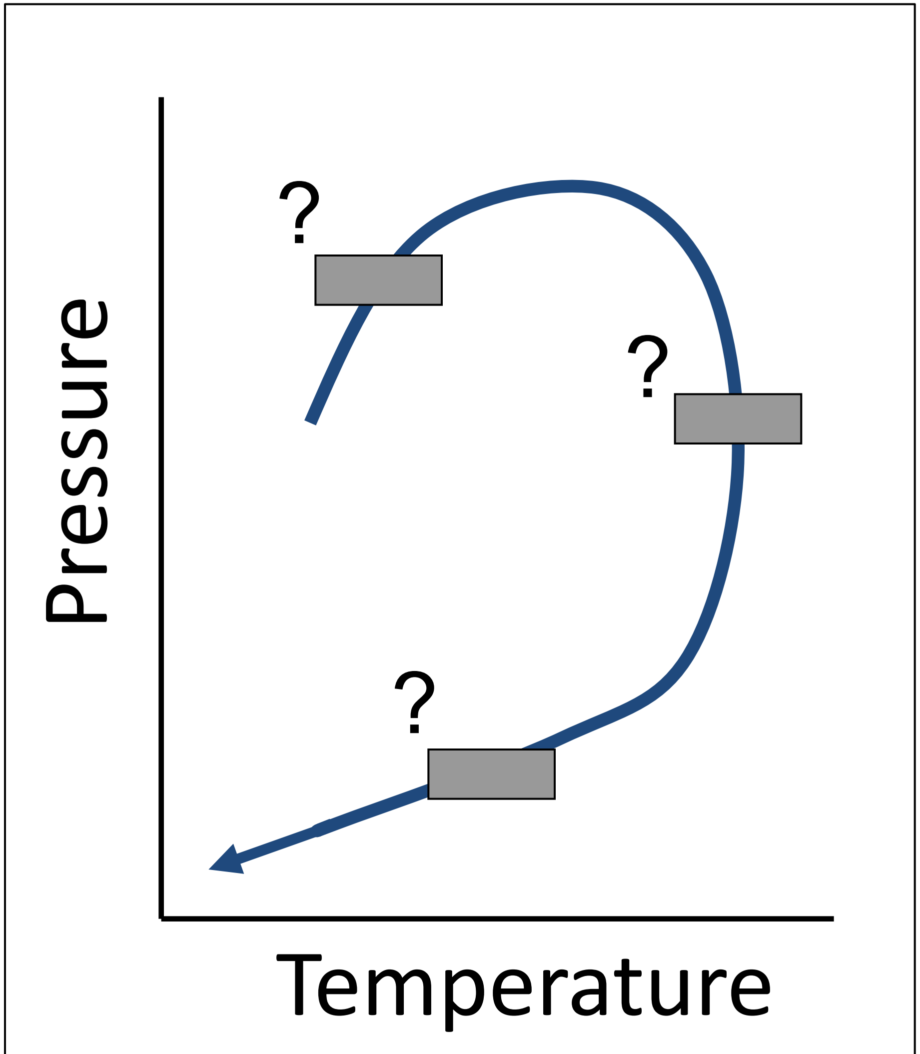
Yes?
Diffusion profiles?

No?
Crysallisation ages?
Or….
Contamination?
Lithological control?



E. Cosette

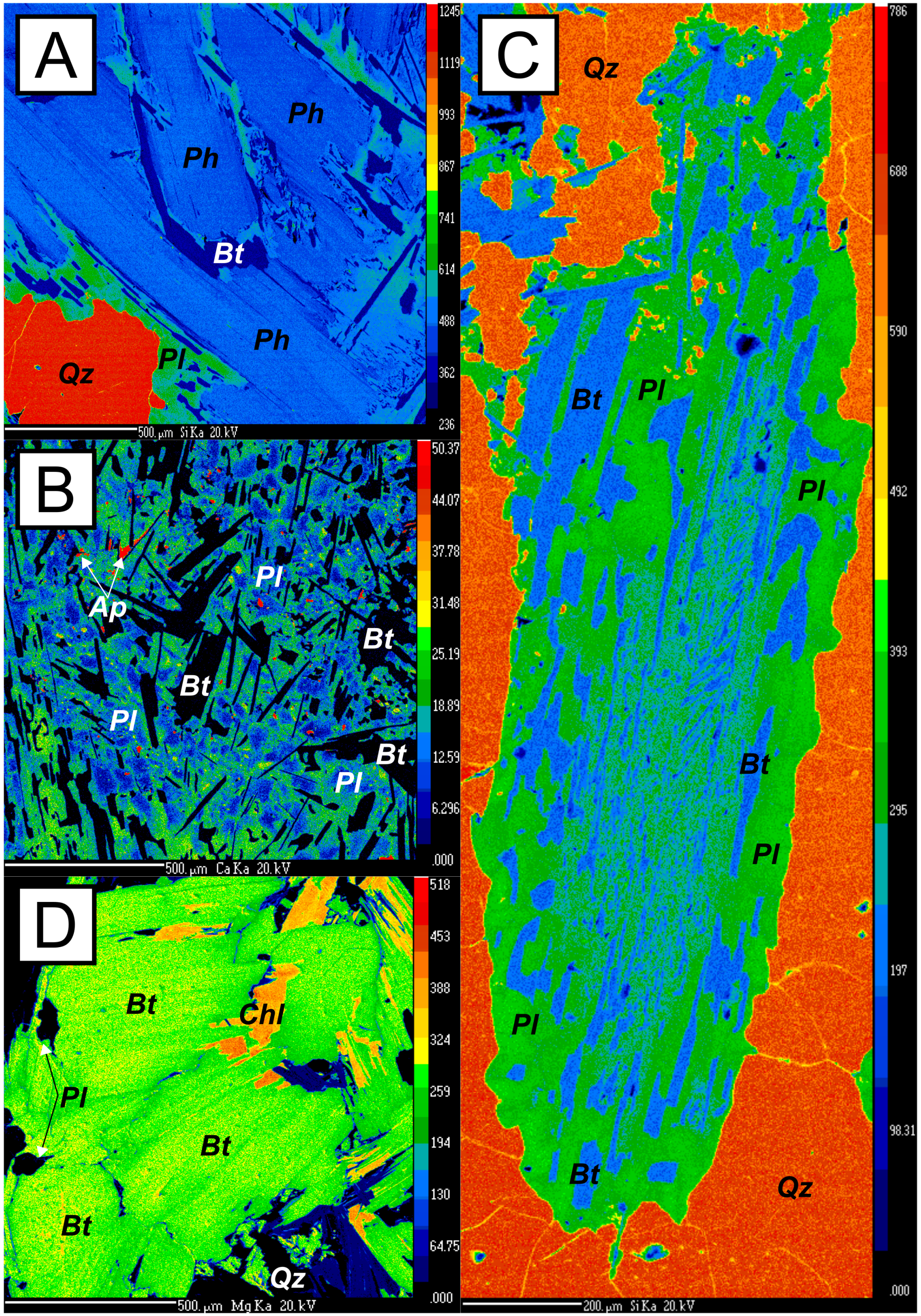
Efficient diffusion conditions?

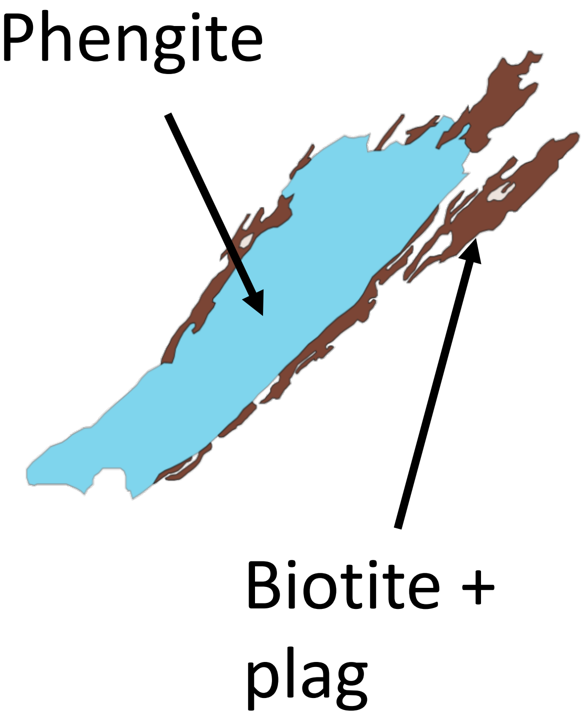


PT conditions of mica growth? (petrography, chemistry)

Did it ever experience conditions for efficient diffusion?

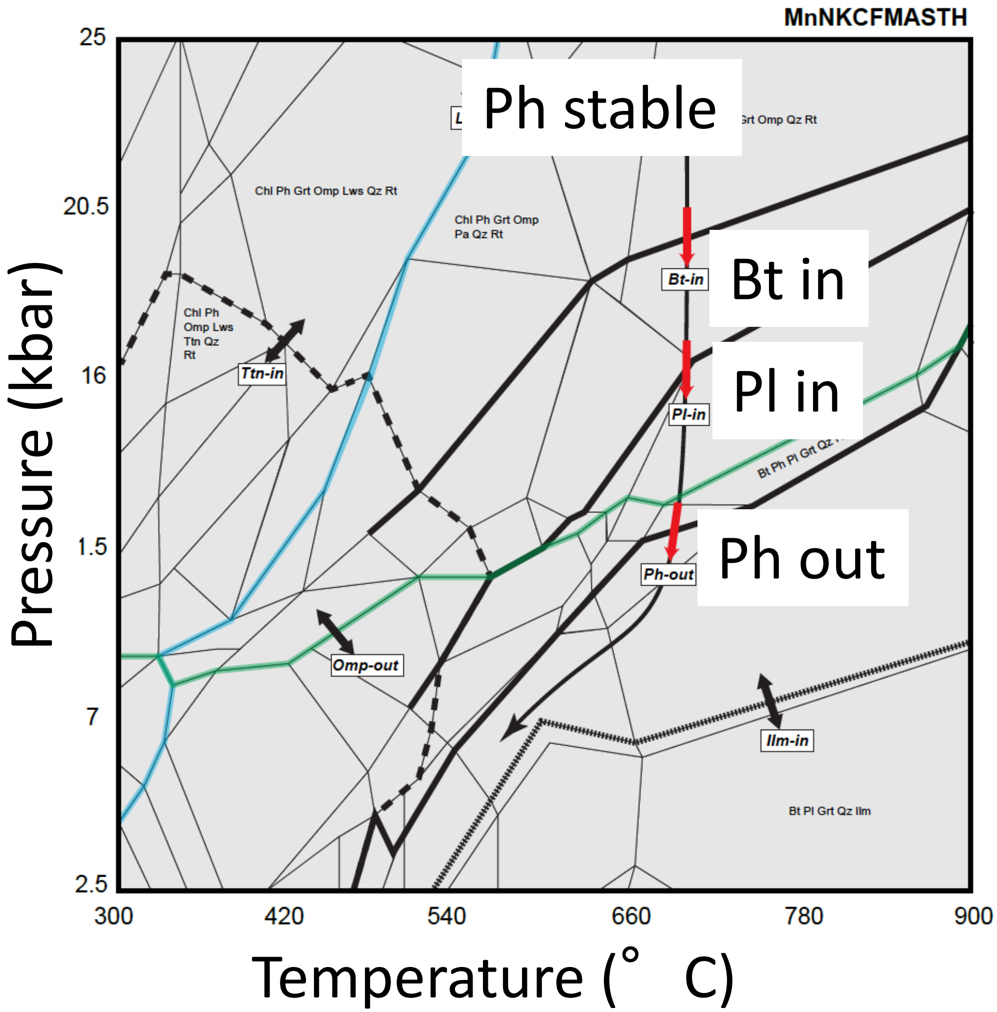
PT framework

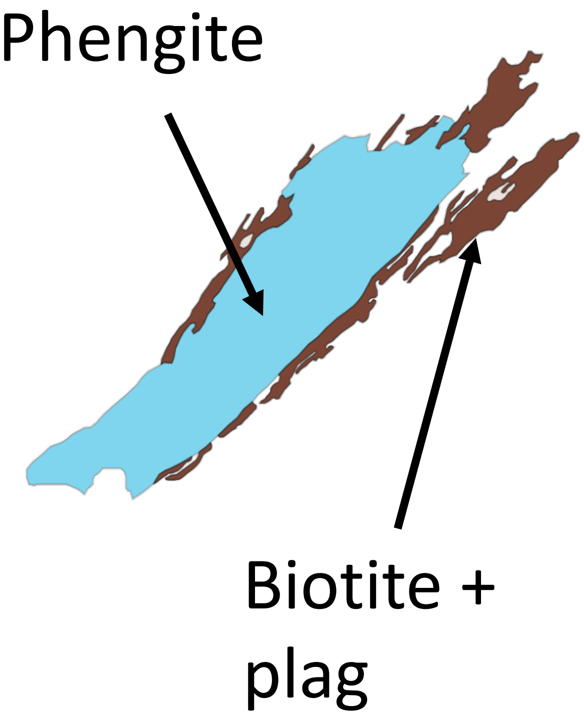




McDonald et al., in review

PT framework





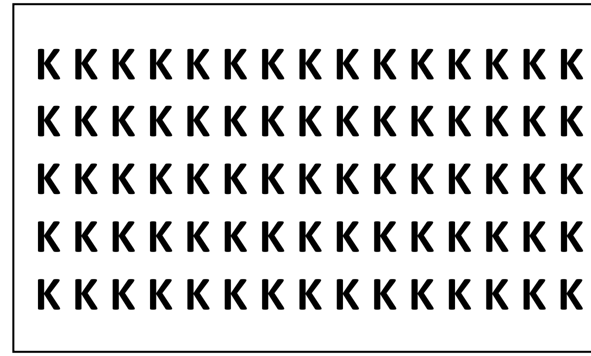
McDonald et al., 2016

Numerical solutions to the diffusion equation

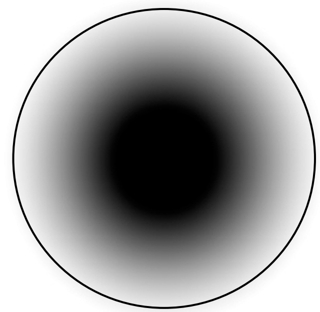
$$\boxed{\frac{\partial c}{\partial t} = D\nabla^2 c + S}$$

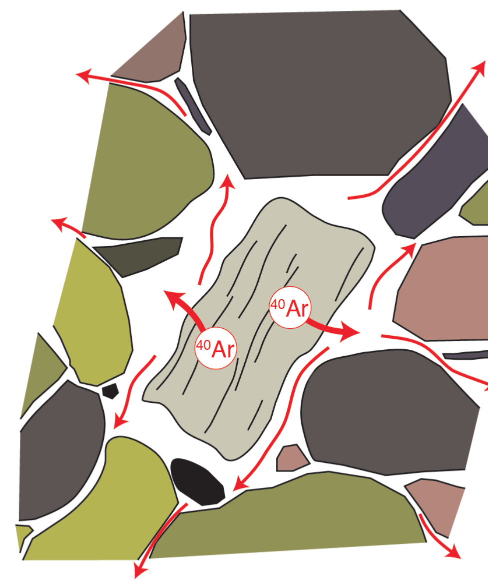
DiffArg: Wheeler 1996 (plots grain age profiles)
MacArgon: Lister 1996 (plots step-heat profiles)

Important: Models based on same assumptions



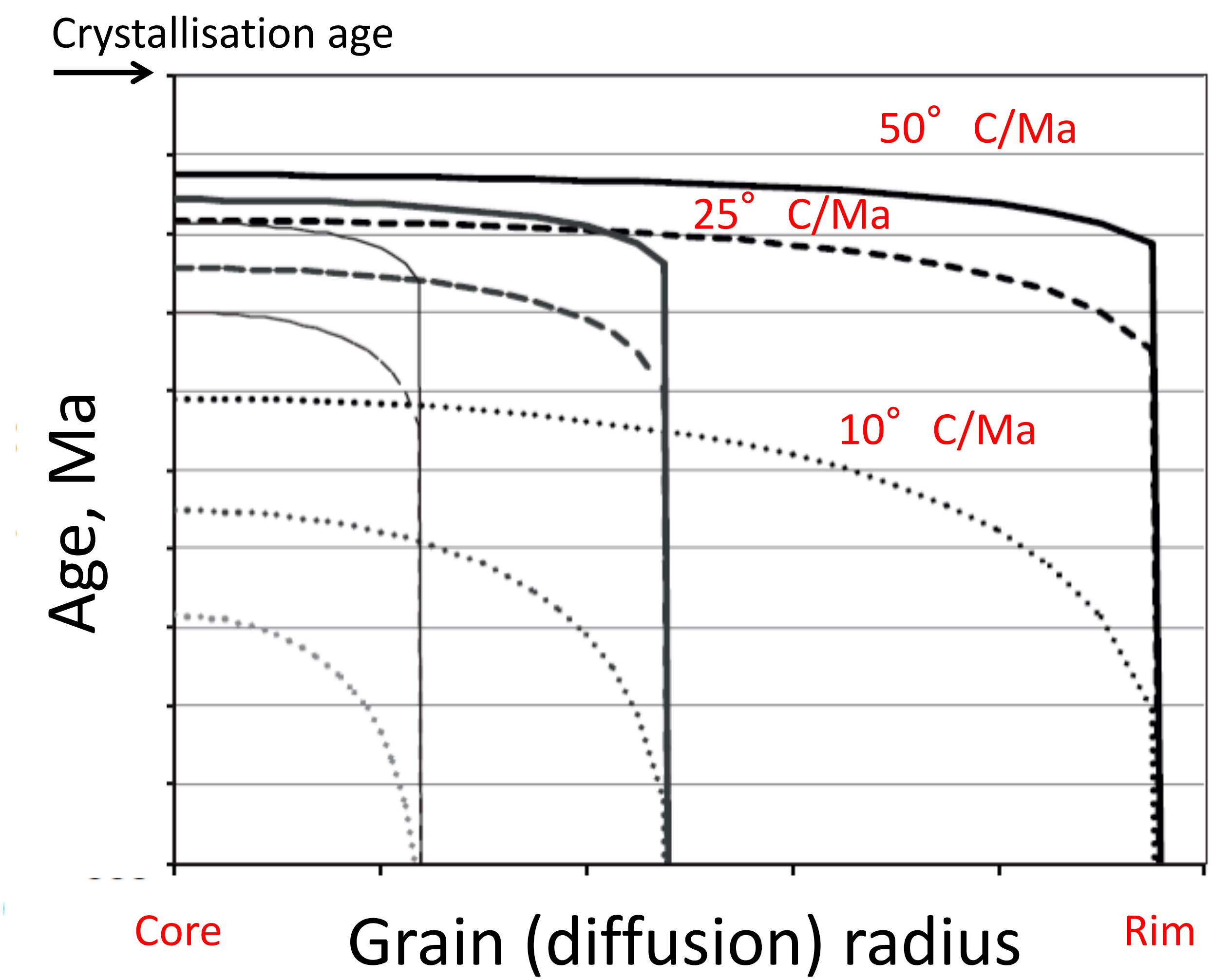
- No initial Ar in grain (but can model)
- Thermally-activated volume diffusion
- Open system (but can model)
- Can model from any temperature





A. Smye

Calculate Ar loss



Thermal diffusion:

Curved core-rim profile

Younger ages = smaller grains

Compare calculated vs obtained profiles

Profiles calculated using Diffarg (Wheeler 1996) for Ar in muscovite and Harrison et al., 2009 diffusion parameters

Diffarg

activity TIME

Wheeler, 1996, modified by Warren et al., to include:

Updated diffusion parameters,
Different minerals,
Incorporation of pressure-dependence (mus, bt)
Modelling 1/T shape cooling paths

Diffarg

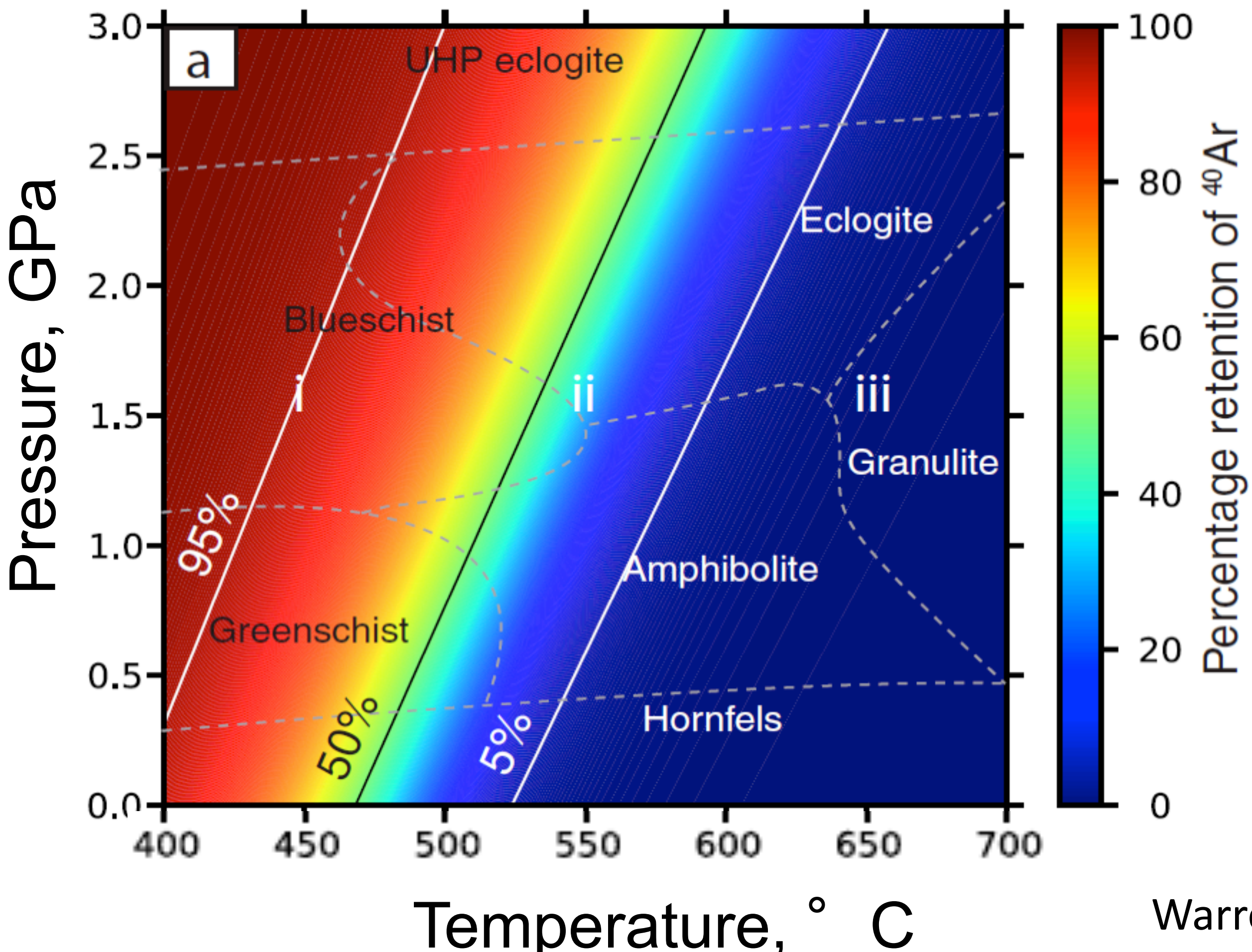
activity TIME

Predict the age of the following grains:

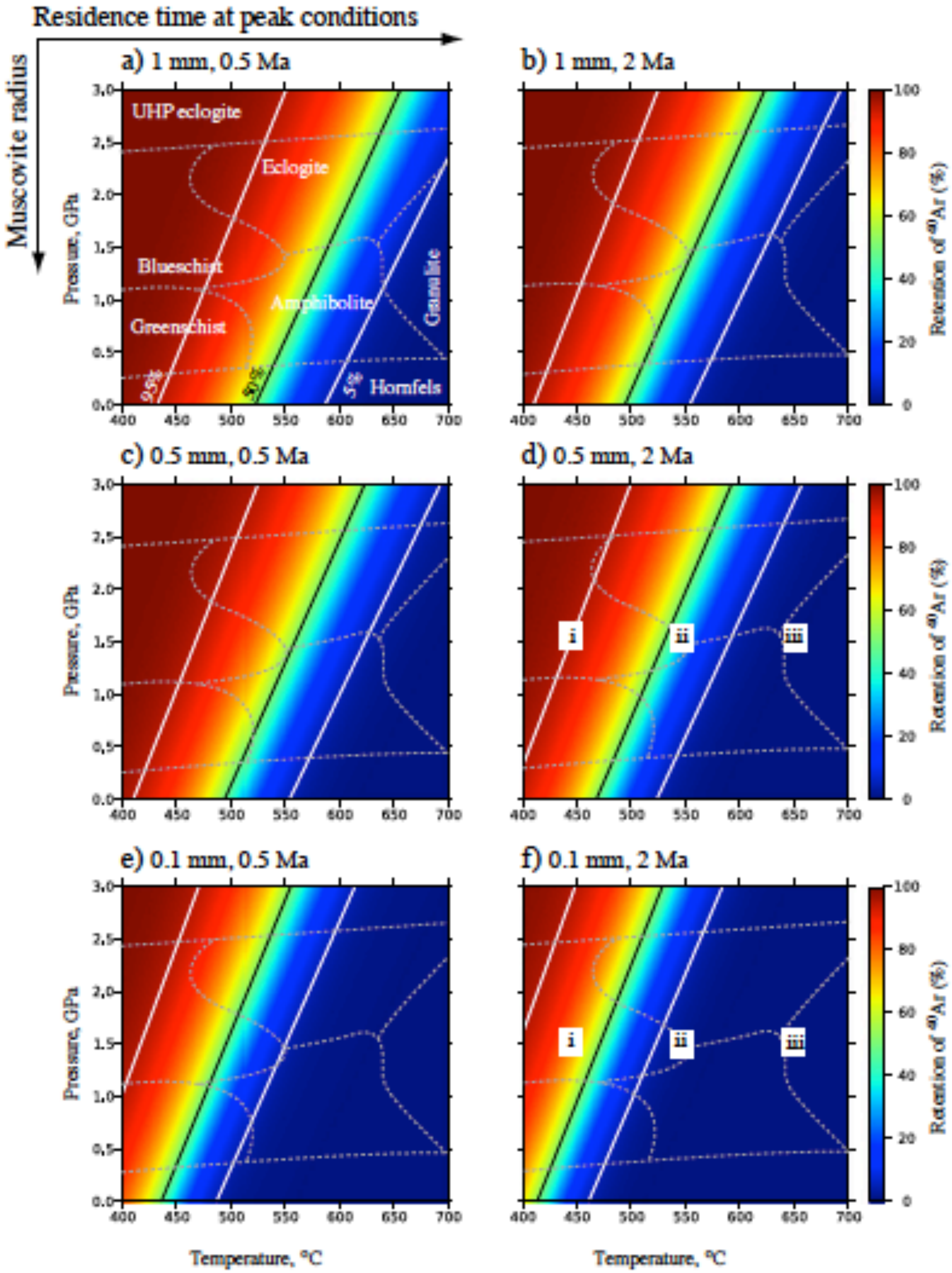
Mineral	Starting T, deg C	Constant P, GPa	Cooling rate, deg C/ Ma	Age?
Mus	600	1	1	
Bt	600	1	1	
Plag	600	1	1	
K-fsp	600	1	1	

Ar retention (muscovite) for the experienced peak PT

1mm grain, held for 0.5 Ma



Warren et al., 2012, Chemical Geology



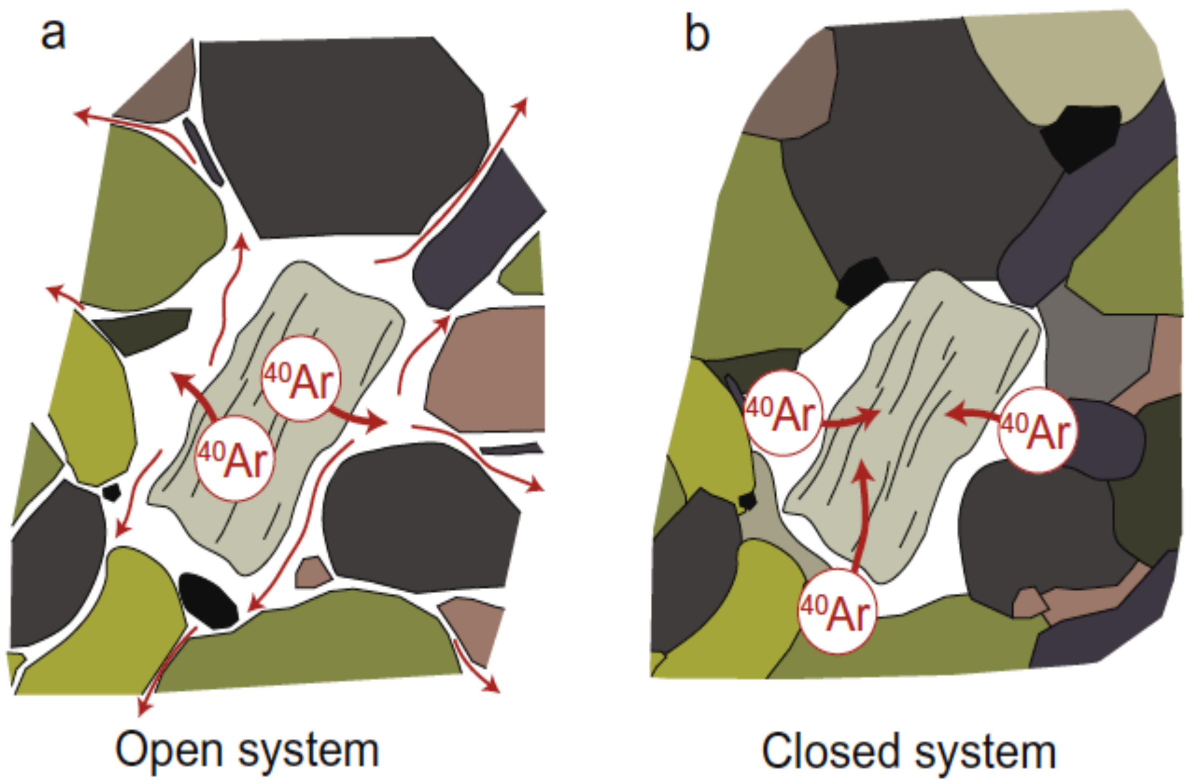
For peak PT and length of time:, how efficient was diffusion?

Red zone: never yield cooling age

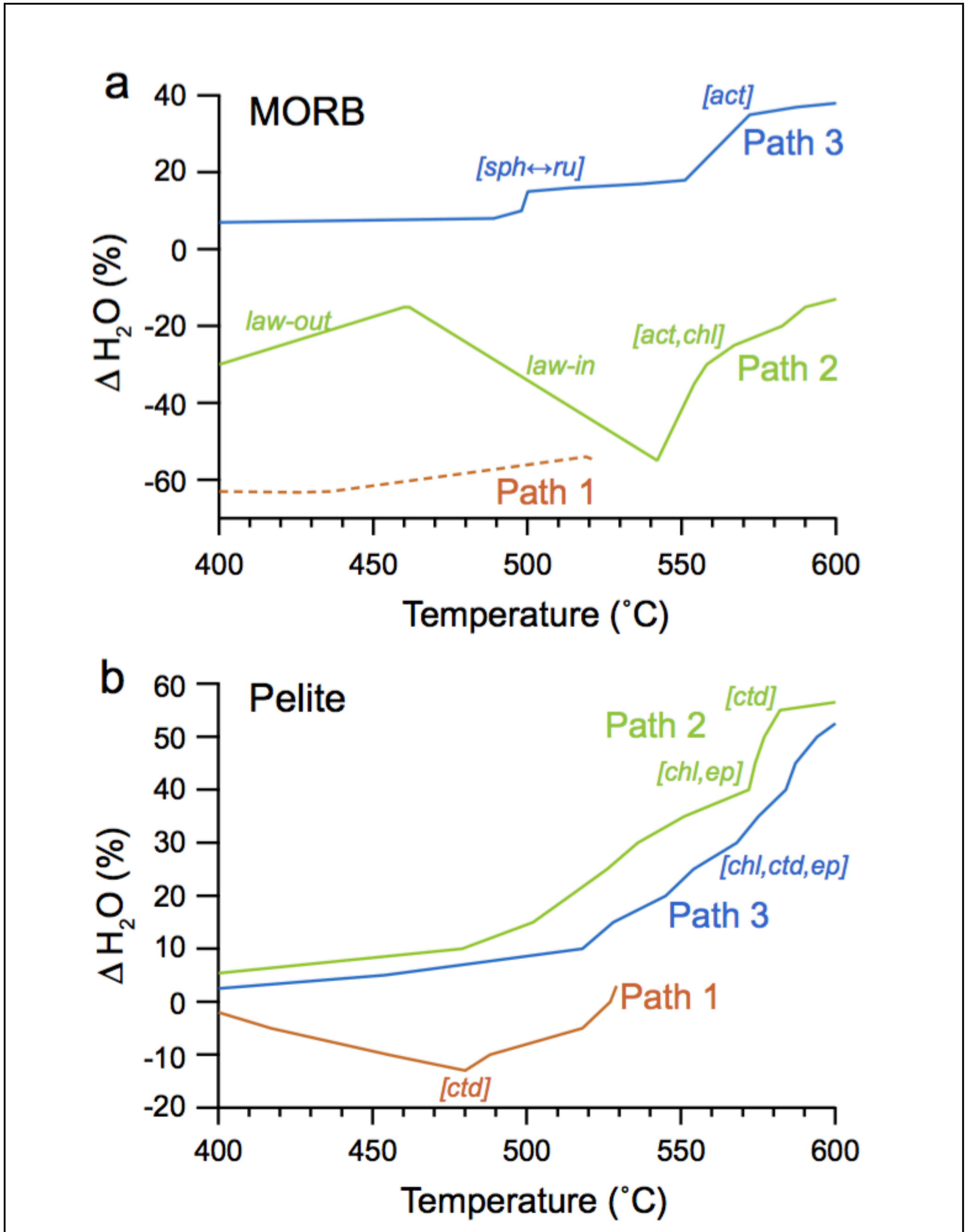
Blue zone: might

Warren et al., 2012, Chemical Geology

Open and closed systems



- Fluids
- Rheology



When are fluids released during metamorphism?

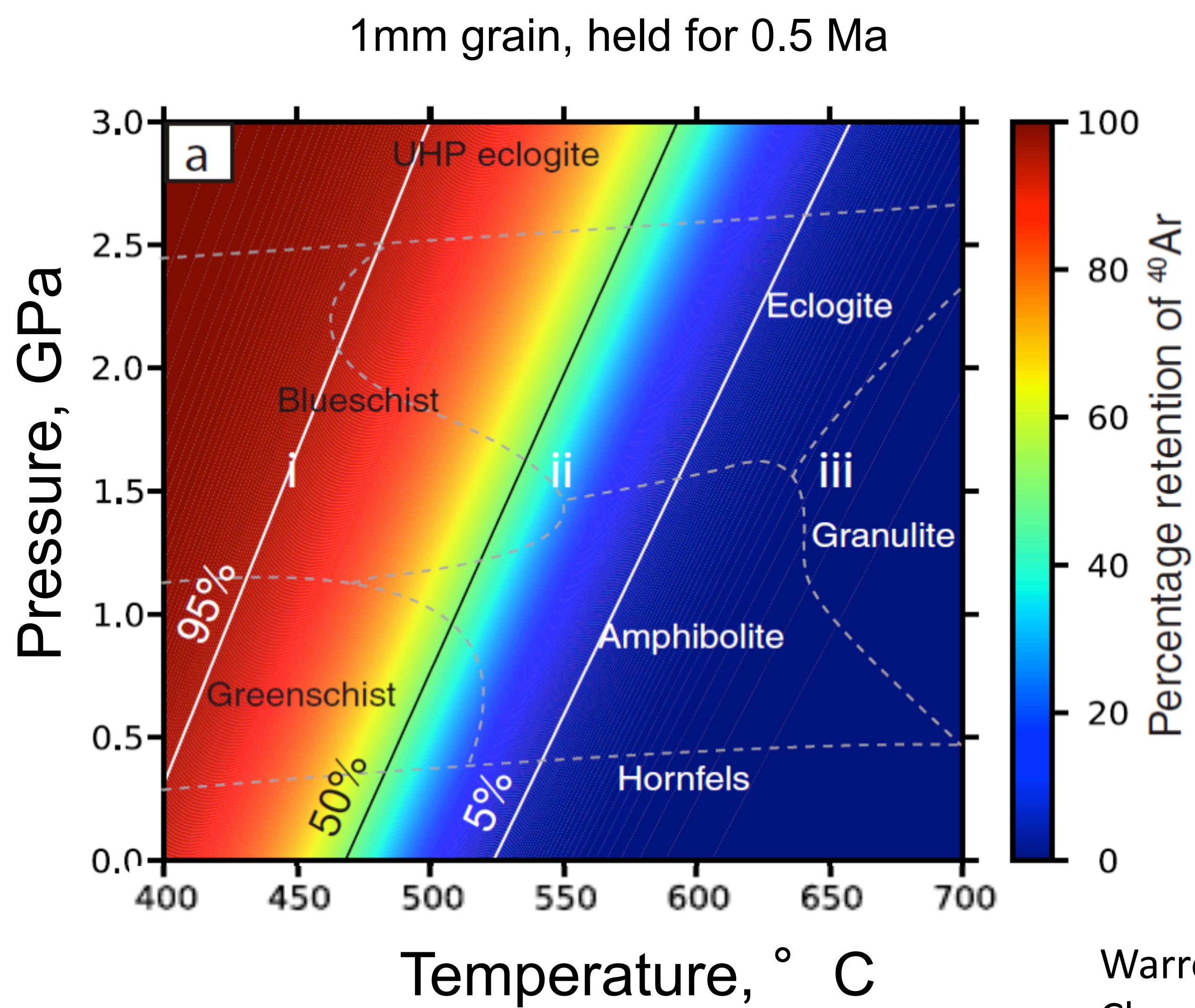
Smye et al., 2013

Cyclades, <400° C

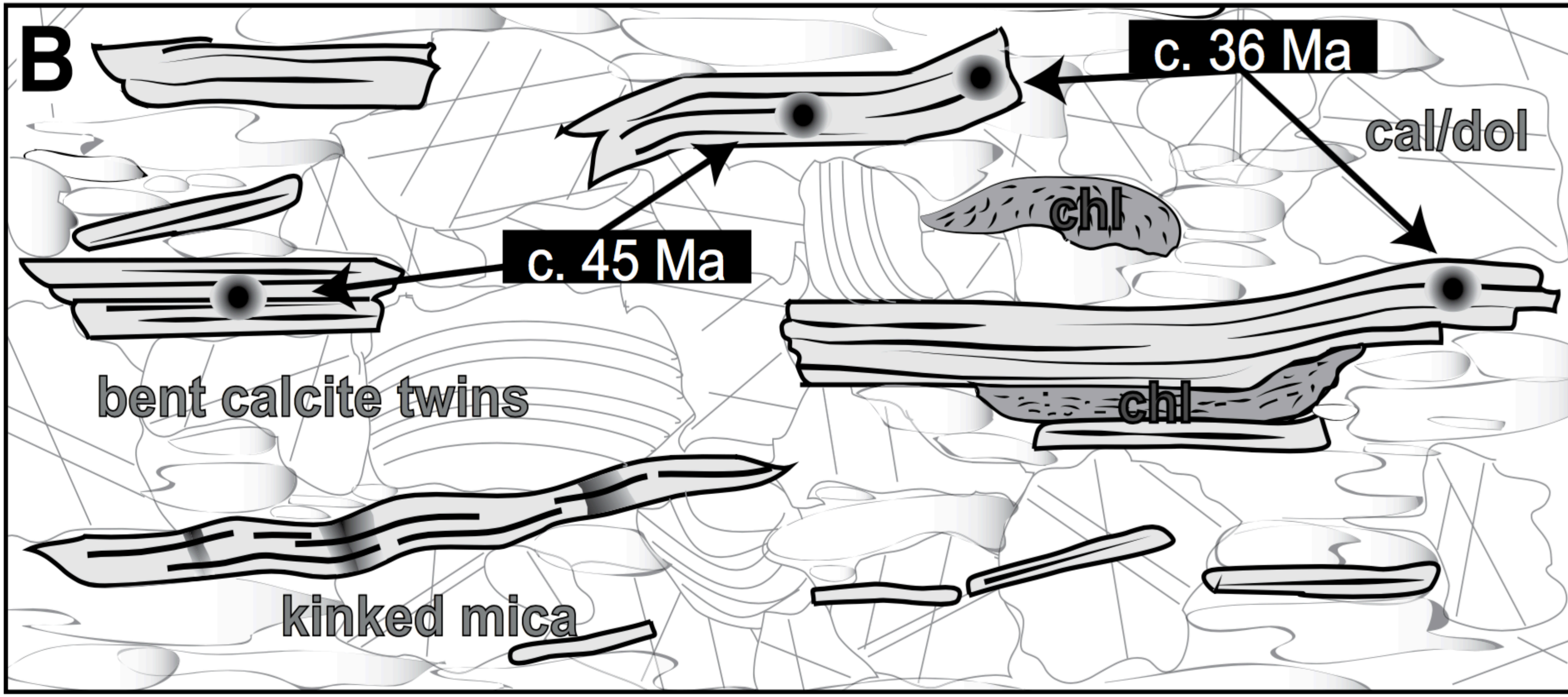
Cyclades: low angle normal fault systems
Kea and Serifos

Cossette et al., 2015

Ar retention for the experienced peak PT

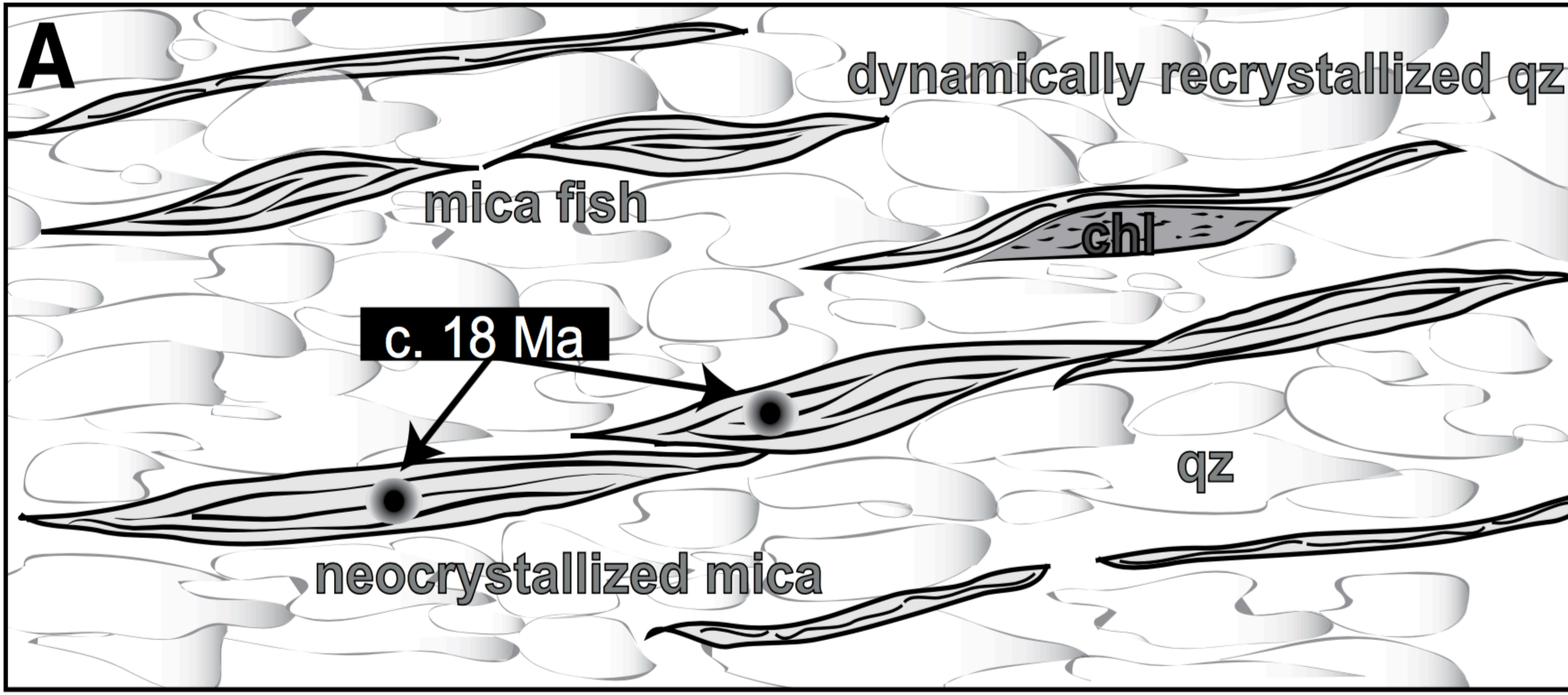


Warren et al., 2012, Chemical Geology



Calcite-rich rocks. 45-36 Ma micas
(Eclogite U-Pb zircon age ~45-50 Ma)

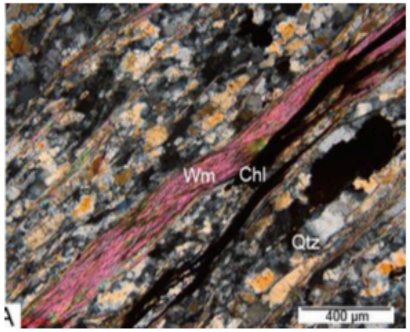
Cossette et al., 2015

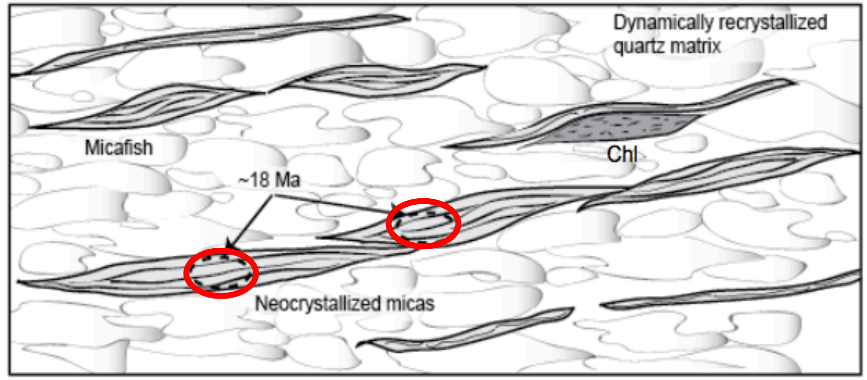


Quartz-rich rocks. 18 Ma micas

Cossette et al., 2015

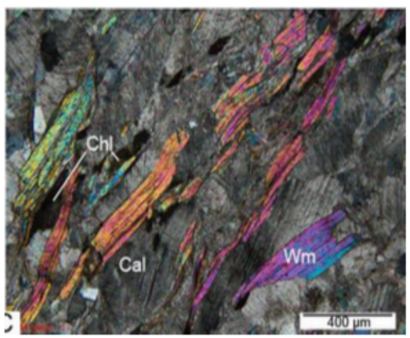
Quartz-rich rock

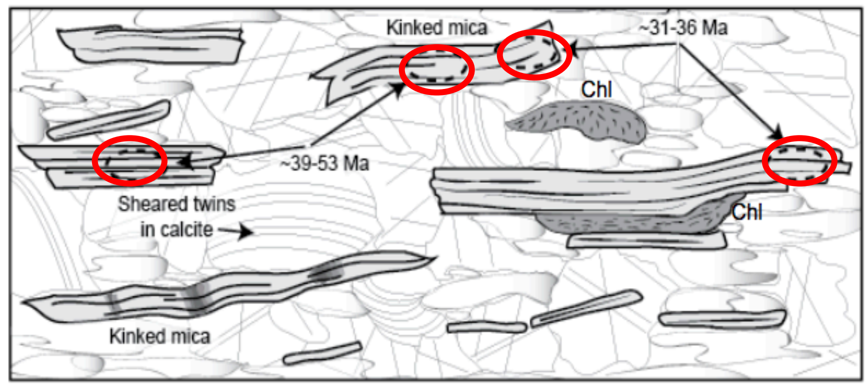




Quartz = strong; micas = weak

Calcite-rich rock



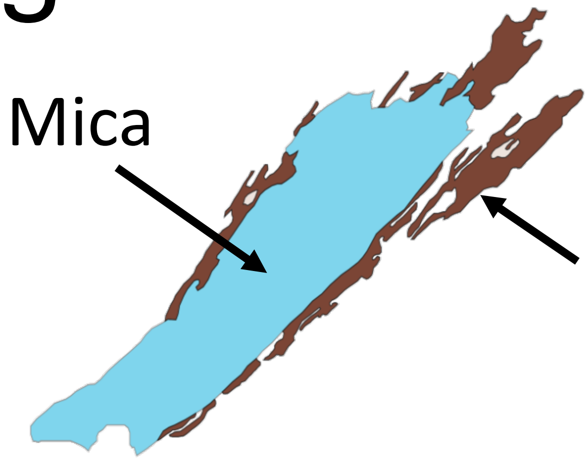


Calcite = weak; micas = strong

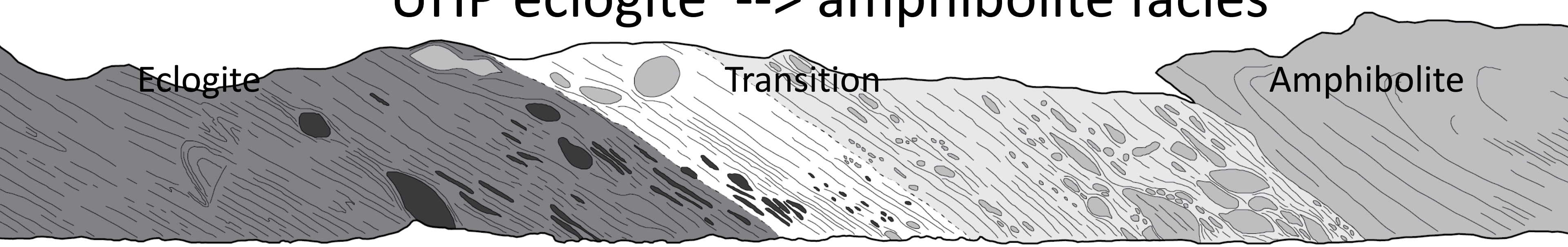
Cossette et al., 2015

‘Hot’ systems: >600° C
Ar recycling during exhumation

~700-750°C,
27-10 kbar



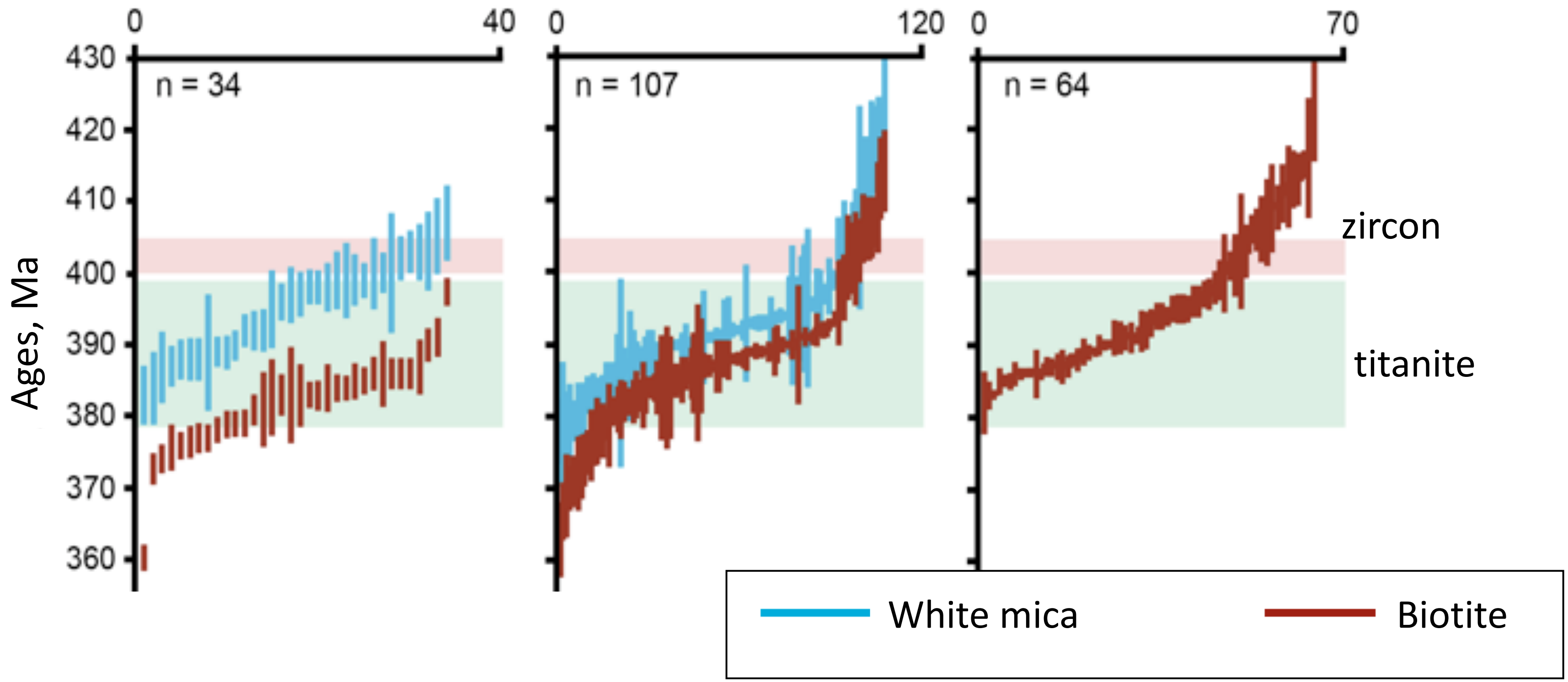
UHP eclogite --> amphibolite facies



Same HP-HT path, different petrographic record

Chris McDonald images

Dispersion in $^{40}Ar/^{39}Ar$ data

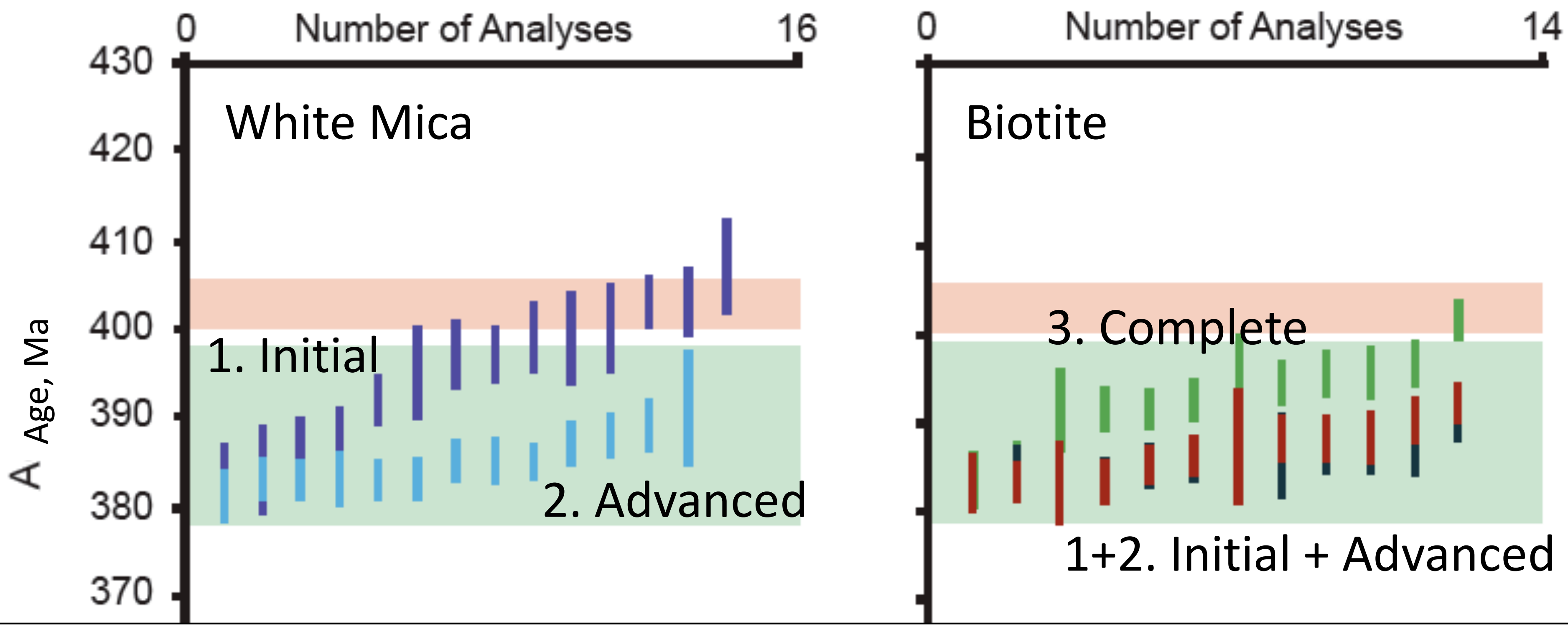


Single grain fusion, 1mm diameter grains

Caledonides: ~400 Ma. Argon ‘ages’ from 420-360 Ma

Ar: Chris McDonald PhD data; Zir: Hacker et al.; Titanite: Kylander-Clark et al.

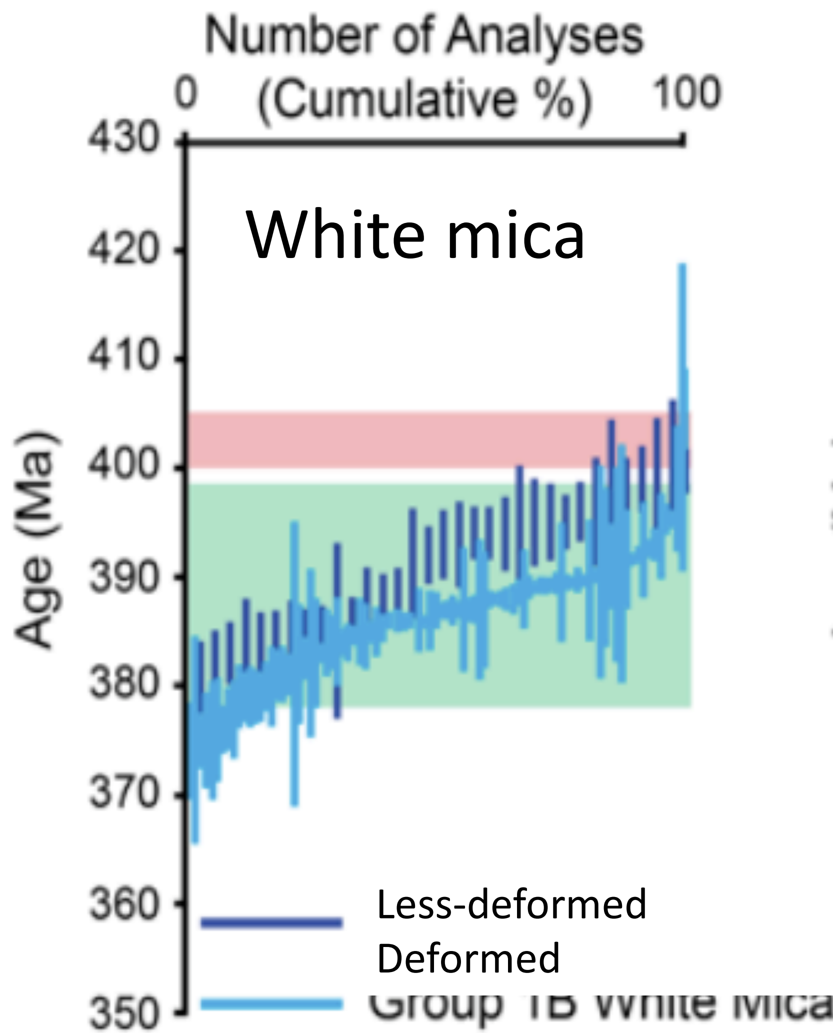
Effect of reaction completion

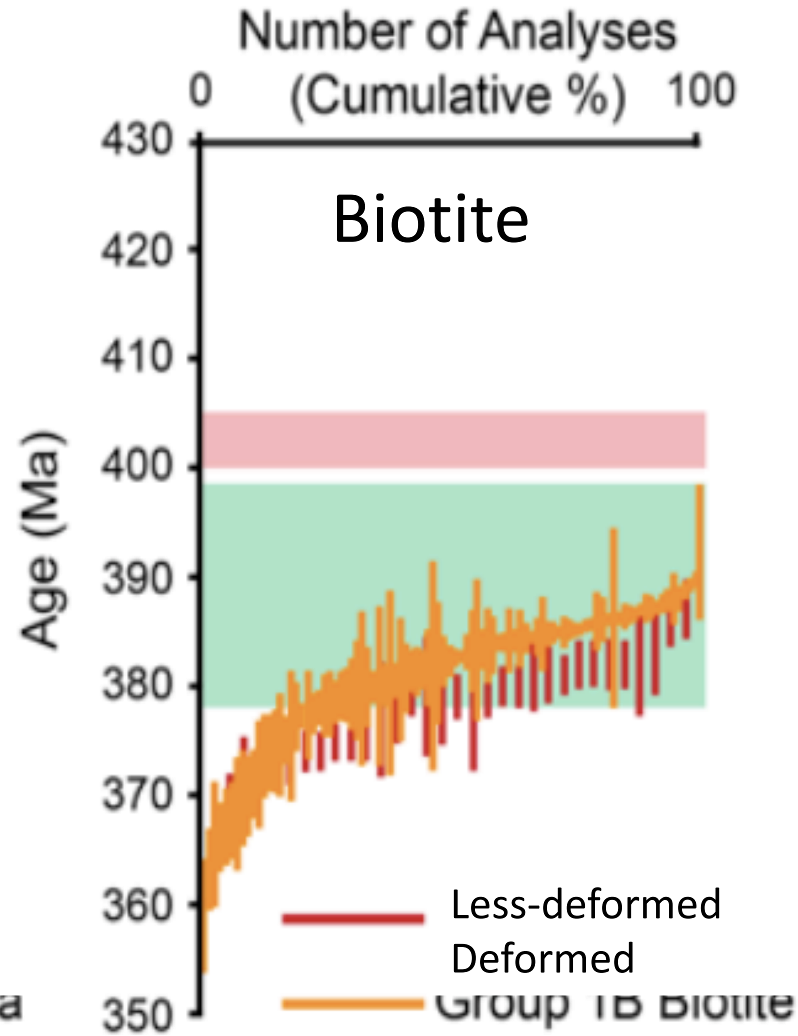


Same PT experience, different petrographic record

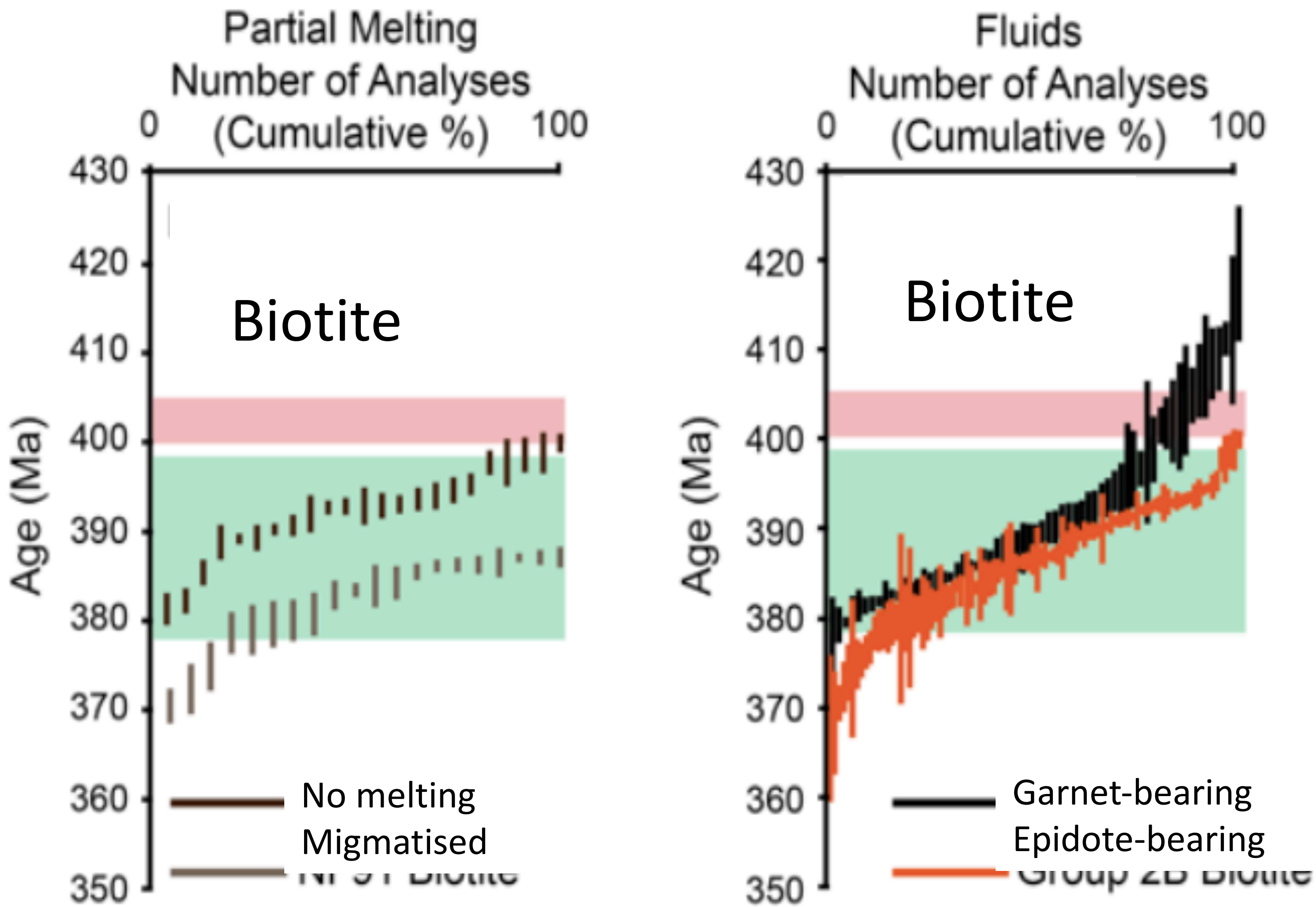
Chris McDonald PhD data

Effect of deformation





Effect of partial melting and fluids



Looking at real data

activity TIME

Work in groups of 3-4
Plot up data
Model cooling history
Compare interpretations with paper

Ar/Ar thermochronology

Dodson's "closure temperature" approximation only applicable under certain assumptions:

these are verifiable with modern tools

Compare data with models : are the ages in the range of reasonable expectation?

Dates vs Ages : do the "dates" constrain the age of a geological event?

Learning Outcomes

- You will become familiar with:
  - Thinking about assumptions underpinning diffusion theory
  - Assessing data against models

- You will be able to:
  - Carry out simple calculations using DiffArg
  - Plot up and think about data