

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

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Helsinki

24 October 2017



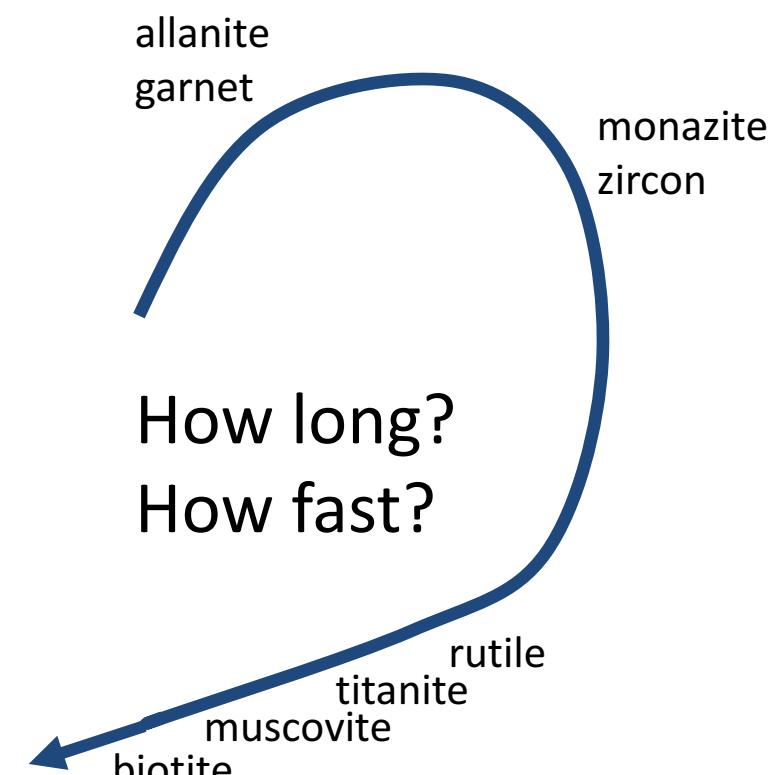
The Open  
University

# Learning Outcomes

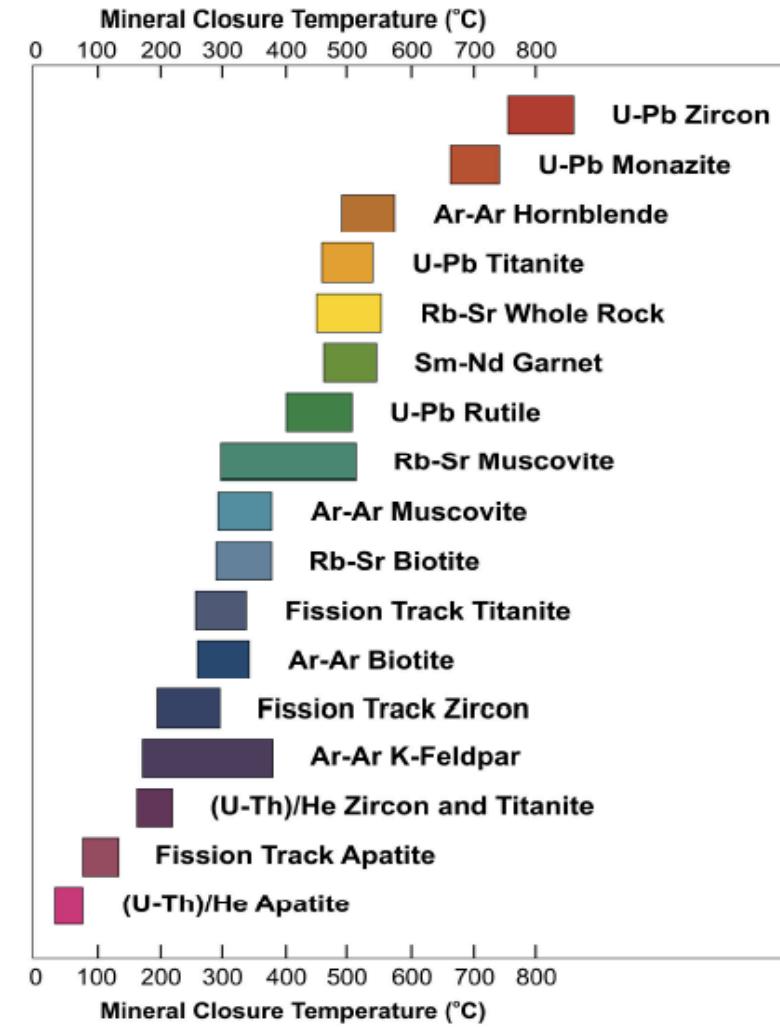
- You will become familiar with:
  - Thinking about assumptions underpinning diffusion theory
  - Assessing data against models
- You will be able to:
  - Carry out simple calculations using DiffArg
  - Plot up and think about data

# The ideal

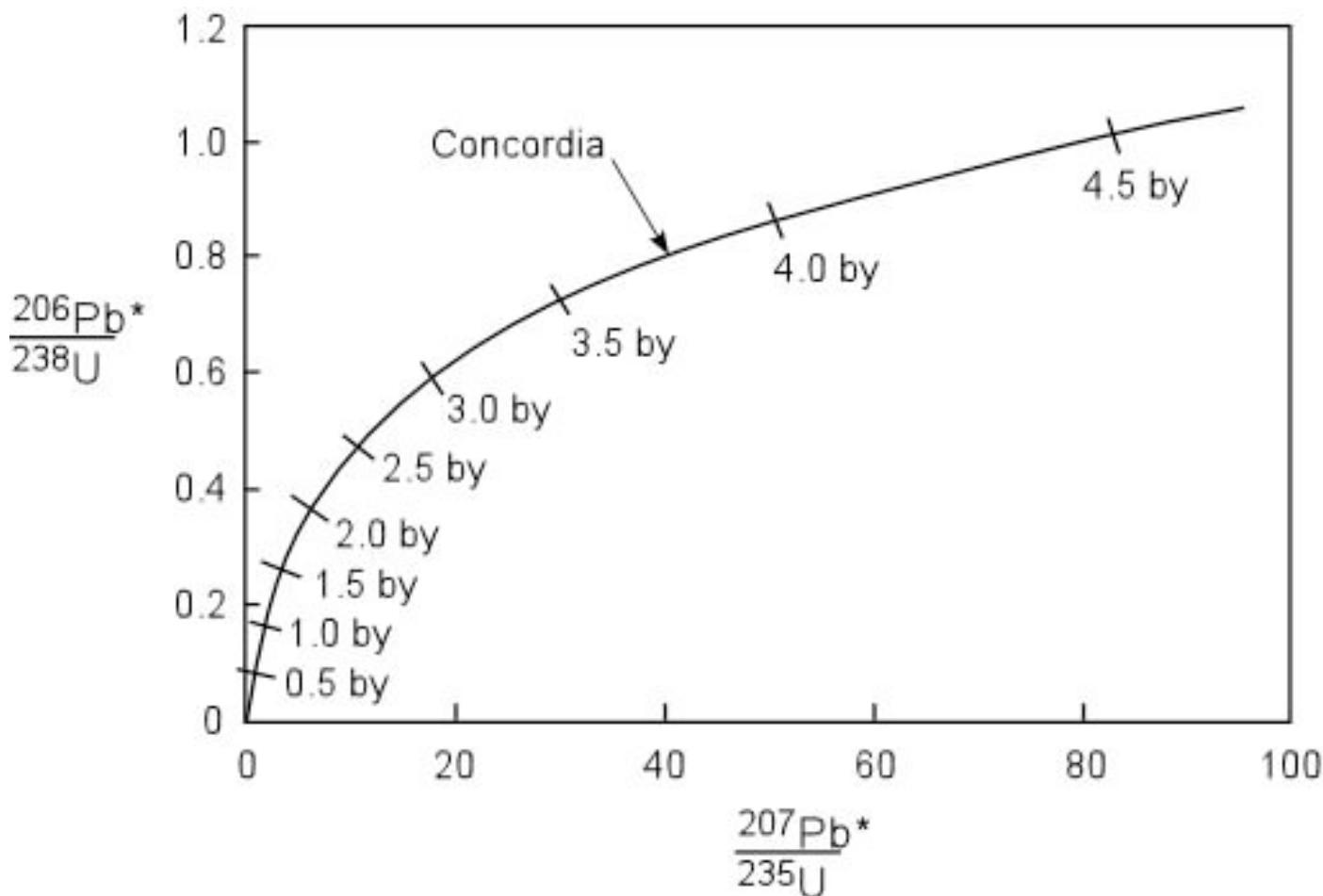
Pressure



Temperature



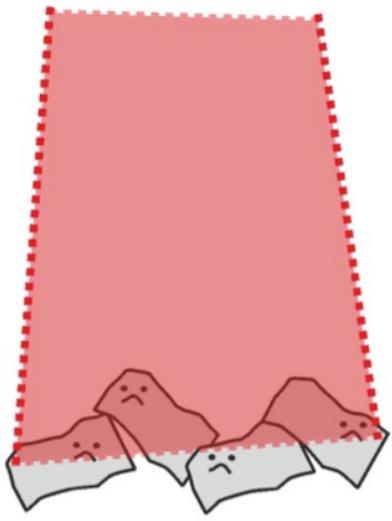
# But no internal consistency check!



Only 1  
isotope of Ar  
is radiogenic

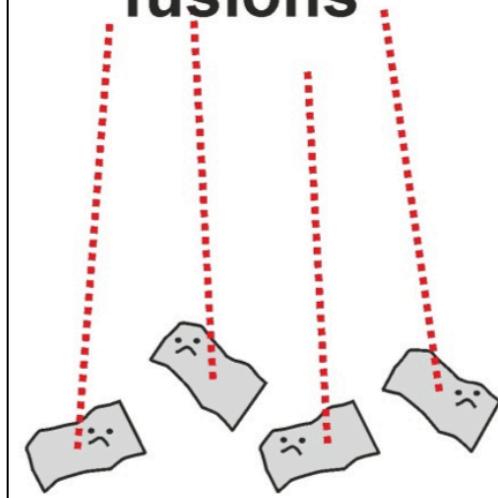
# Analytical Evolution

## Step heats



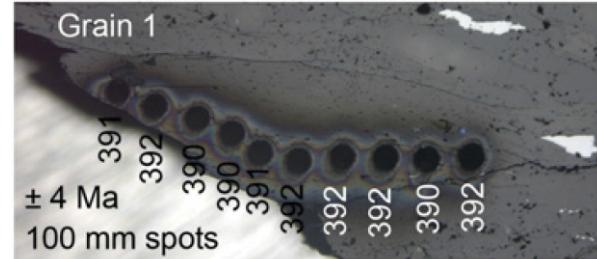
Multi-grain;  
Single grain

## Single grain fusions



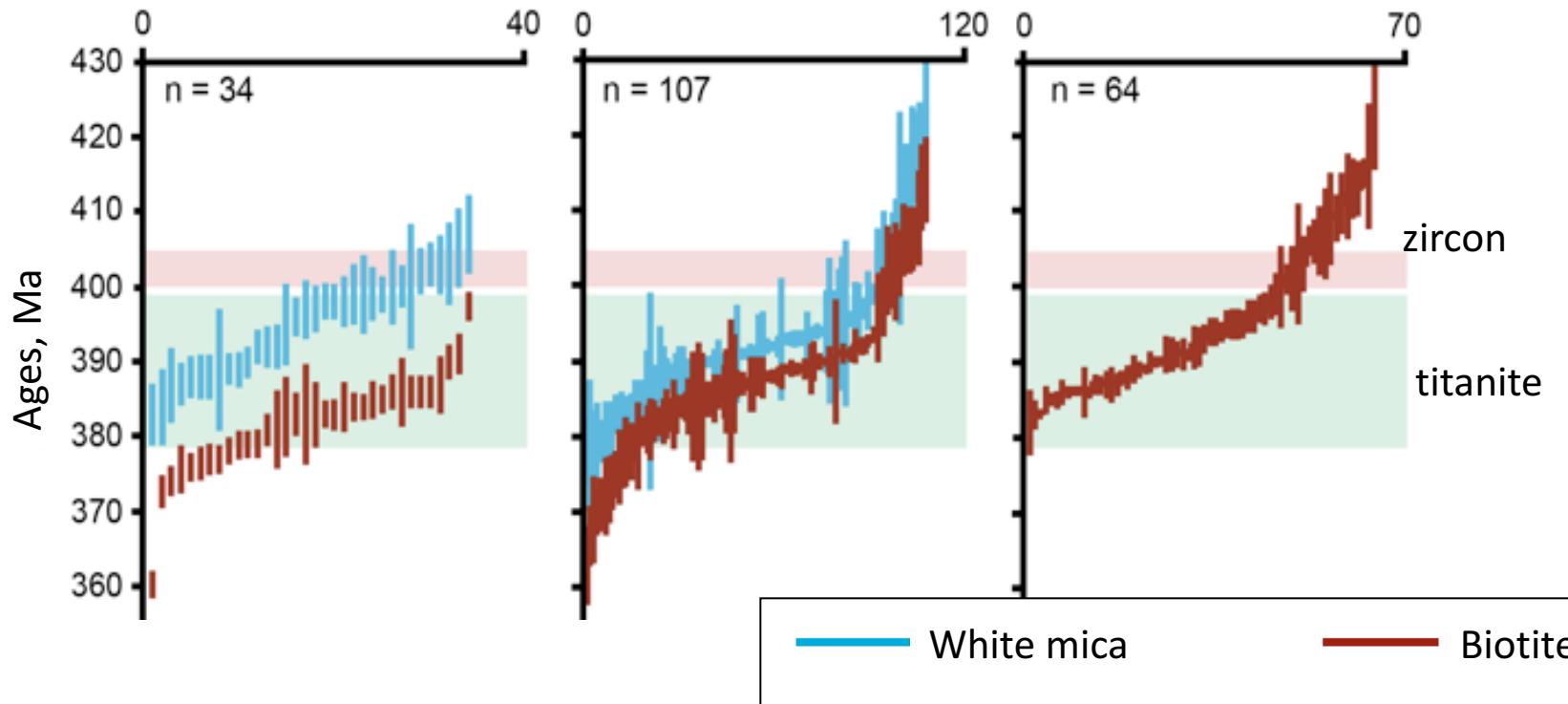
Single grain

## Laser probe



Single spot

# Dispersion in $^{40}\text{Ar}/^{39}\text{Ar}$ data

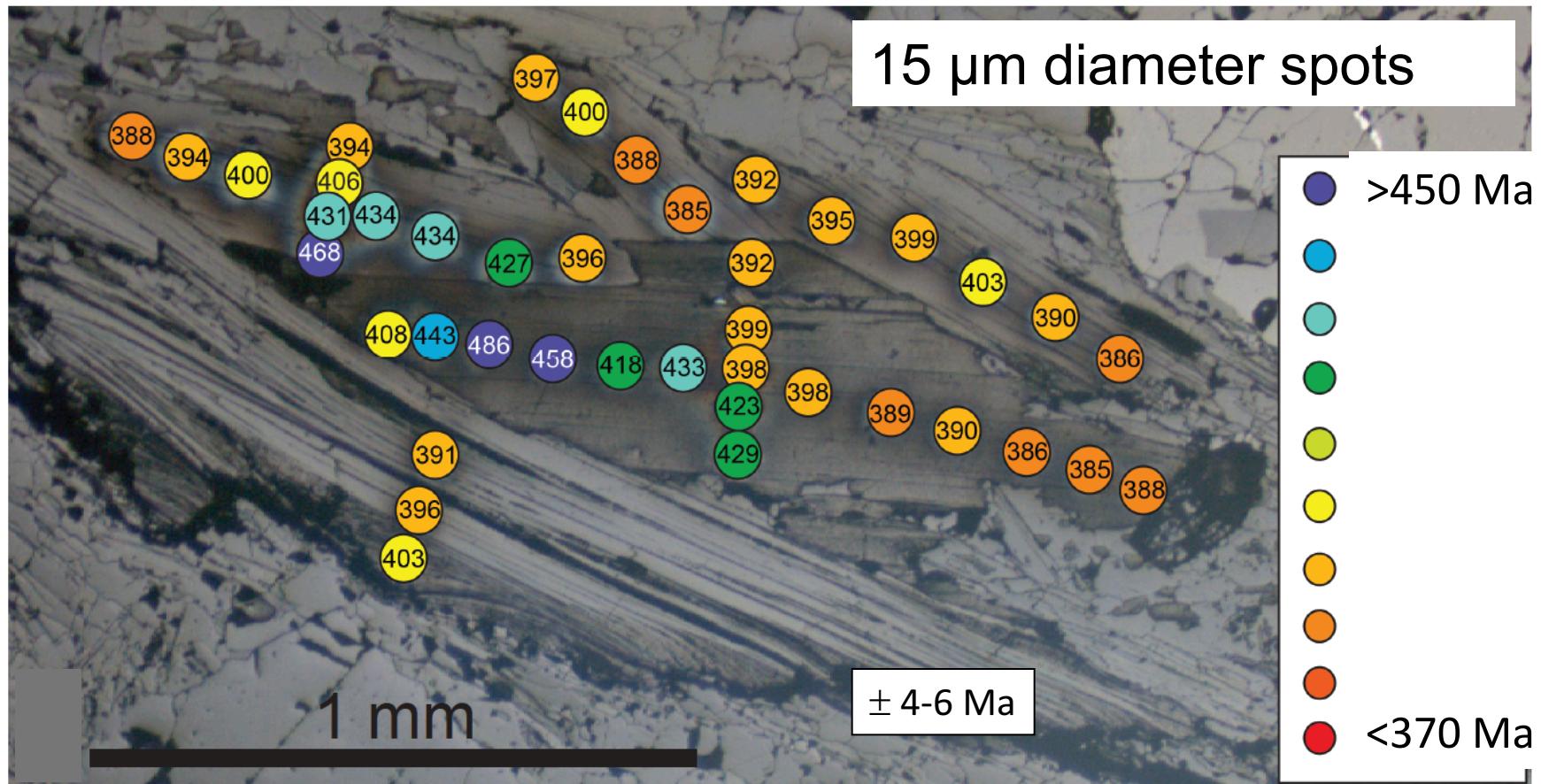


Single grain fusion, 1mm diameter grains

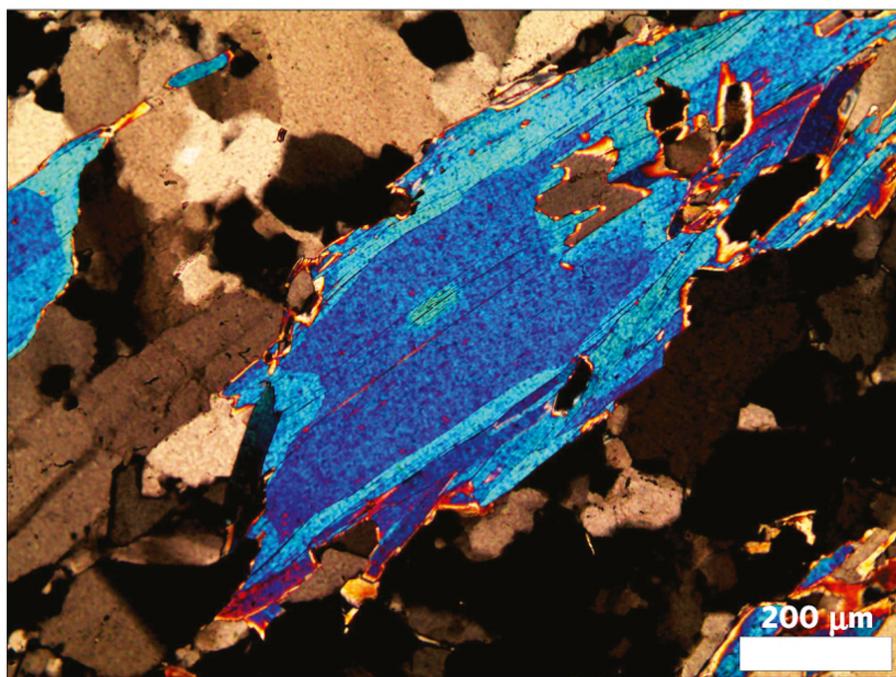
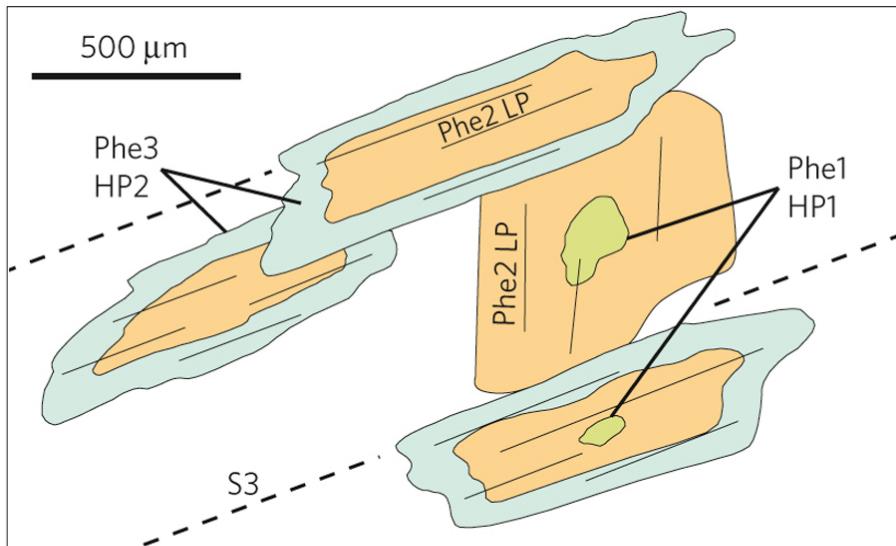
Caledonides: ~400 Ma. Argon ‘ages’ from 420-360

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

# Within-grain variability



Same spread within grains as between grains



# Mineral zoning?

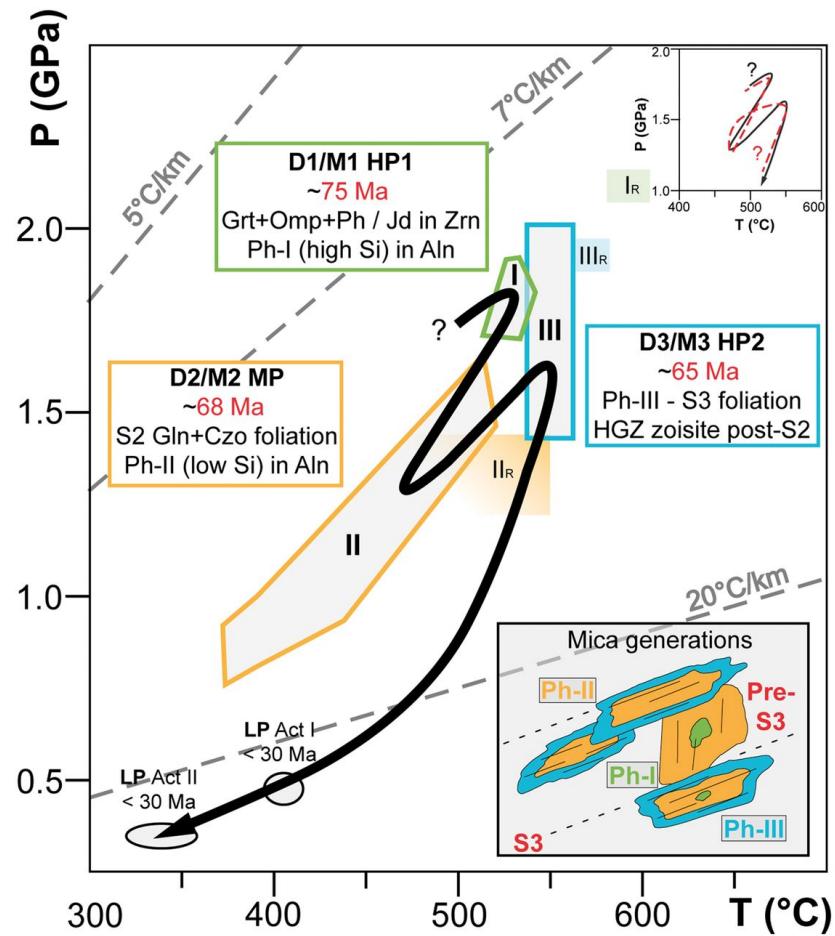
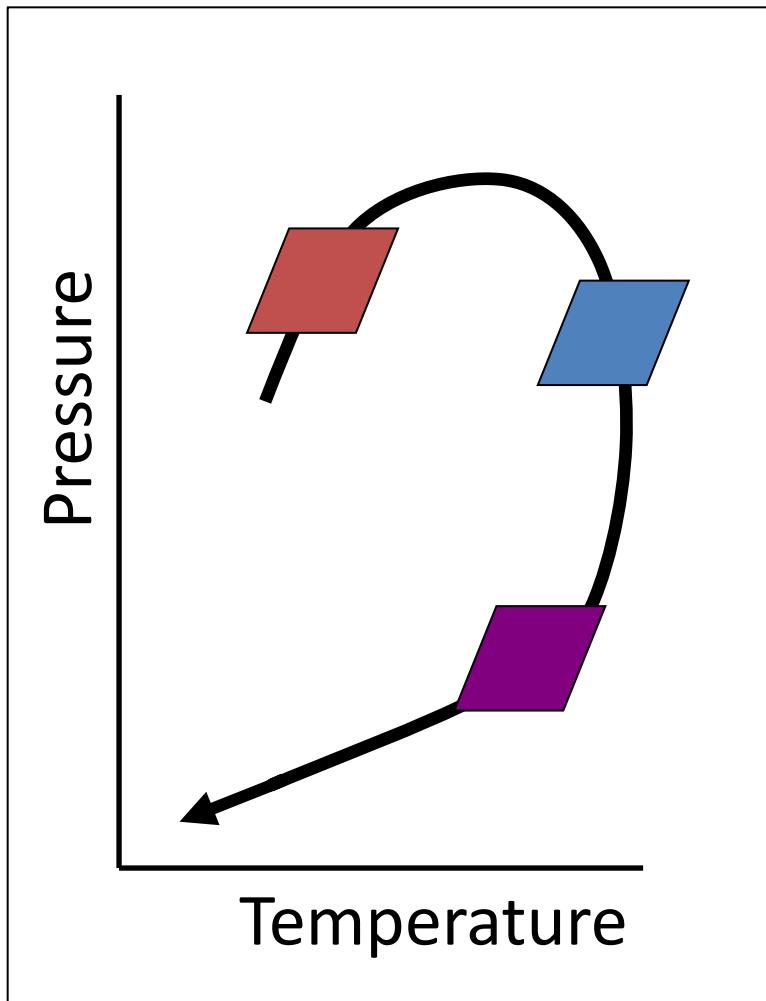


Image: Rubatto et al., 2011

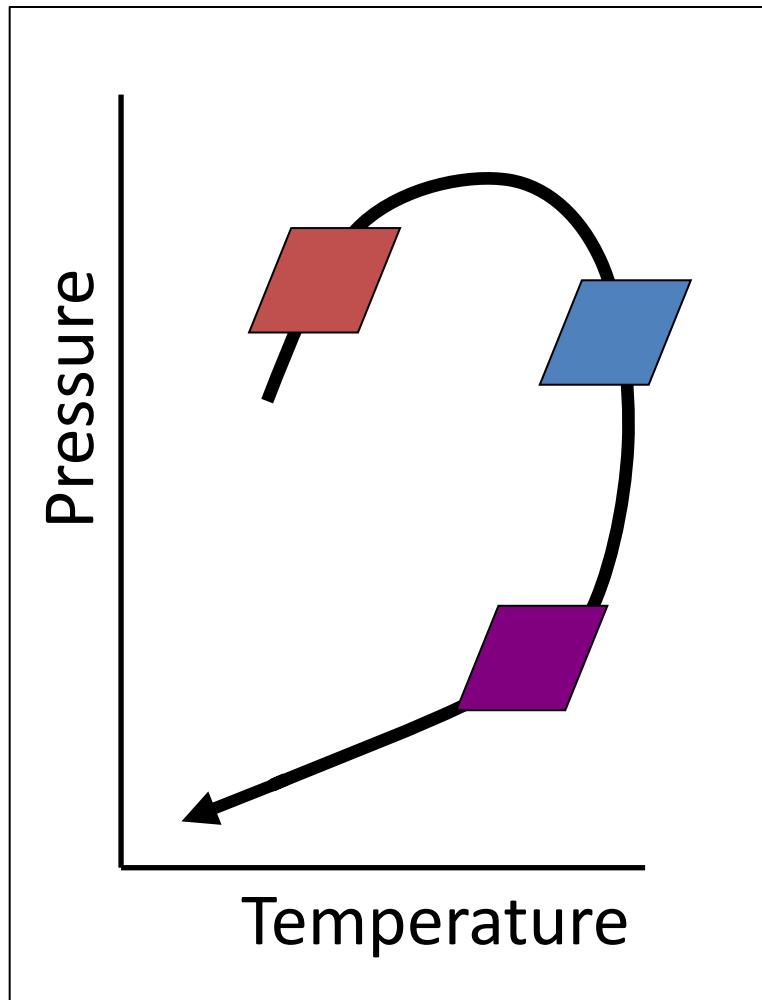
# What do metamorphic Ar/Ar ‘ages’ mean?



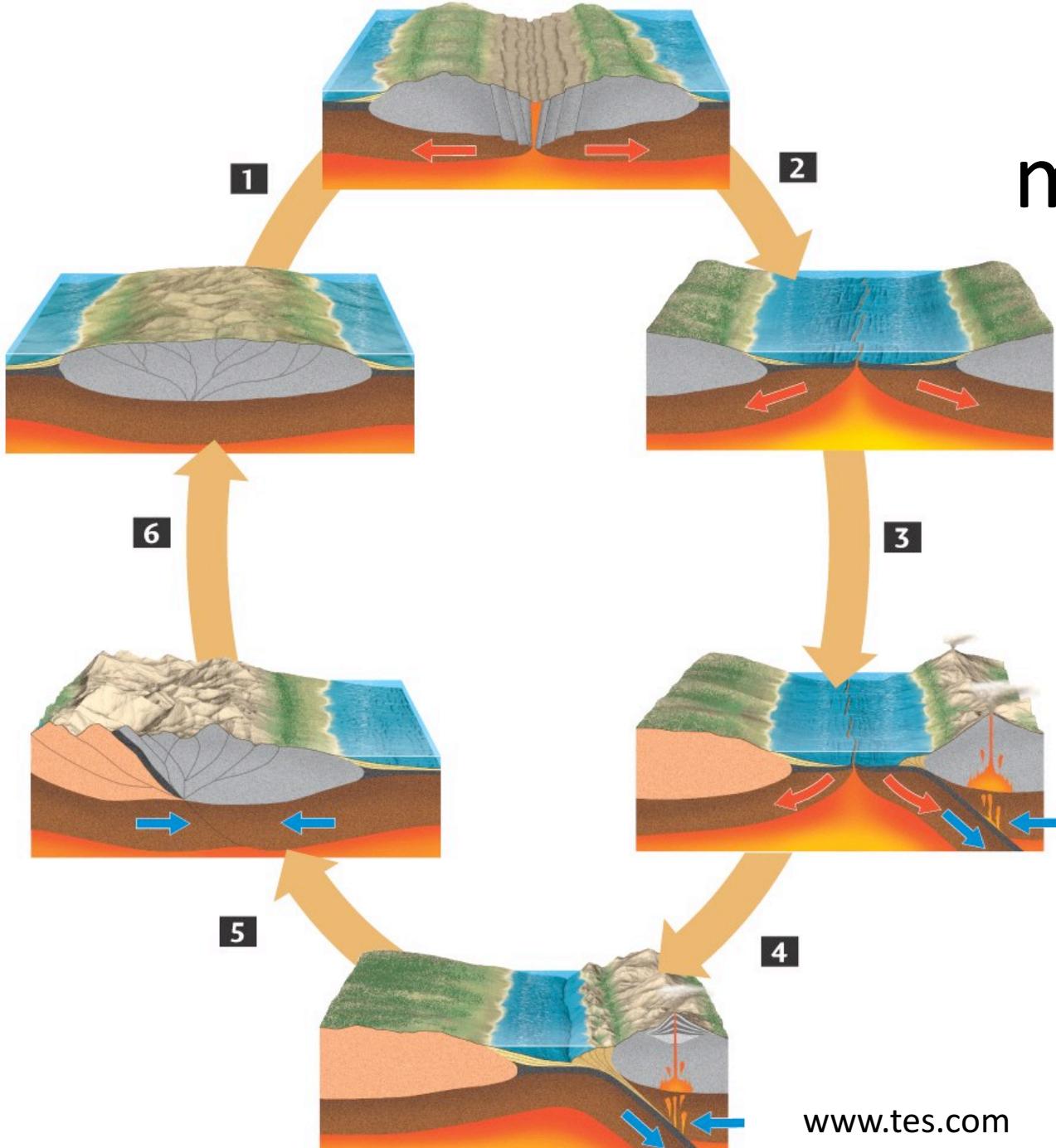
Difference between a date and an age?

# What do metamorphic Ar/Ar 'ages' mean?

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

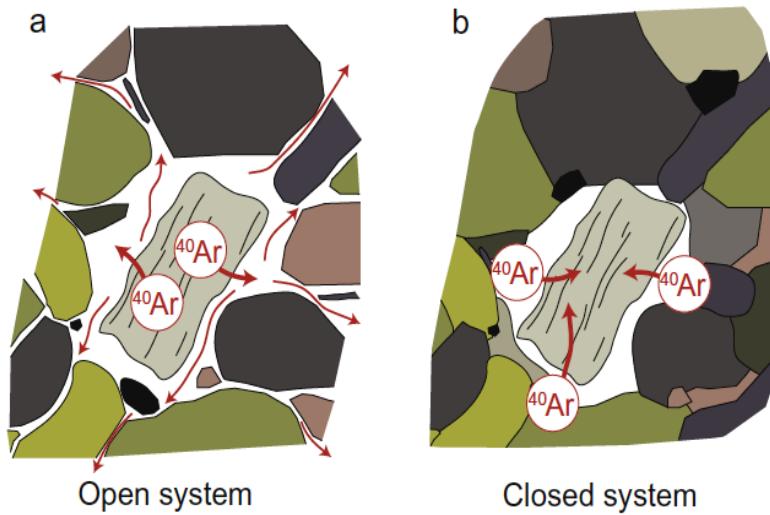
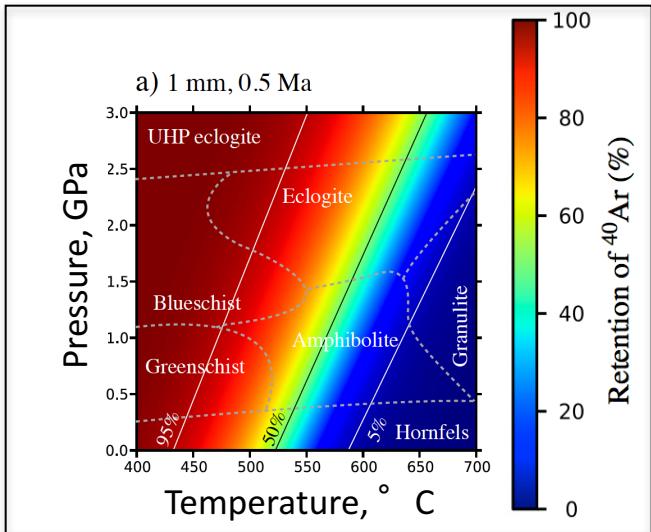


# Two main metamorphic scenarios



# Thermochronometer considerations

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



activity  
**TIME**

# How might you test/check for these approximations?

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

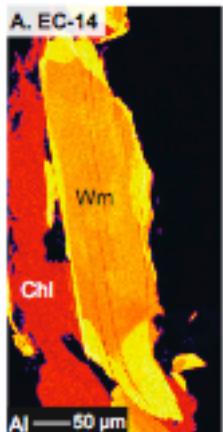
- Dependence of grain size with age
- Inverse isochrons
- Other age framework?
- Geological “sense”?

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

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

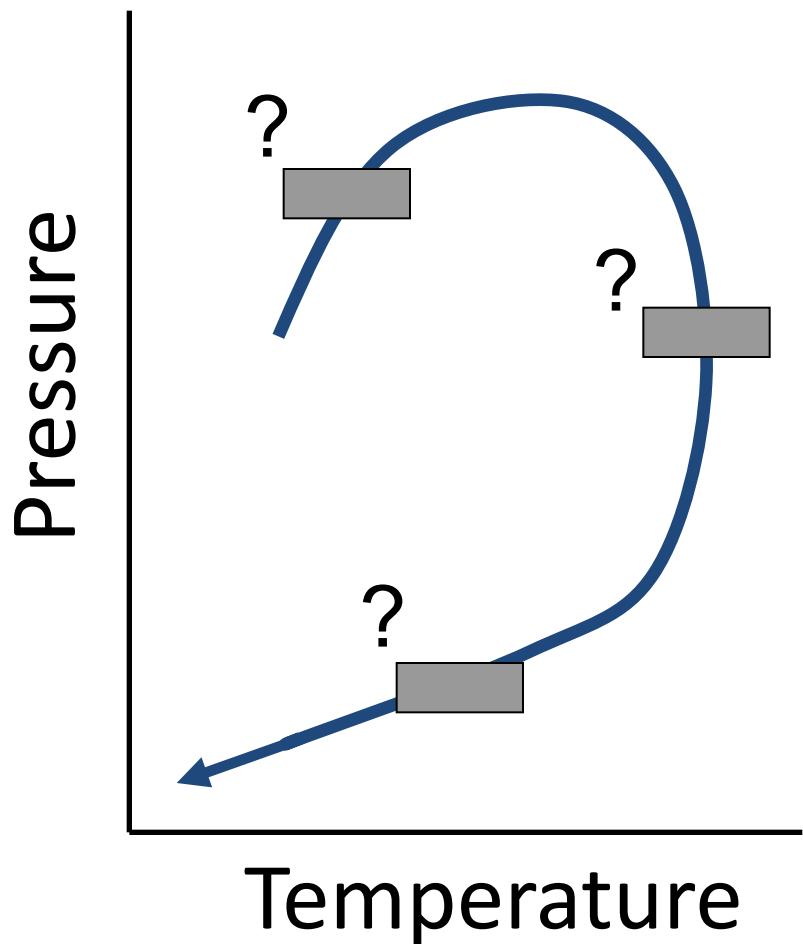
Yes?  
Diffusion profiles?

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



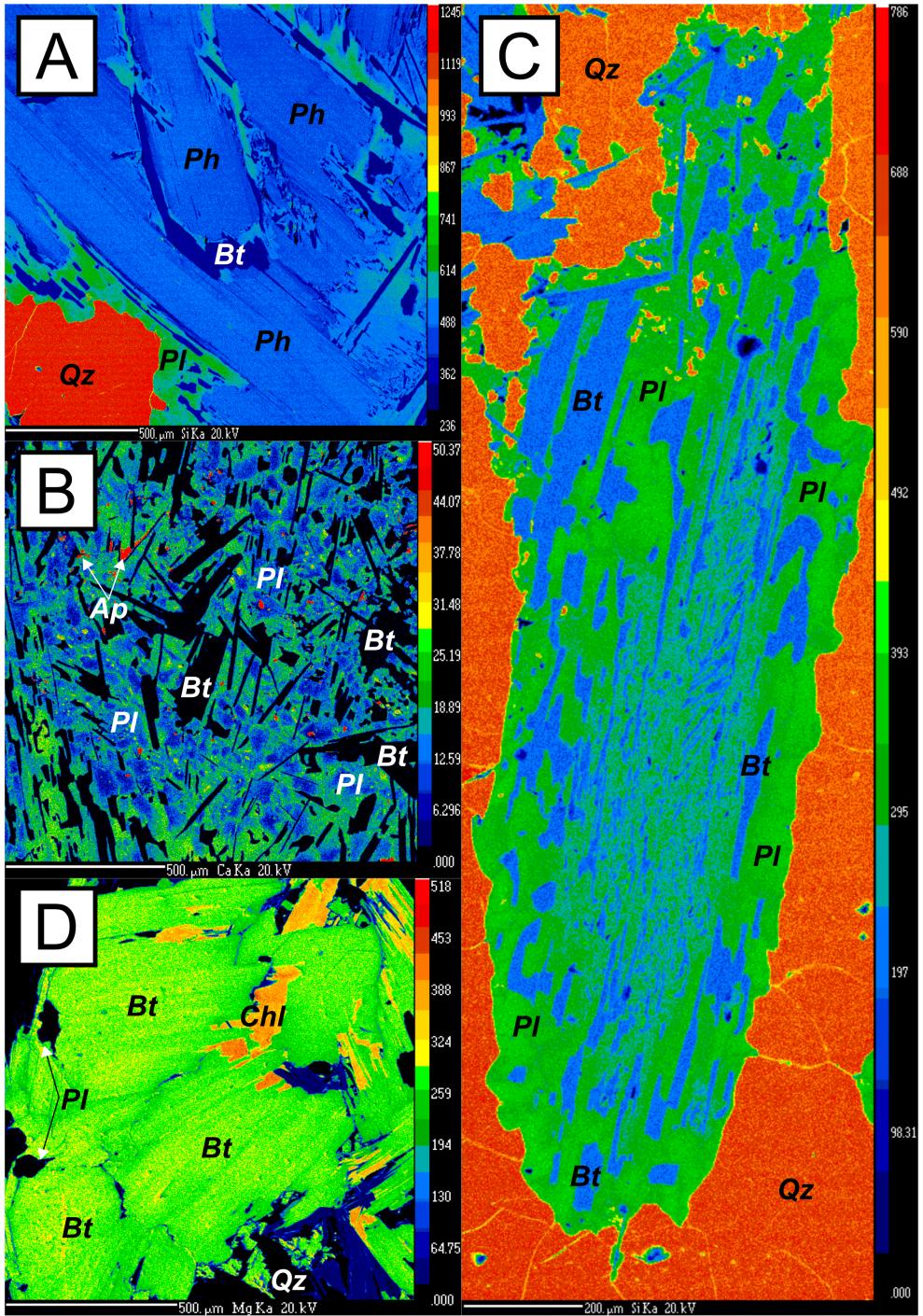
E. Cosette

# Efficient diffusion conditions?



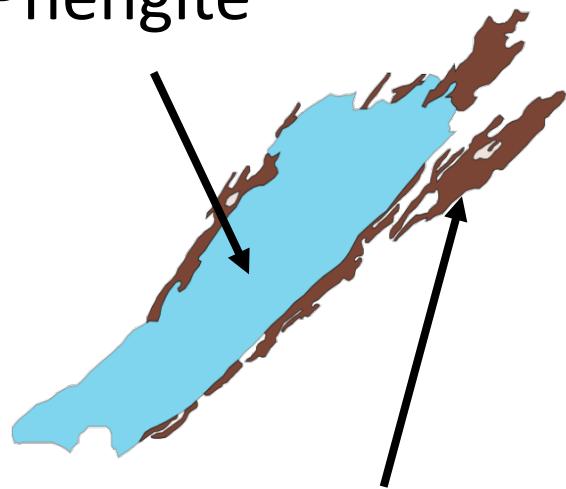
PT conditions of mica growth?  
(petrography,  
chemistry)

Did it ever experience  
conditions for efficient  
diffusion?

**A****C**

# PT framework

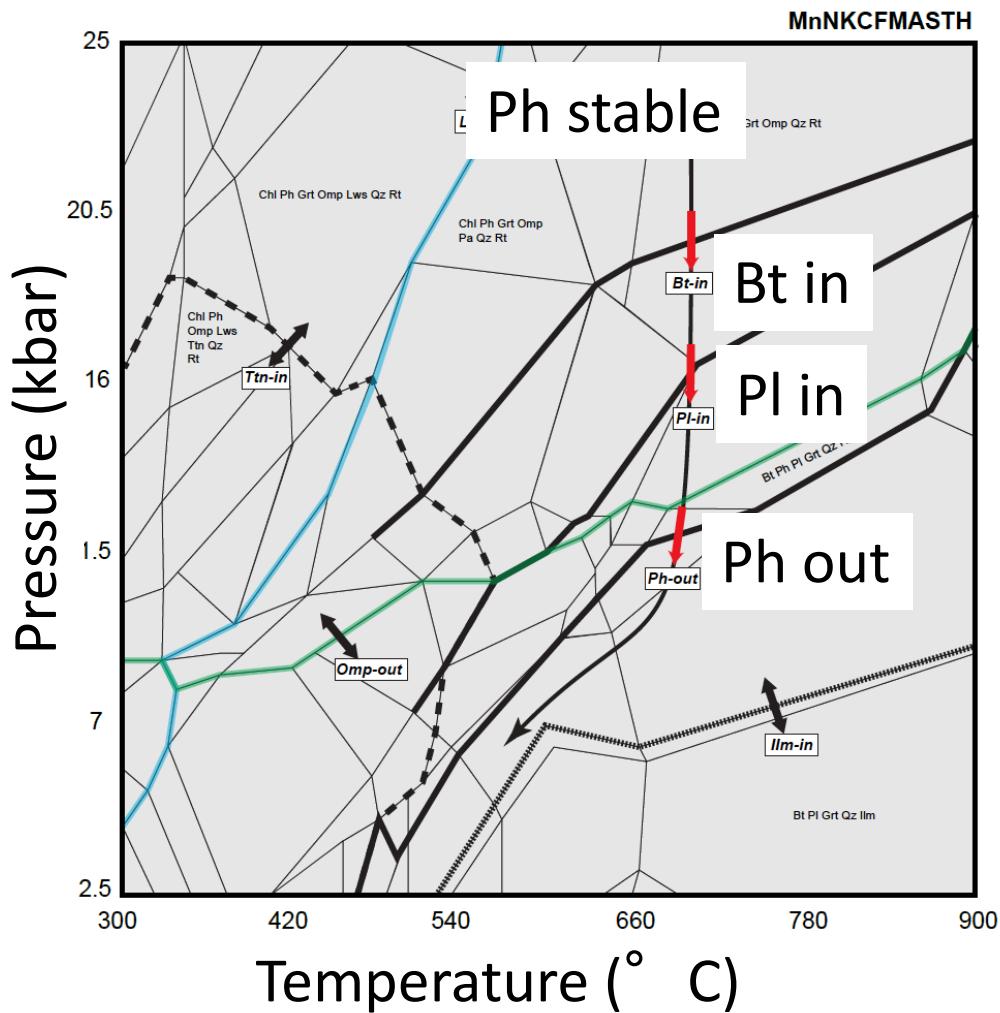
Phengite



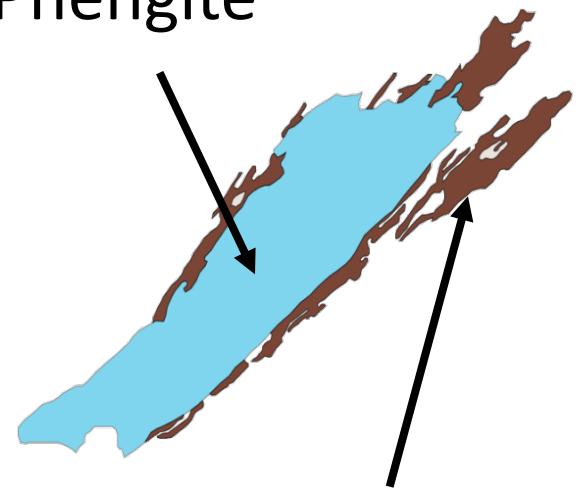
Biotite +  
plagioclase

McDonald et al., in review

# PT framework



Phengite



Biotite +  
plag

# Numerical solutions to the diffusion equation

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

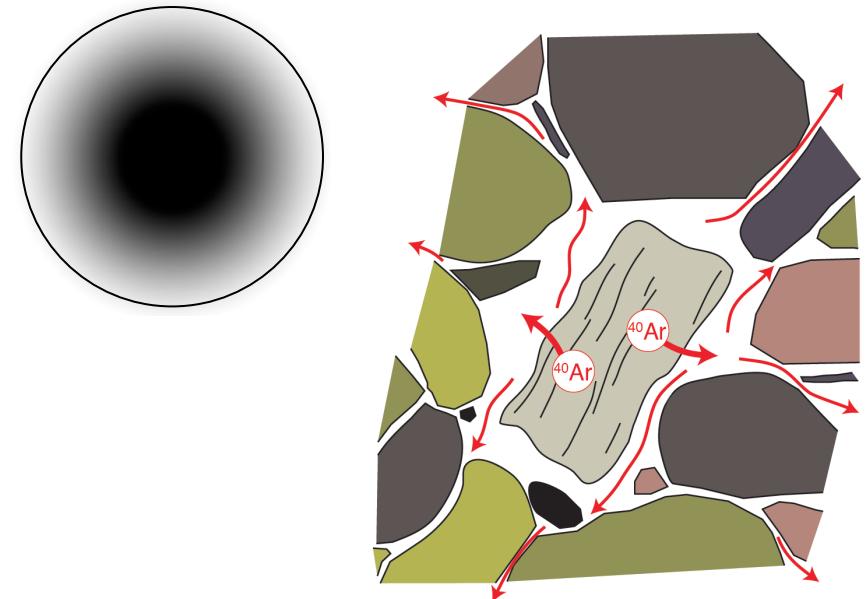
DiffArg: Wheeler 1996 (plots grain age profiles)

MacArgon: Lister 1996 (plots step-heat profiles)

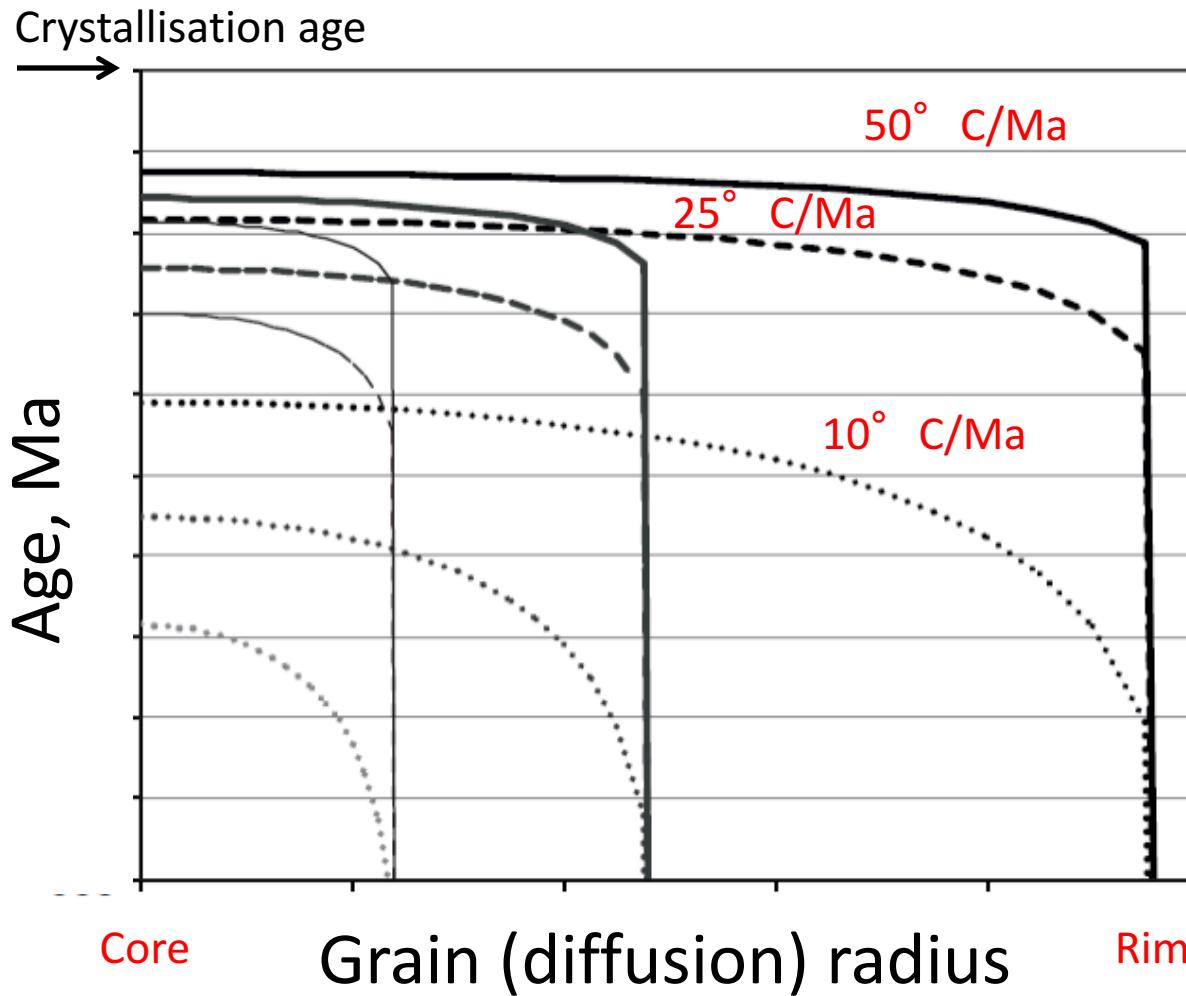
# Important: Models based on same assumptions

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

KKKKKKKKKKKKKKKK  
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# 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

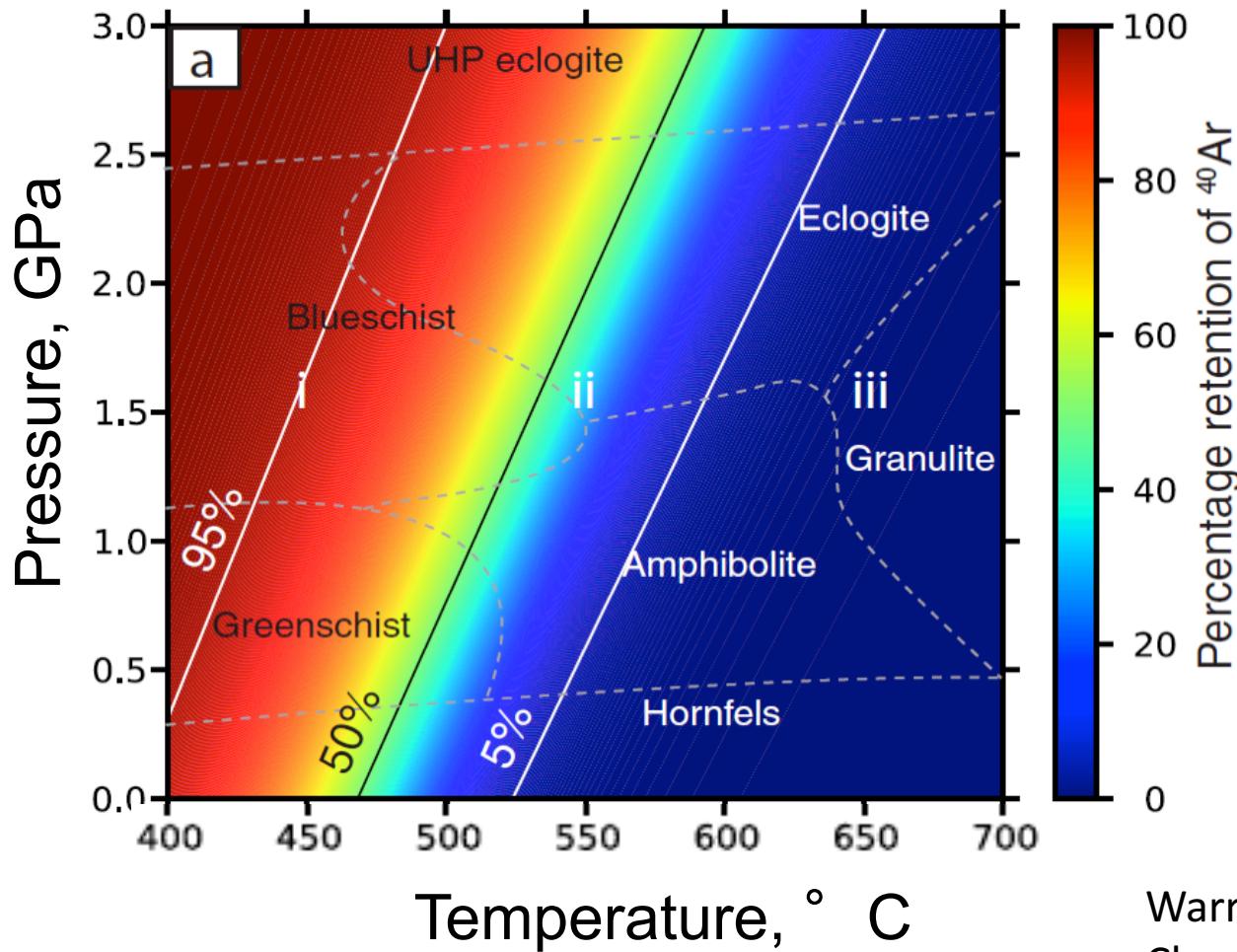
activity  
**TIME**

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	

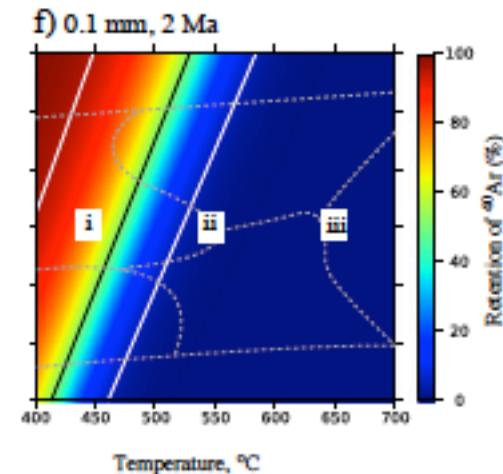
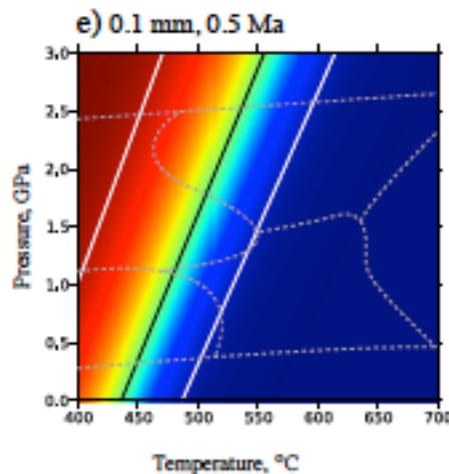
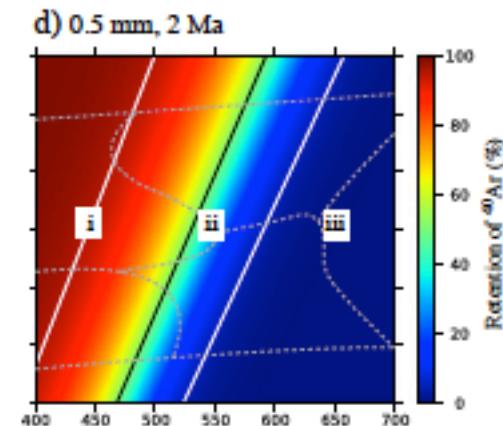
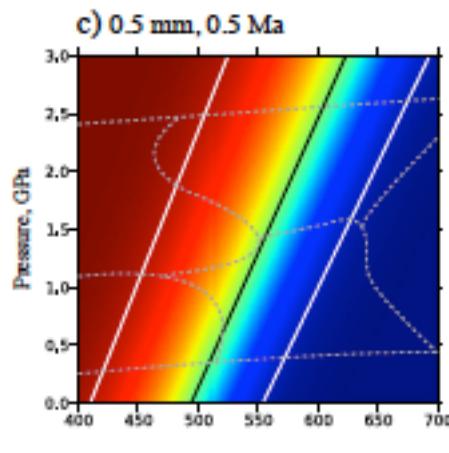
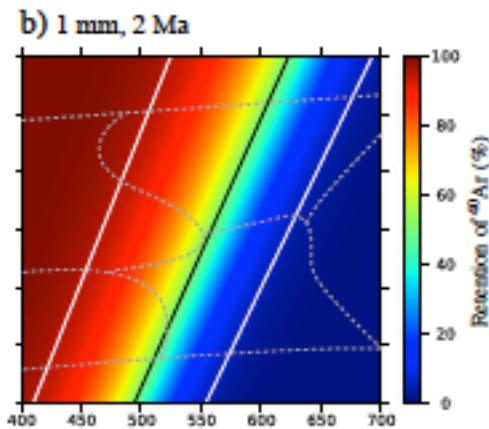
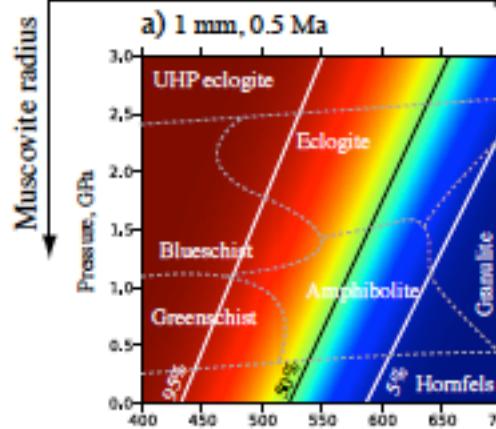
# Ar retention (muscovite) for the experienced peak PT

1mm grain, held for 0.5 Ma



Warren et al., 2012,  
Chemical Geology

Residence time at peak conditions



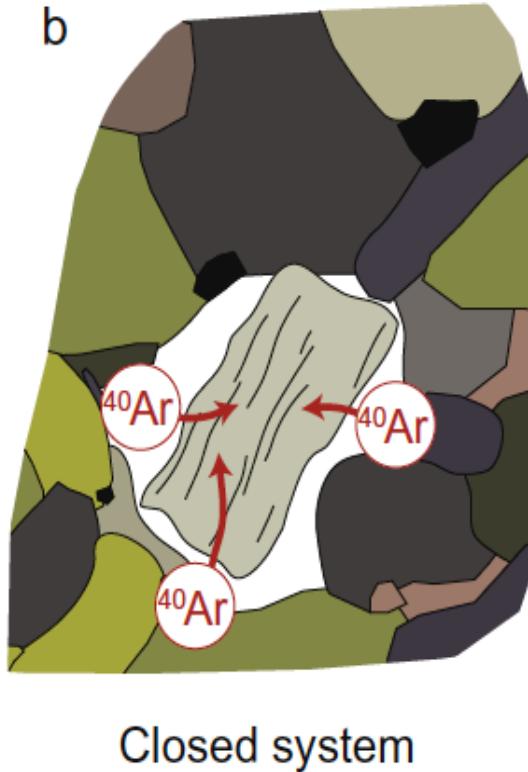
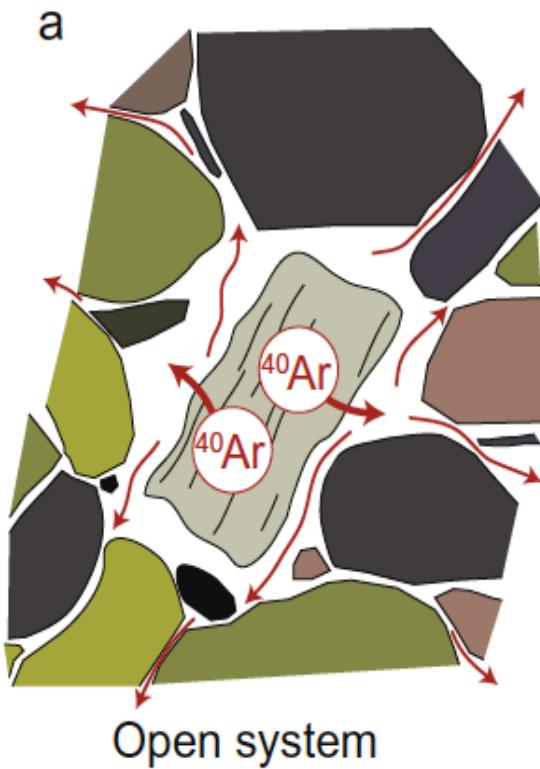
For peak PT and length of time:,  
how efficient was diffusion?

Red zone: never  
yield cooling age

Blue zone: might

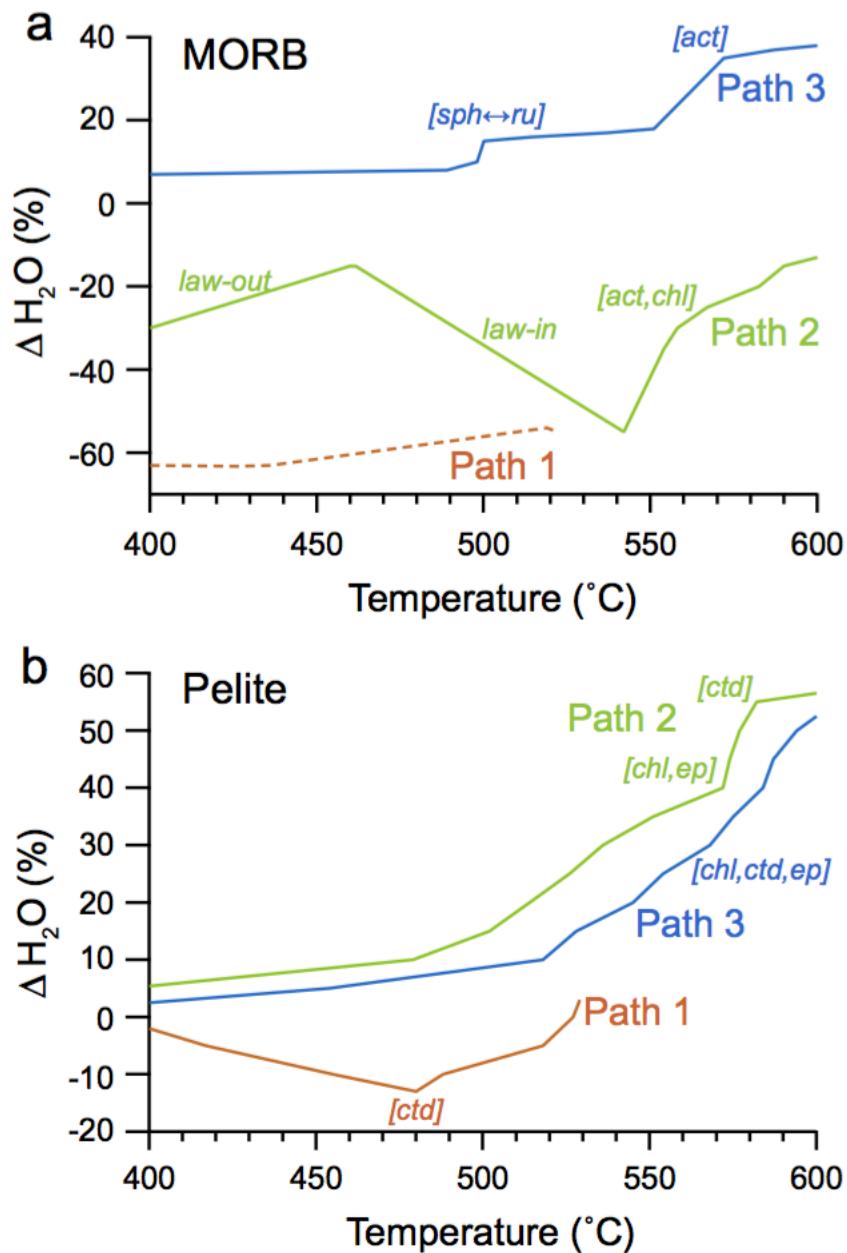
Warren et al., 2012,  
Chemical Geology

# Open and closed systems

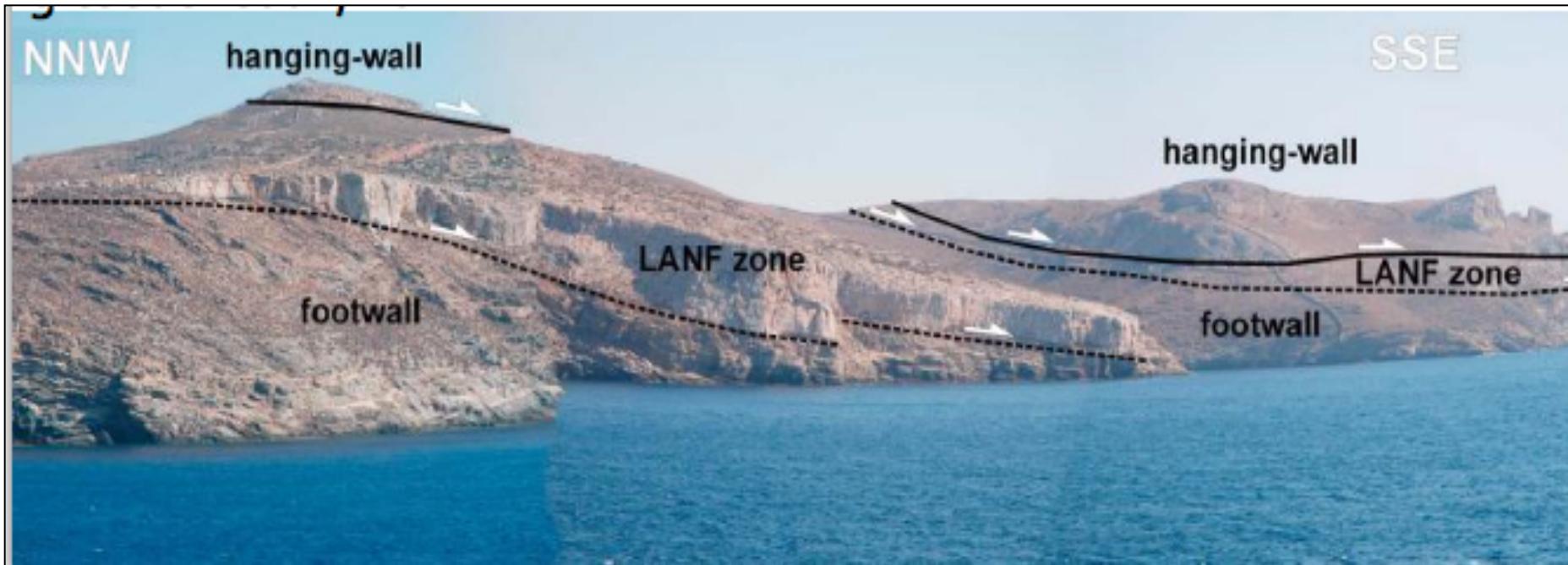


- Fluids
- Rheology

# When are fluids released during metamorphism?



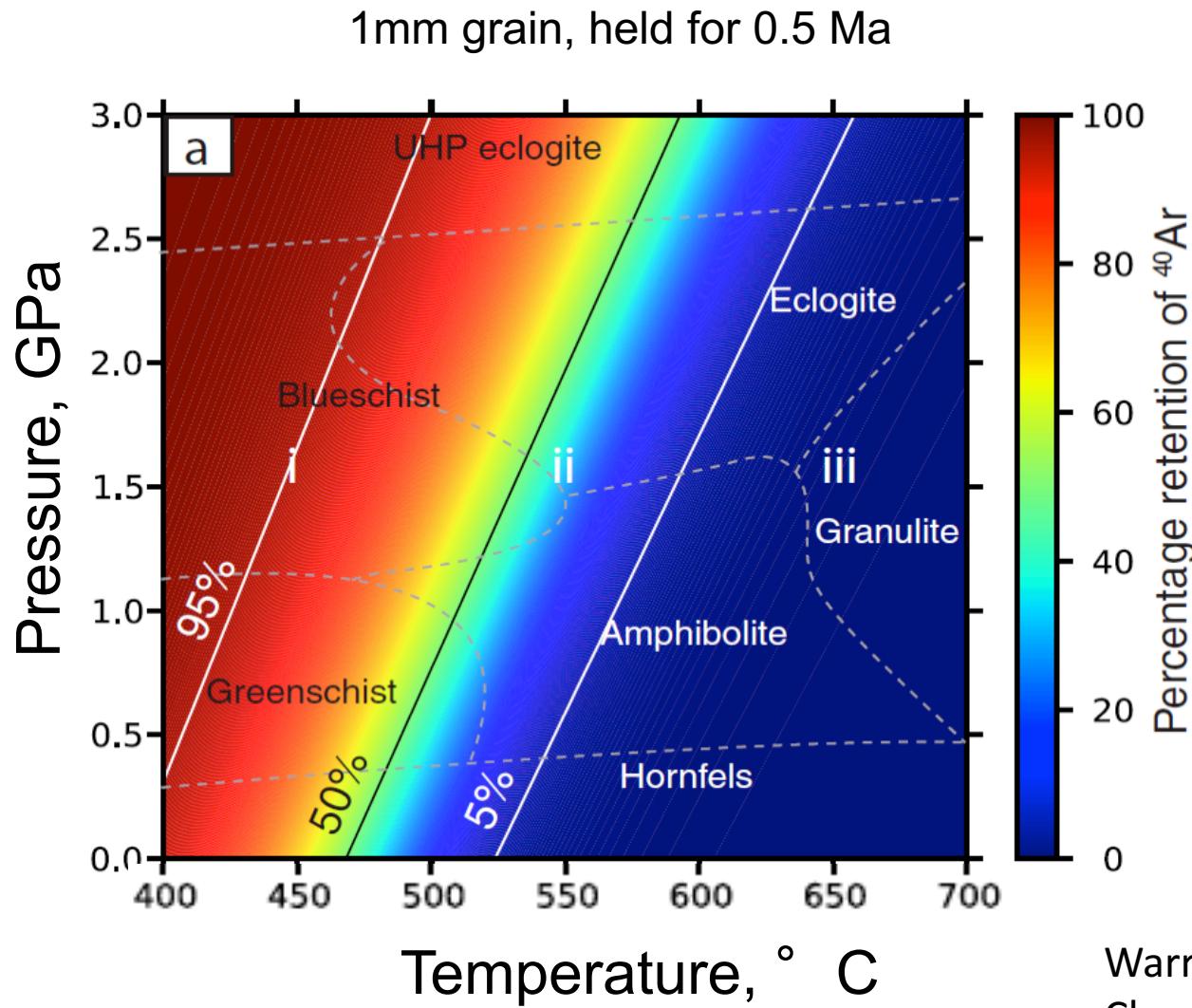
# Cyclades, <400° C

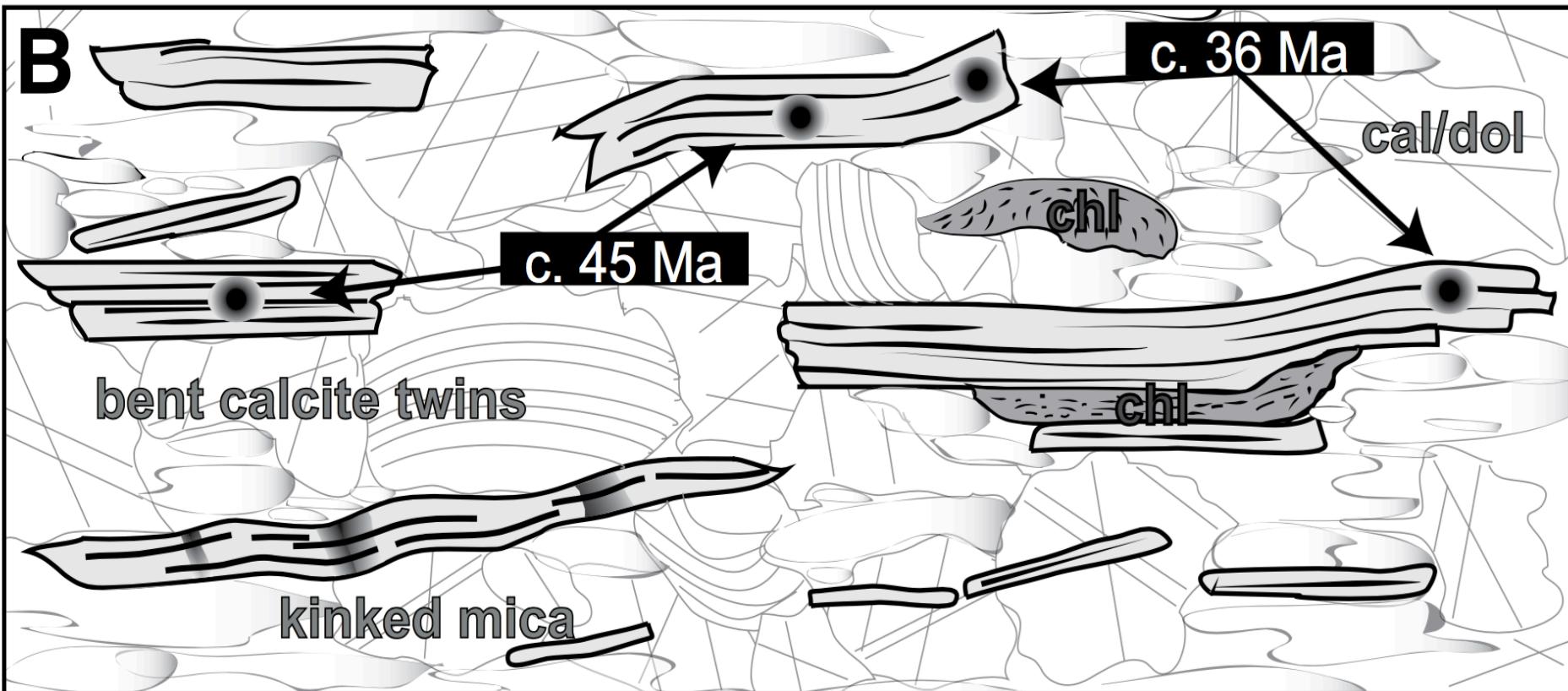


Cyclades: low angle normal fault systems  
Kea and Serifos

Cossette et al., 2015

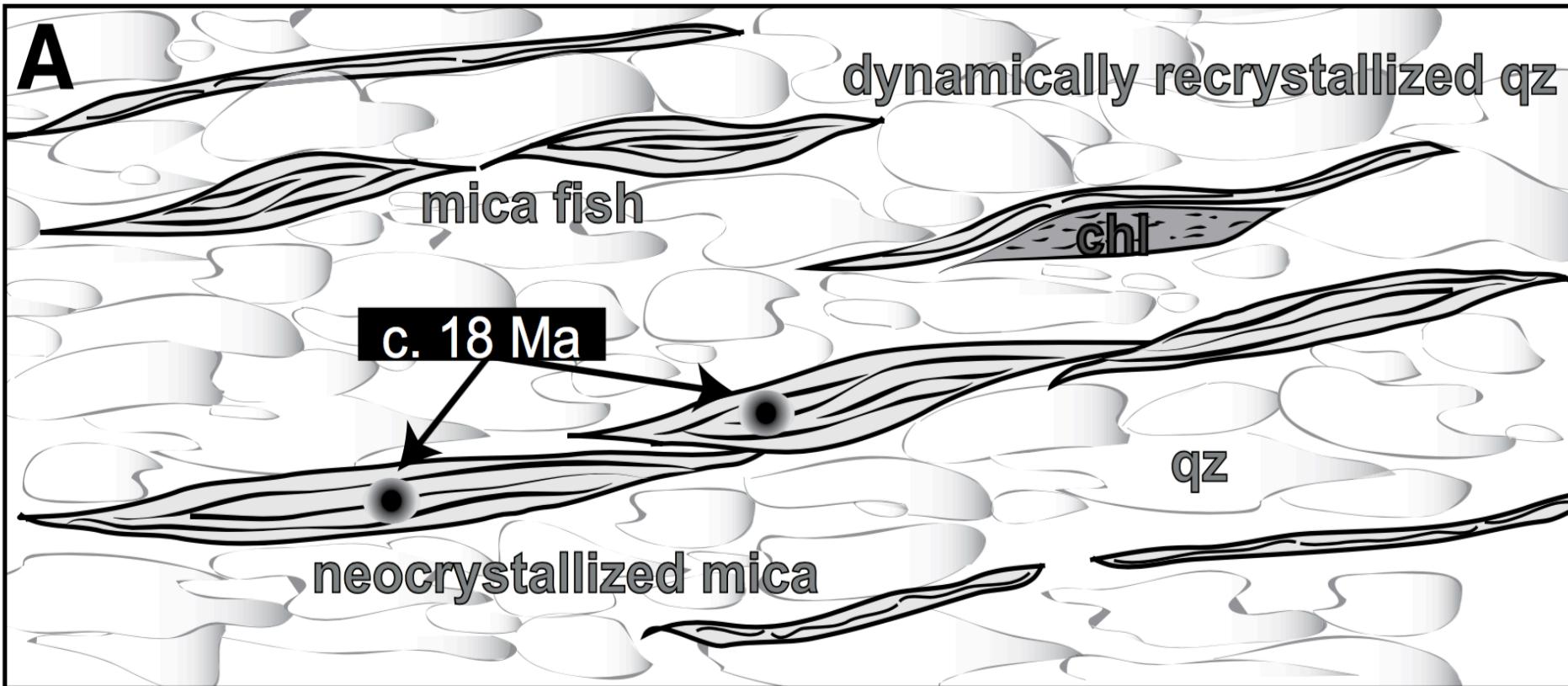
# Ar retention for the experienced peak PT





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

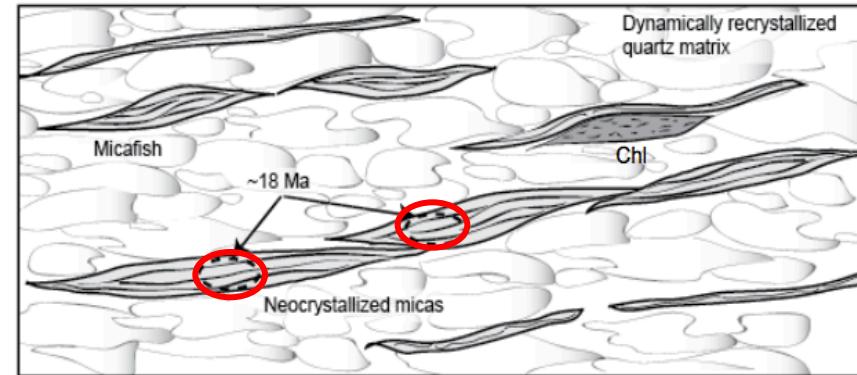
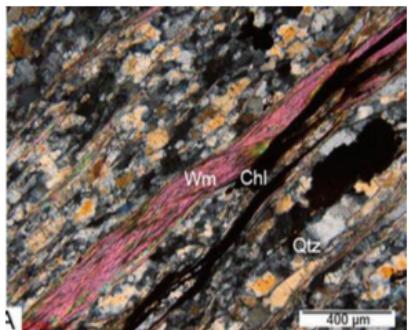
Cossette et al., 2015



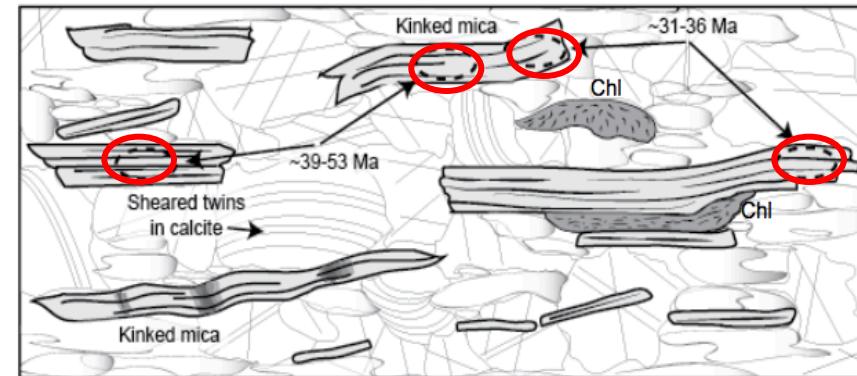
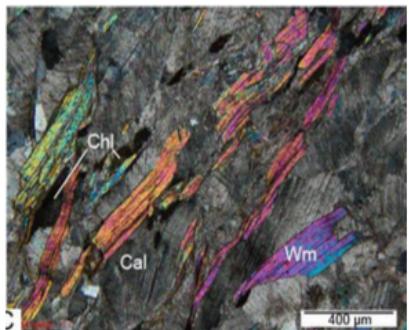
Quartz-rich rocks. 18 Ma micas

Cossette et al., 2015

### Quartz-rich rock



### Calcite-rich rock



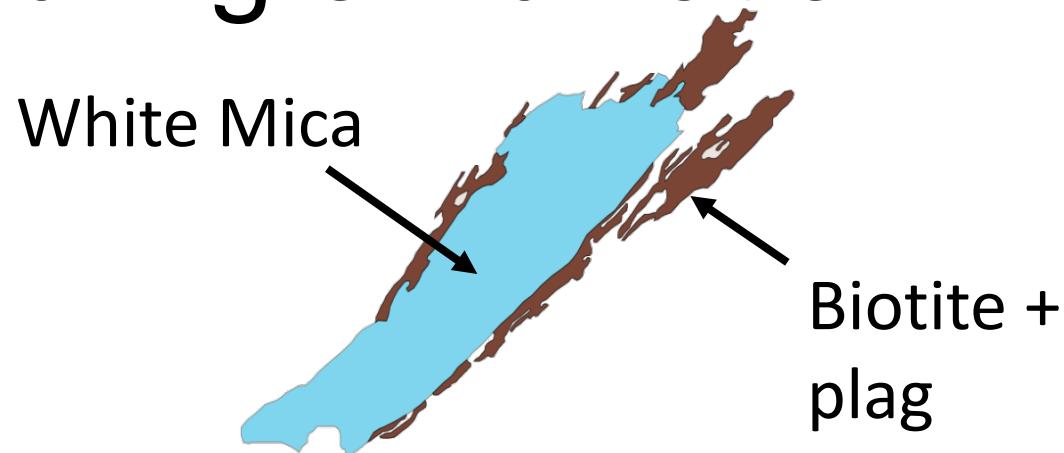
Quartz = strong; micas = weak

Calcite = weak; micas = strong

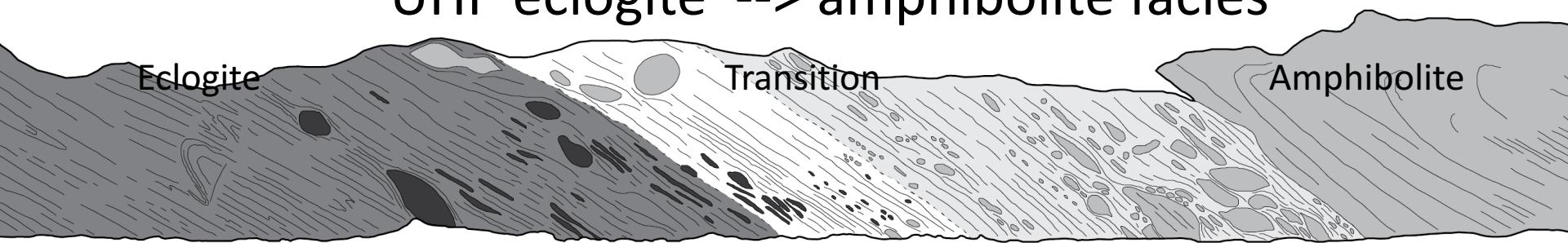
# 'Hot' systems: >600° C

## Ar recycling during exhumation

~700-750°C,  
27-10 kbar

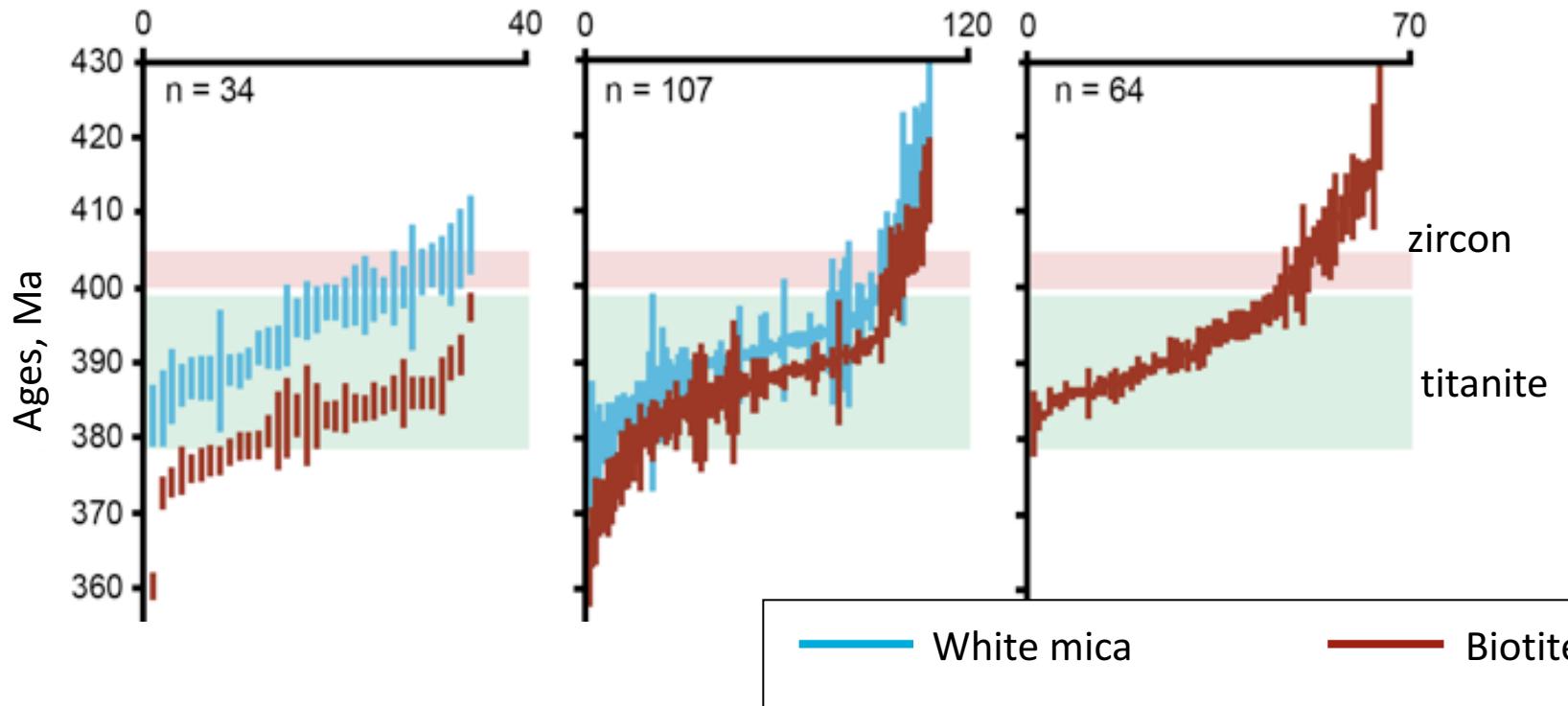


UHP eclogite --> amphibolite facies



Same HP-HT path, different petrographic record

# Dispersion in $^{40}\text{Ar}/^{39}\text{Ar}$ data

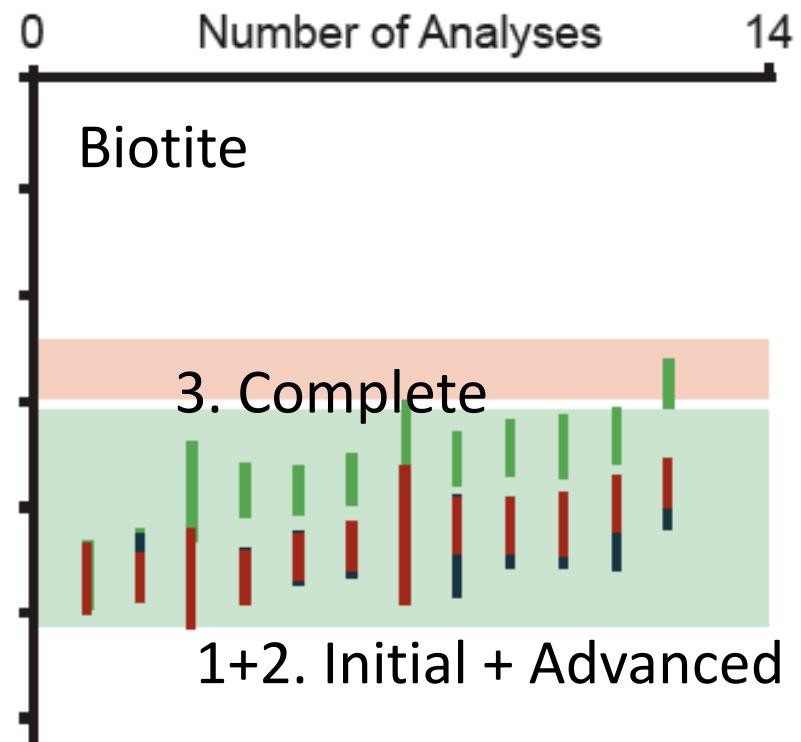
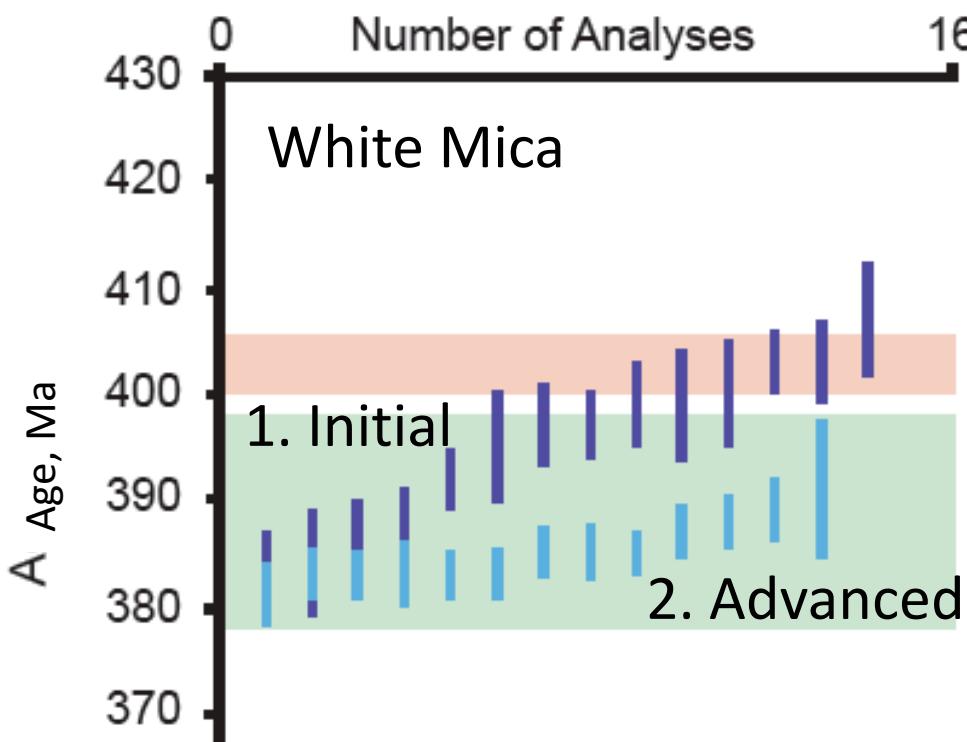
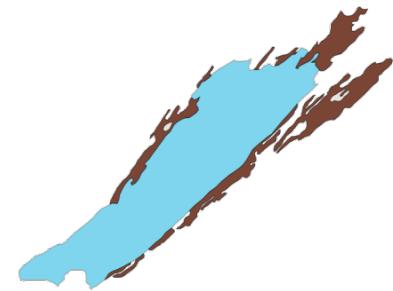


Single grain fusion, 1mm diameter grains

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

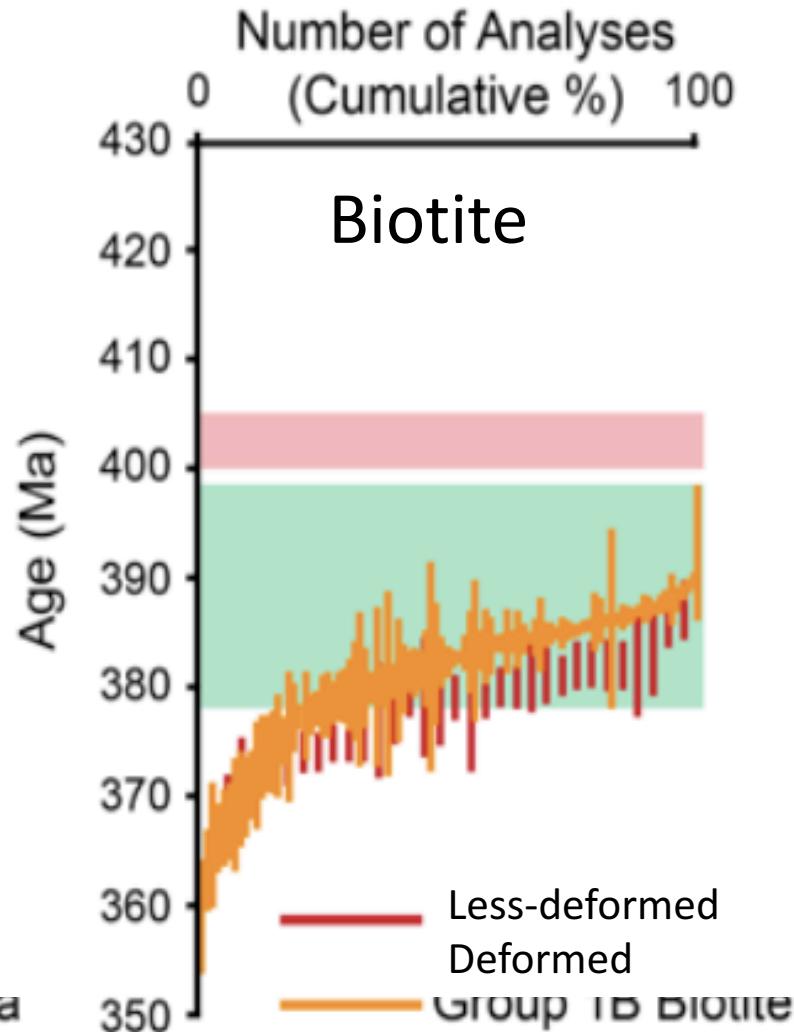
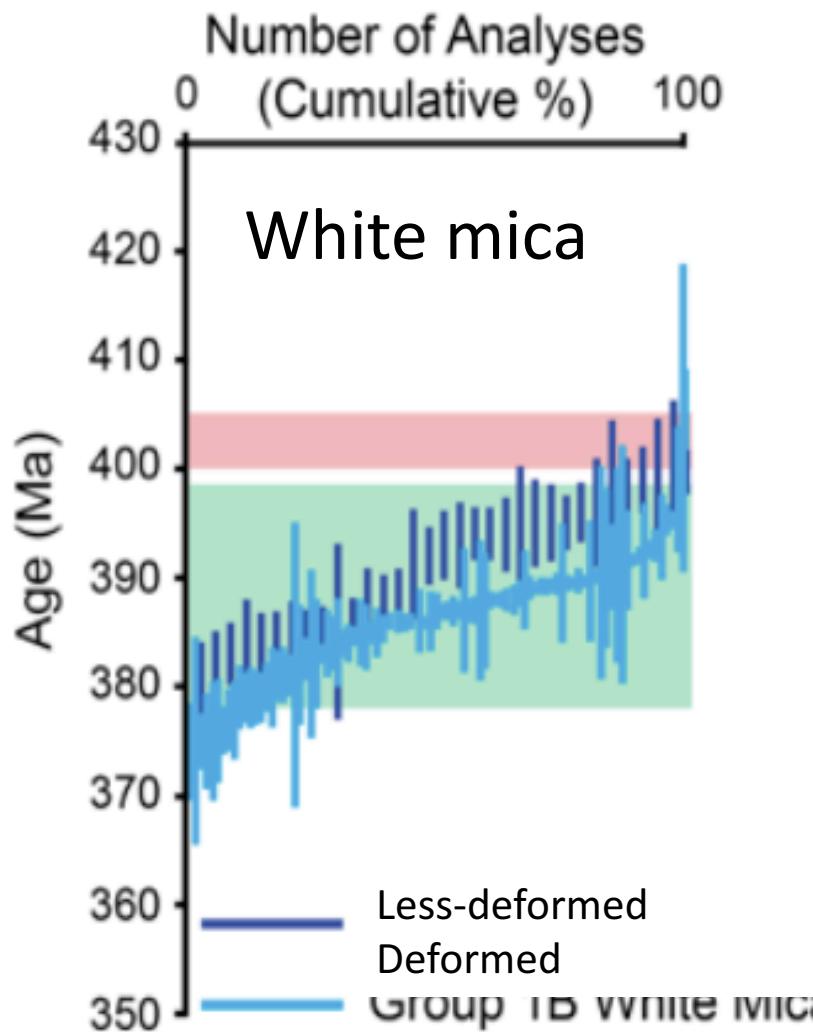
Ar: ~~McDonald~~ McDonald PhD data; Zir: Hacker et al.; Titanite: Kylander-Clark et al.

# Effect of reaction completion

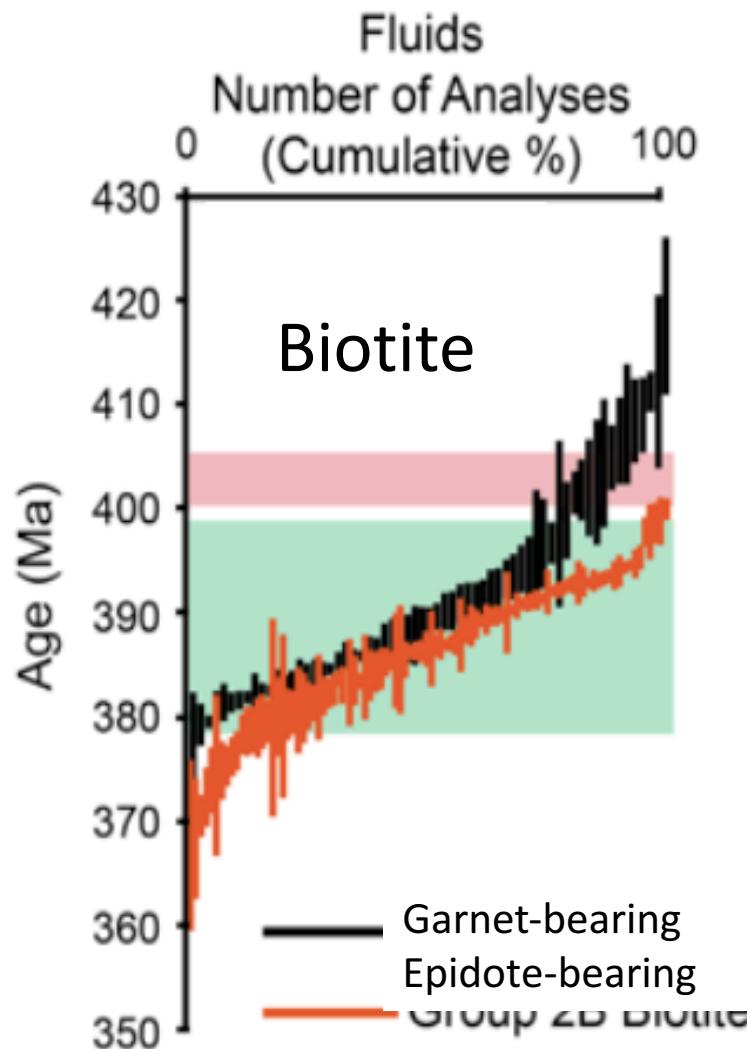
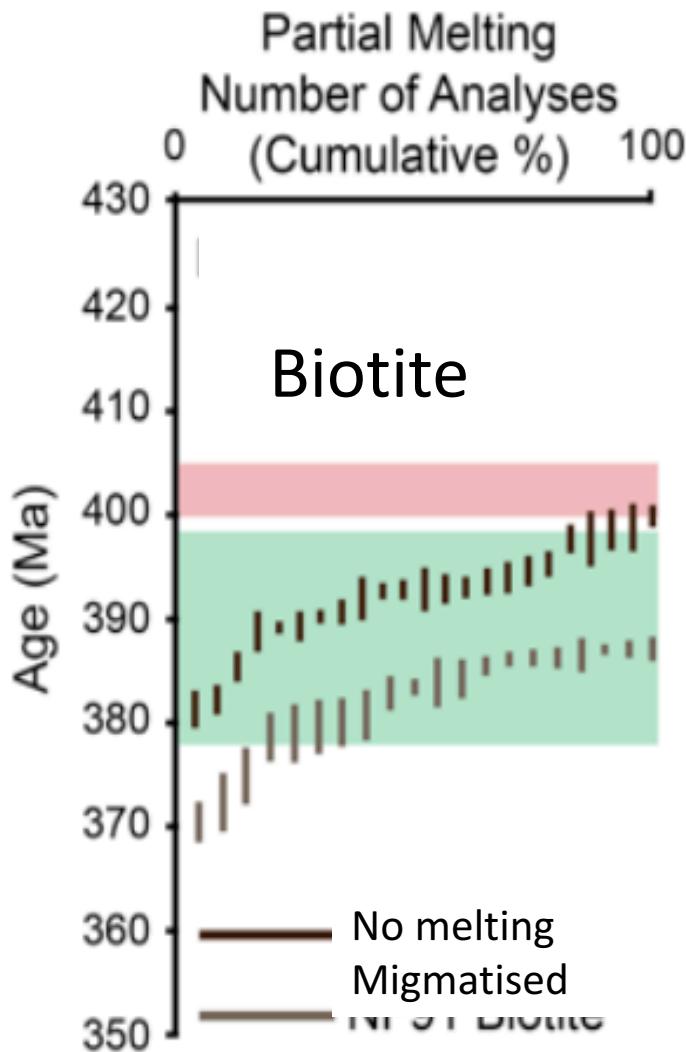


Same PT experience, different petrographic record

# 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?

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