The generation, relaxation and geological implication of grain-scale stress variation in metamorphic rock

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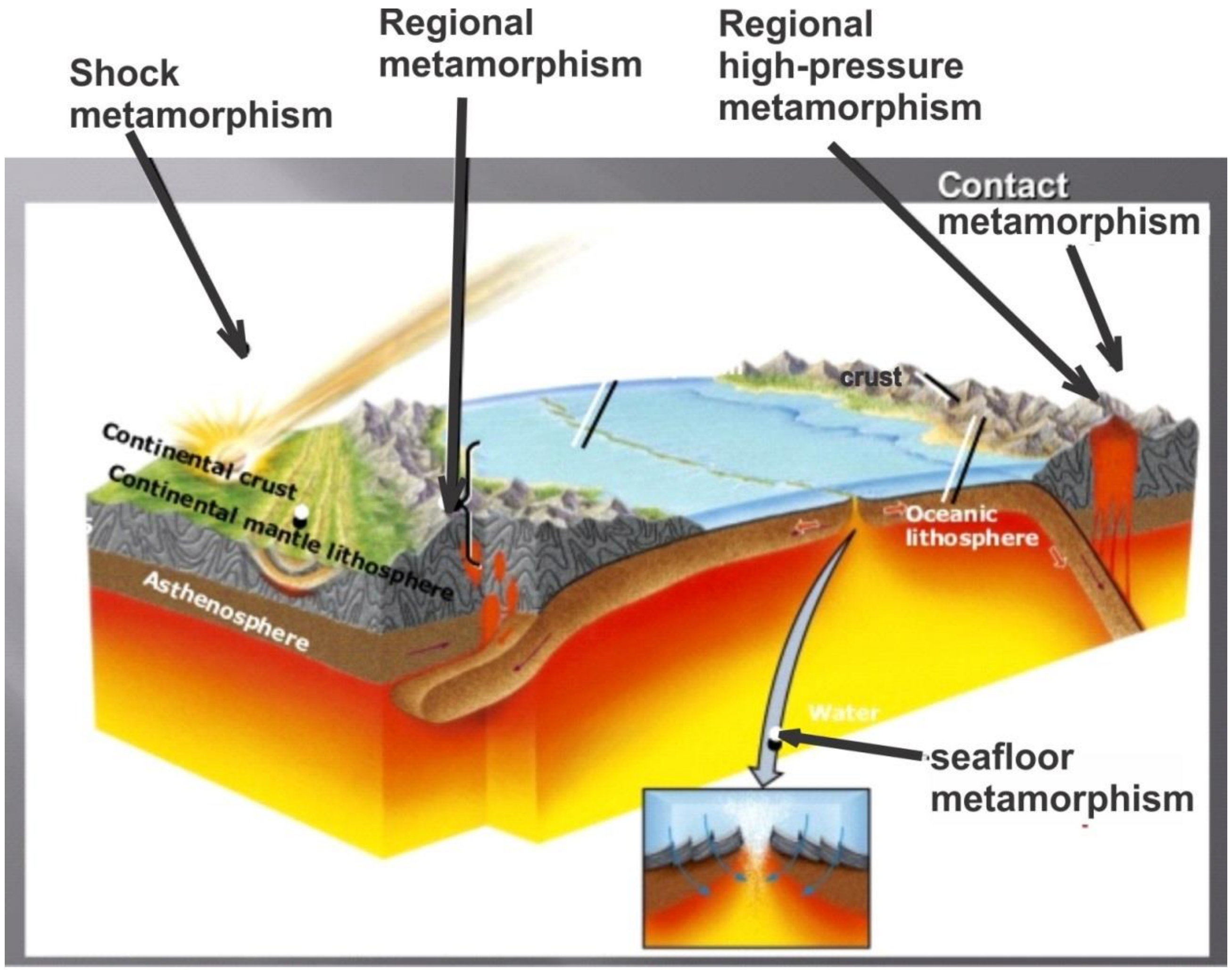
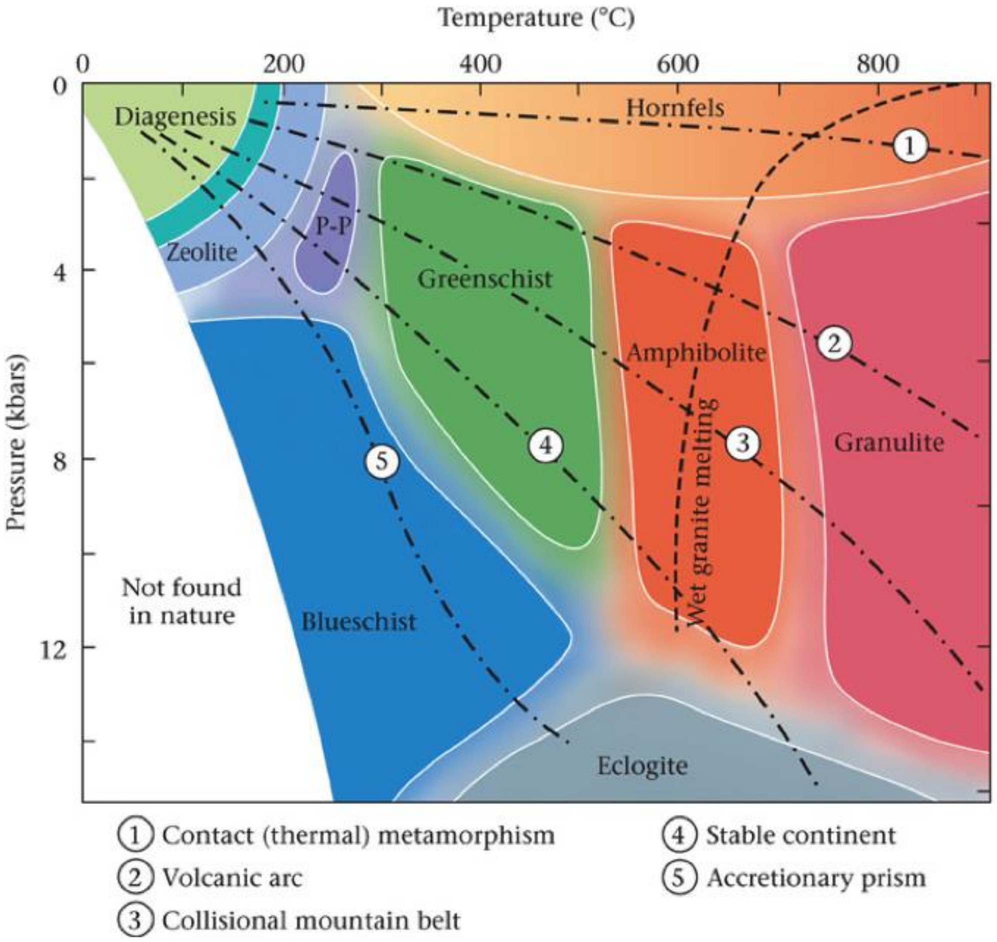
Presenter: Xin Zhong
Freie Universität Berlin
Mineralogy and Petrology

1. Metamorphism





2. Conventional methods

Phase equilibria

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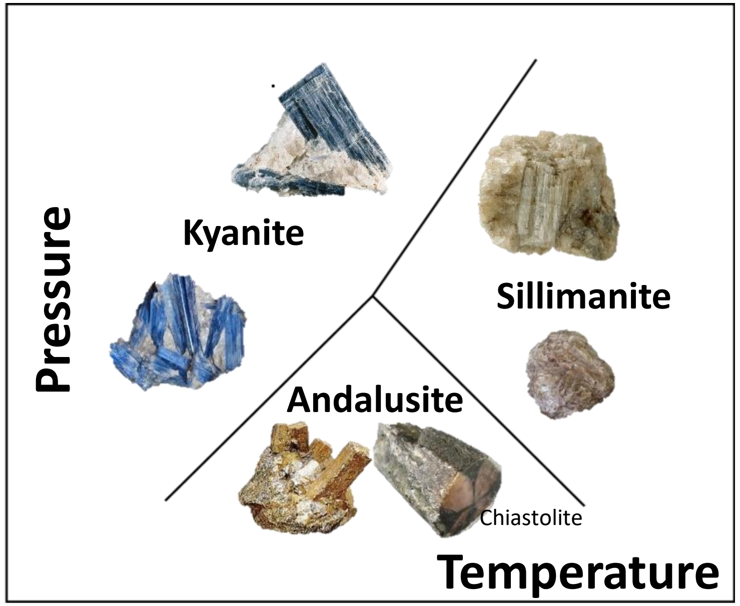
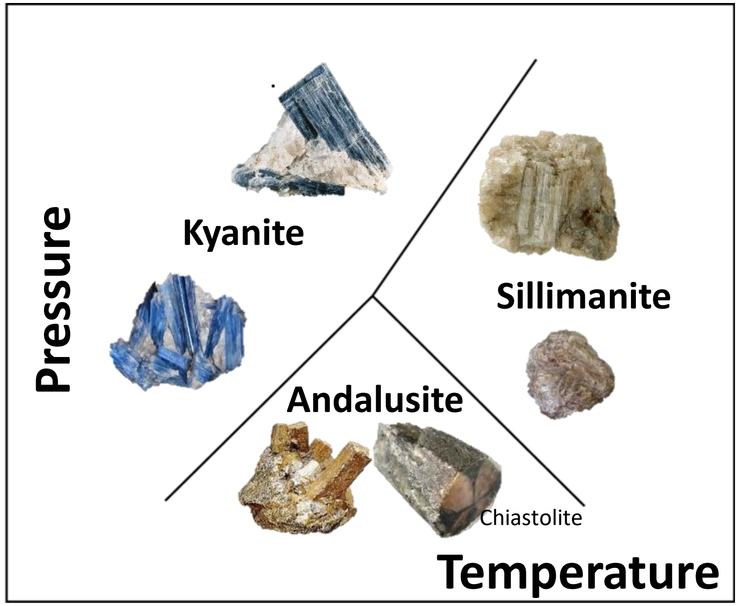
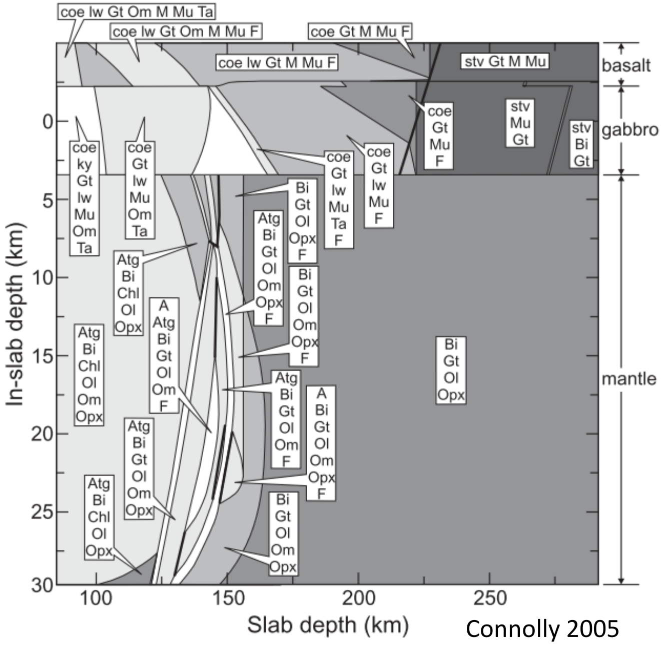
Phase equilibria



2. Conventional methods

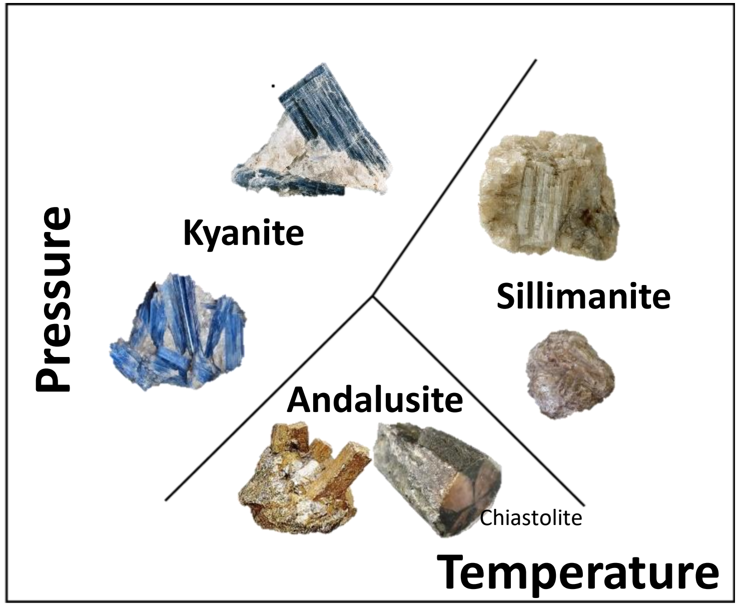
Phase equilibria

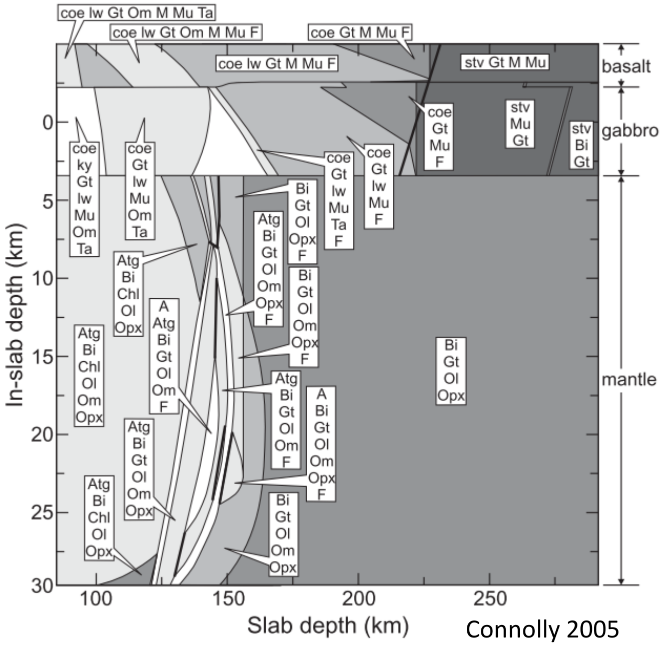




2. Conventional methods

Phase equilibria





Geothermobarometry

Fe / Mg

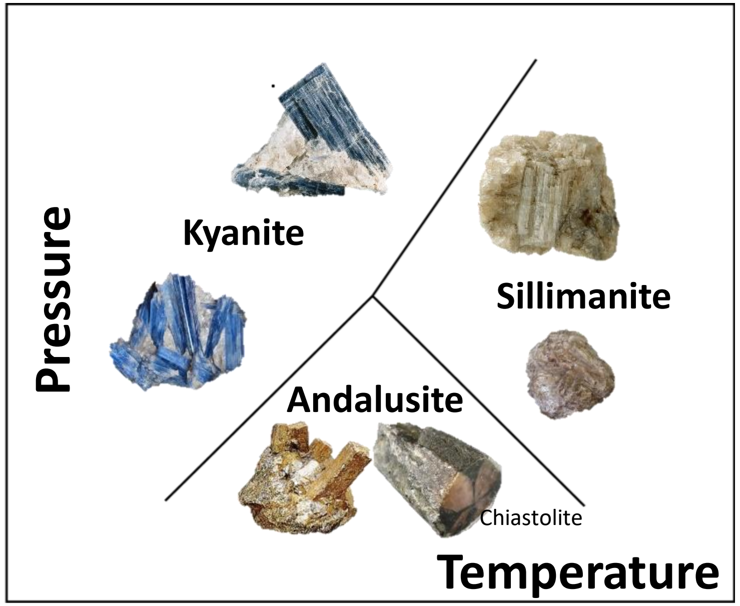
T dependent exchange

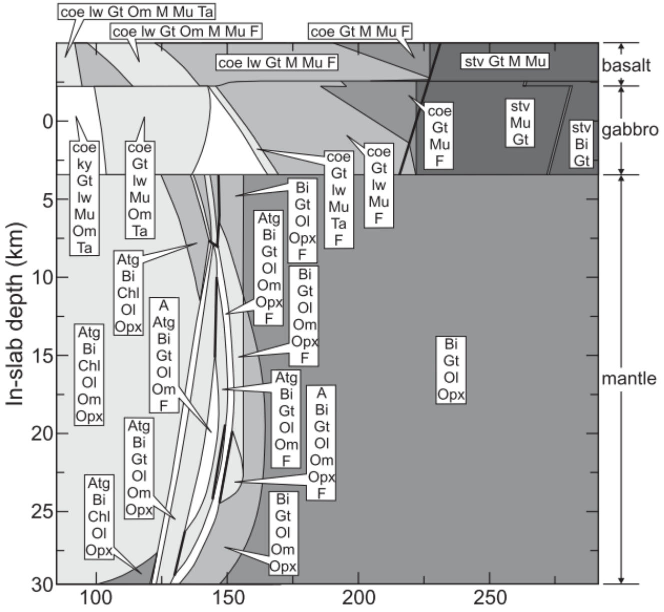
Clinopyroxene

Garnet

2. Conventional methods

Phase equilibria





Connolly 2005

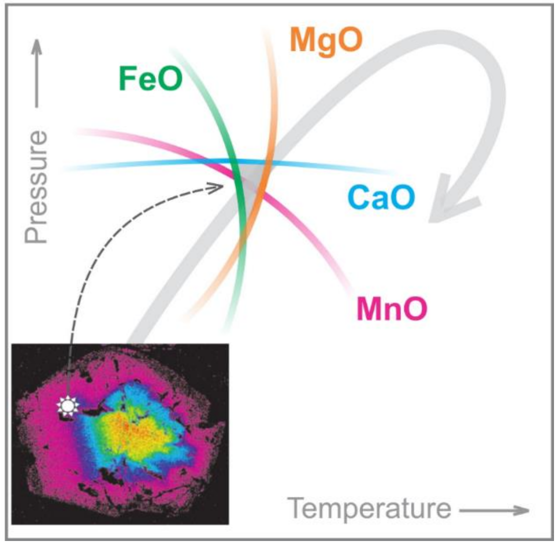
Geothermobarometry

Clinopyroxene

Fe / Mg

T dependent exchange

Garnet



2. Conventional methods

Advantage

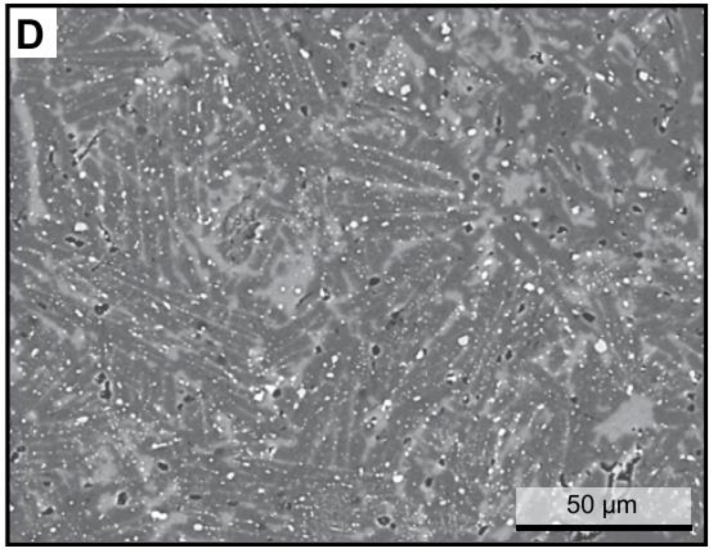
- Based on solid thermodynamic theory.
- Well-established database and solution models.
- Many available software to do calculations (e.g. Thermocalc; PerpleX; Theriak/Domino; Thermolab).
- Standard analytical methods (SEM, EPMA, EBSD, ICP-MS etc.)

2. Conventional methods

Questions

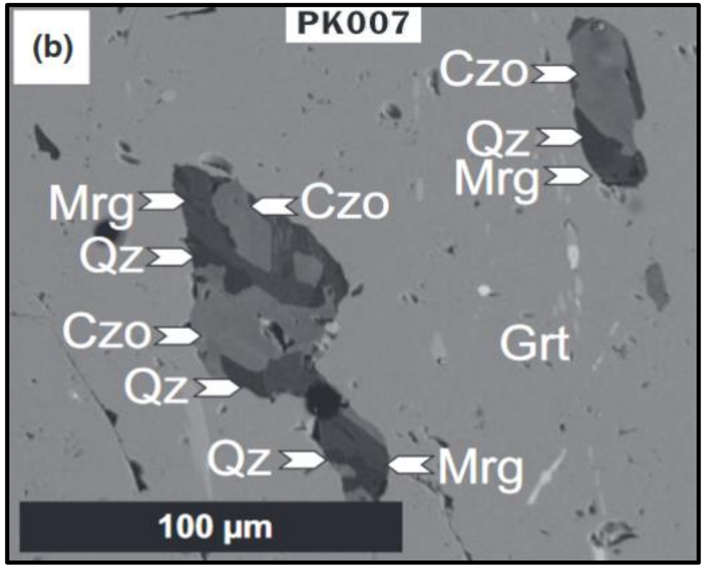
- Is the rock under chemical equilibrium?

Pseudotachylyte



(Dunkel et al. 2020)

Pseudomorph



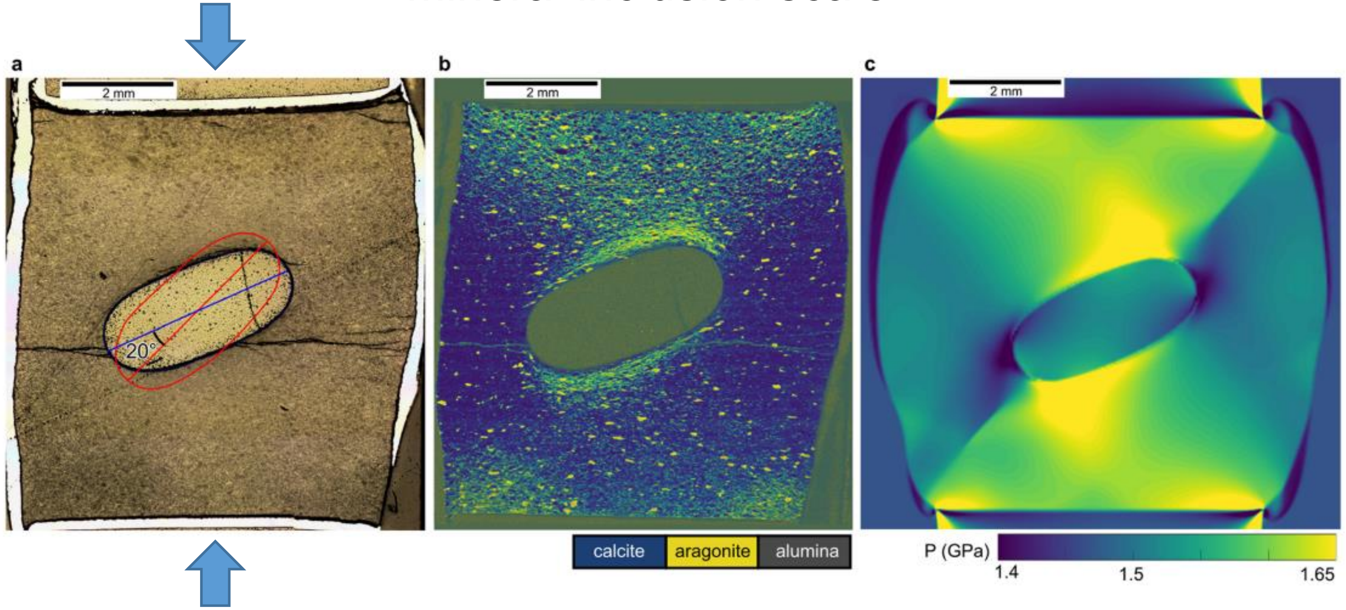
(Szczepański et al. 2021)

3. Inclusion-host system

Questions

- <u>Was stress homogeneous and hydrostatic when rock formed?</u>

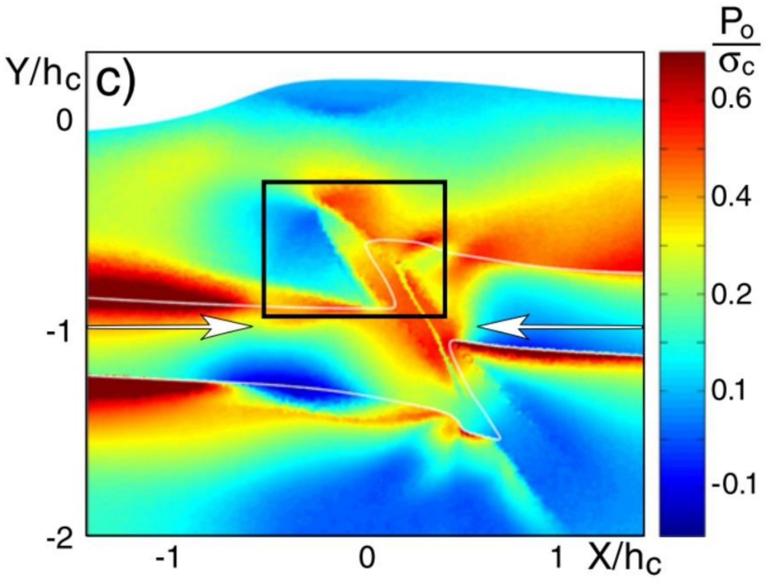
Mineral inclusion scale



(Cionoiu et al. 2019)

Calcite-aragonite transition under non-hydrostatic stress

Geodynamic scale



(Moulas et al. 2014)

Modelling pressure variations for subduction

[AMERICAN JOURNAL OF SCIENCE, VOL. 259, SUMMER 1961, P. 519-541]

PRESSURE AND TEMPERATURE OF CRYSTALLIZATION FROM ELASTIC EFFECTS AROUND SOLID INCLUSIONS IN MINERALS?

JOHN L. ROSENFELD and ARMOND B. CHASE

Department of Geology, University of California, Los Angeles, California

" . . . I argue that there is no necessary connexion between the size of an object and the value of a fact, . . . "

Henry Clifton Sorby—1858

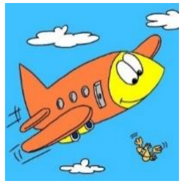
ABSTRACT. Earth processes commonly result in the transfer of a mineral grain from the pressure-temperature (P,T) condition of its origin to considerably different pressure-temperature conditions. If a mineral grain (h) includes a grain of another mineral (i), transfer to new P-T conditions commonly will cause anisotropic elastic strain effects around the inclusion owing to different coefficients of thermal expansion (α) and compressibility (β) for the two minerals. To the extent that these elastic effects remain reversible over geologic time intervals, they represent stored information concerning the pressure and temperature of origin. The differential equation for the pressure-temperature curve representing absence of anisotropic stress around an inclusion of one isometric crystal (also a homogeneous fluid) inside of another isometric crystal is:

$$\left.\frac{dT}{dP}\right|_{P_i=P_h;T_i=T_h} = \frac{\beta_h-\beta_i}{\alpha_h-\alpha_i}$$

Physical analogy: Cola bottle

Pressurized air

On the ground (1atm)



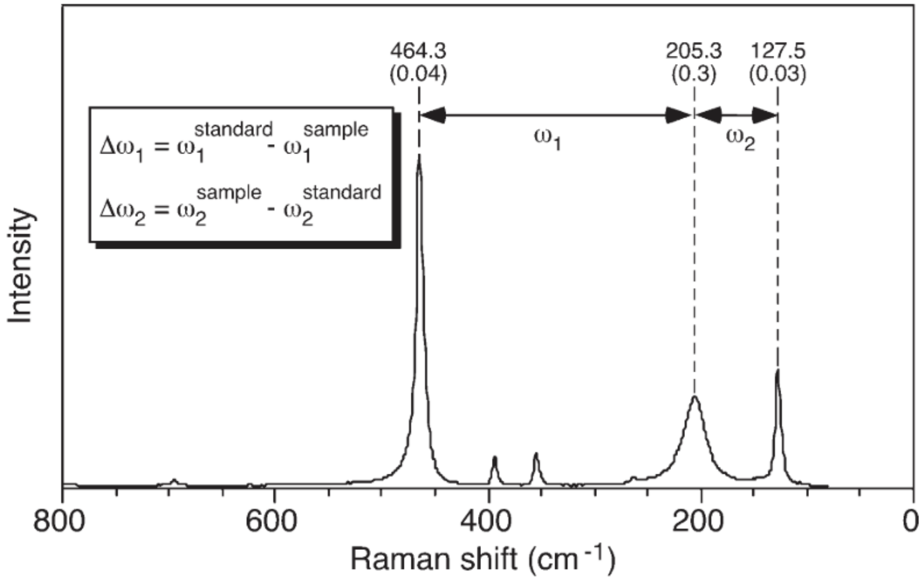
In the cabin (0.7~0.8atm)

3. Inclusion-host system

A direct application: elastic thermobarometry.

Steps: 1) spectroscopic data

1. Raman spectroscopy measurement



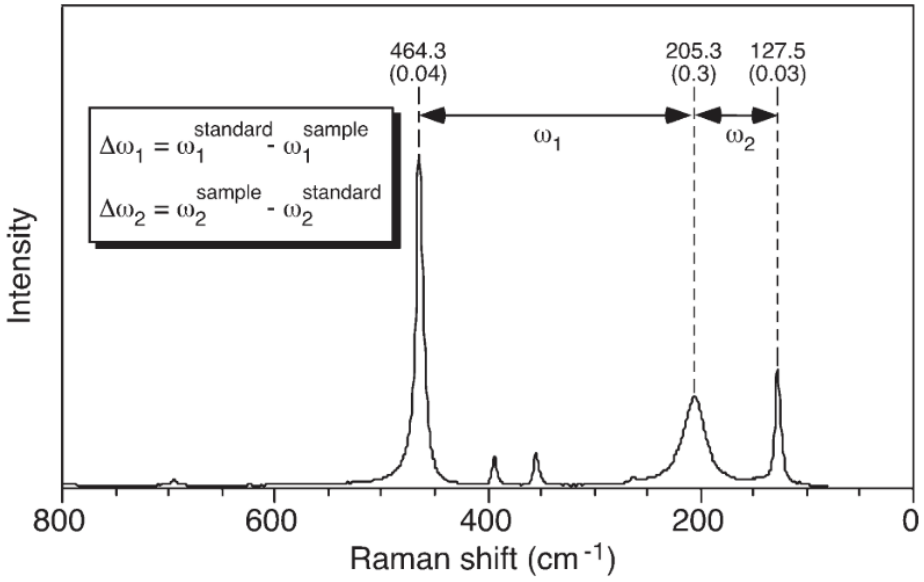
Enami et al. 2007

3. Inclusion-host system

A direct application: elastic thermobarometry.

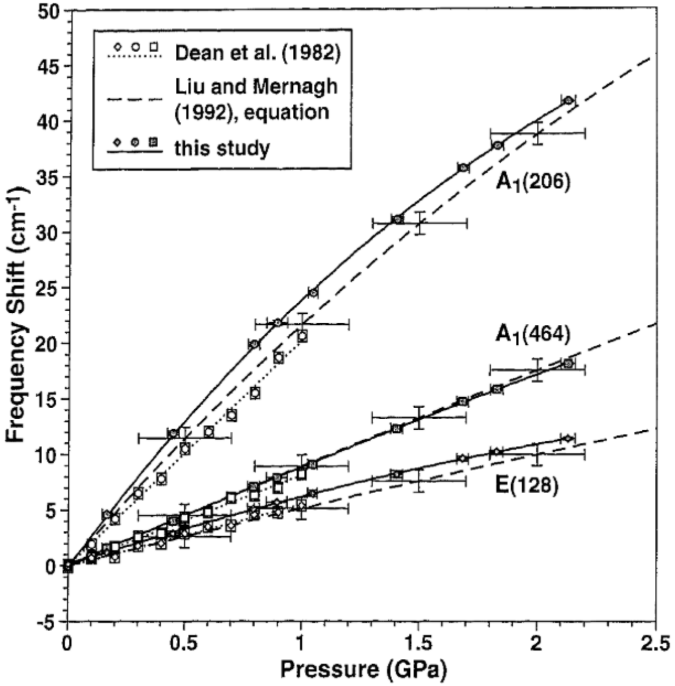
Steps: 1) spectroscopic data; 2) experimental calibrations

1. Raman spectroscopy measurement



Enami et al. 2007

2. Convert Raman shift to pressure



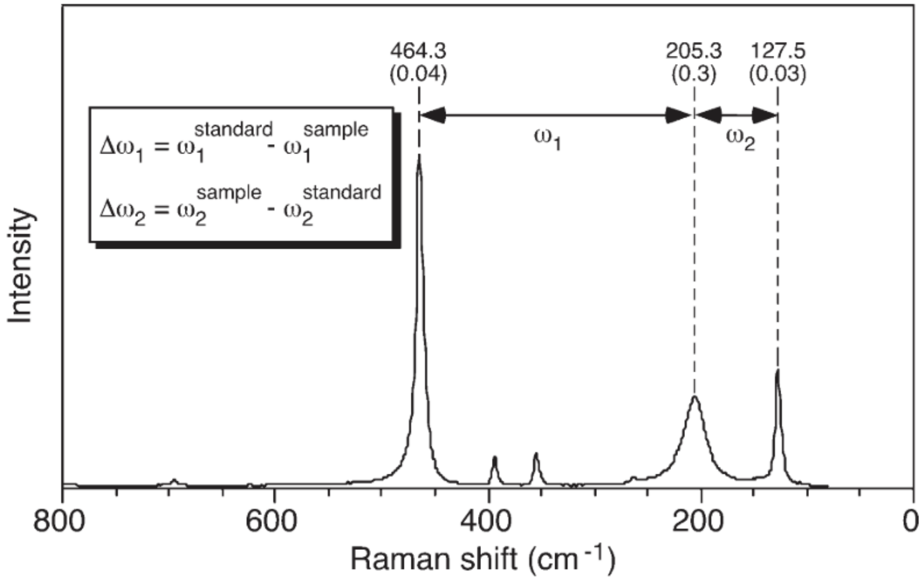
Schmidt and Ziemann 2000

3. Inclusion-host system

A direct application: elastic thermobarometry.

Steps: 1) spectroscopic data ; 2) experimental calibrations ; 3) elastic model (equation of state).

1. Raman spectroscopy measurement



Enami et al. 2007

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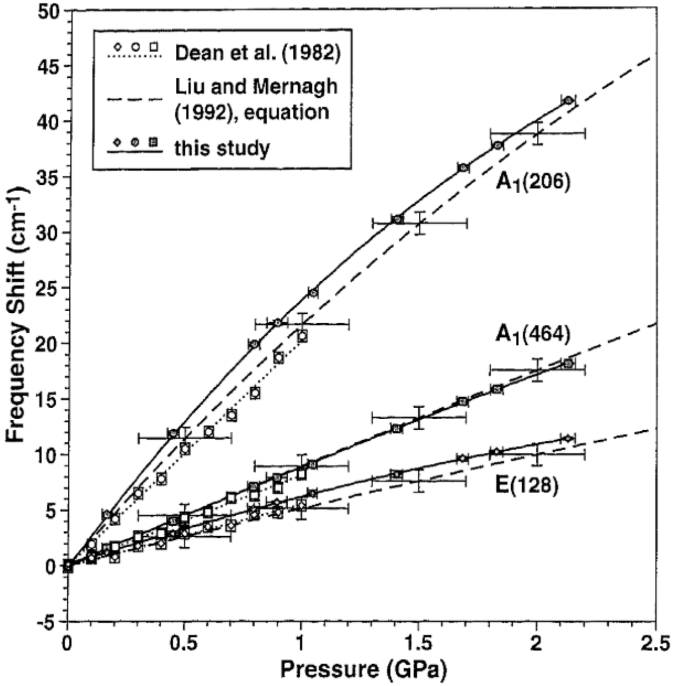
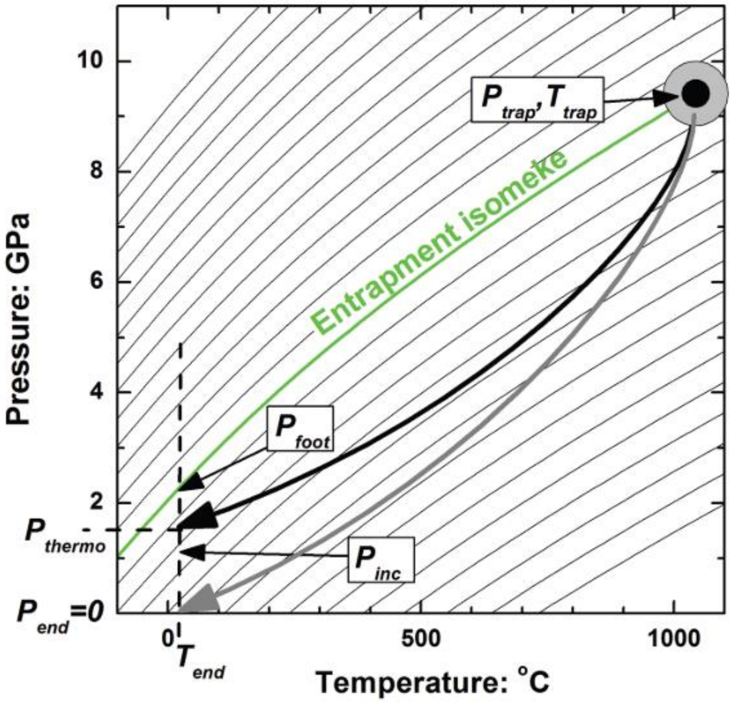


Schmidt and Ziemann 2000

3. Extract geological information



Angel et al. 2017

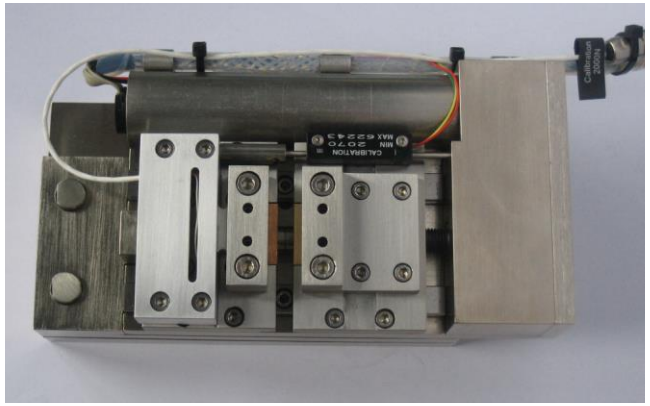
3. Inclusion-host system

Accurate quantifications, e.g. quartz

Determine residual stress or strain

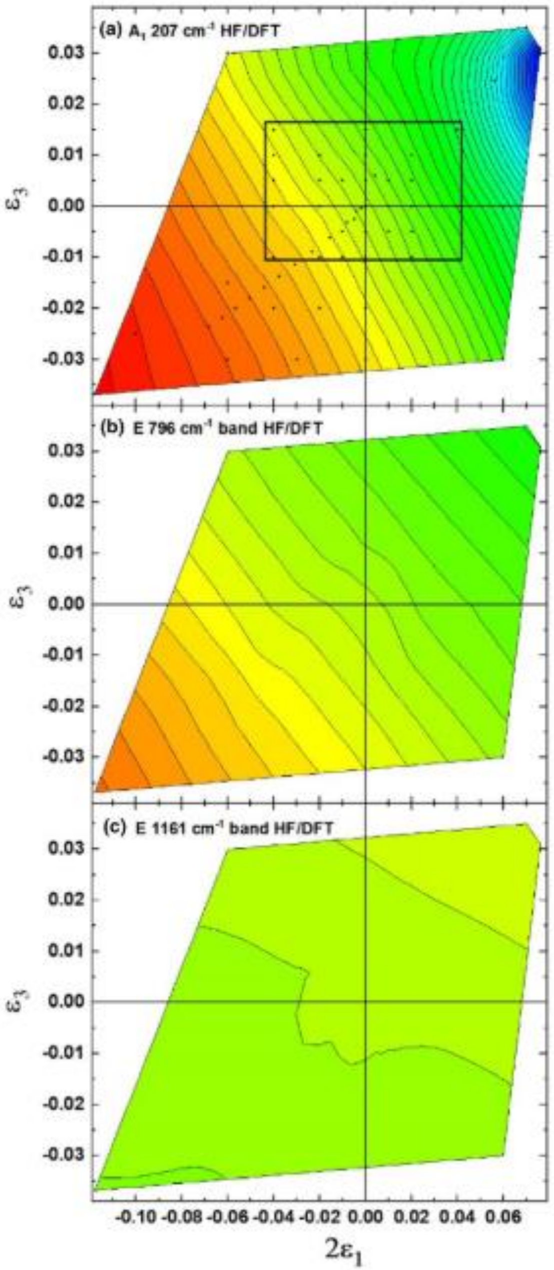
Grüneisen approach (HF-DFT)
From Raman shift to **strain**

Uniaxial experiment on quartz
From Raman shift to **stress**



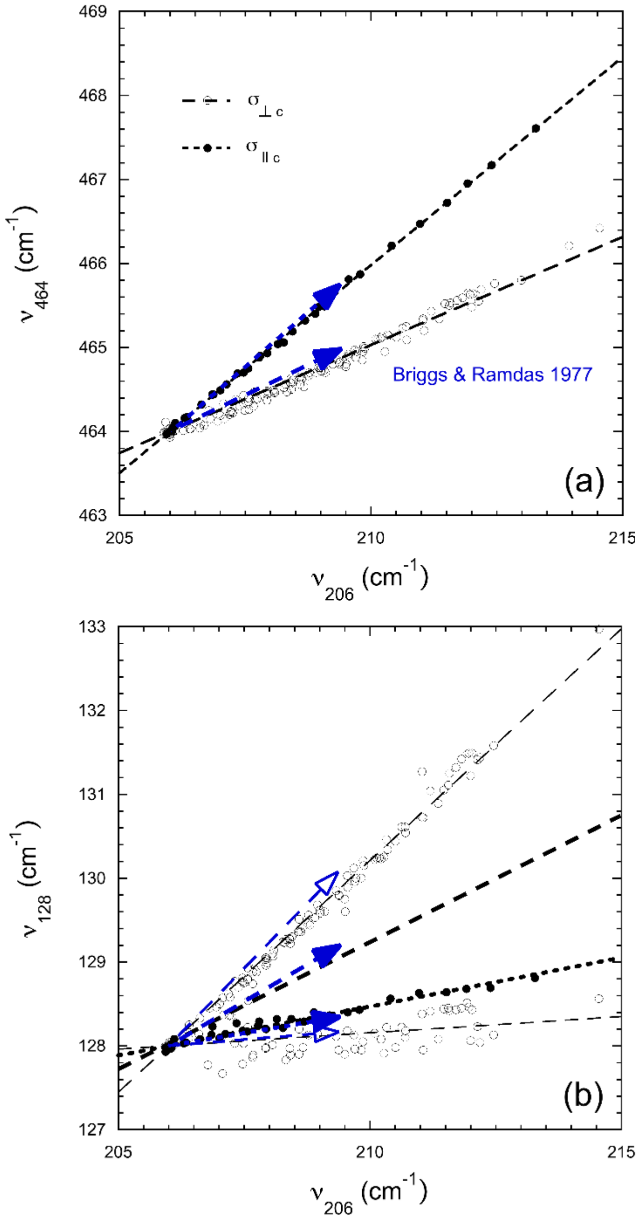
A tension-compression stage (Deben™ 5 kN)

Strain



Murri et al. 2019

Stress



Reynard and Zhong 2023 (EGU solid earth)

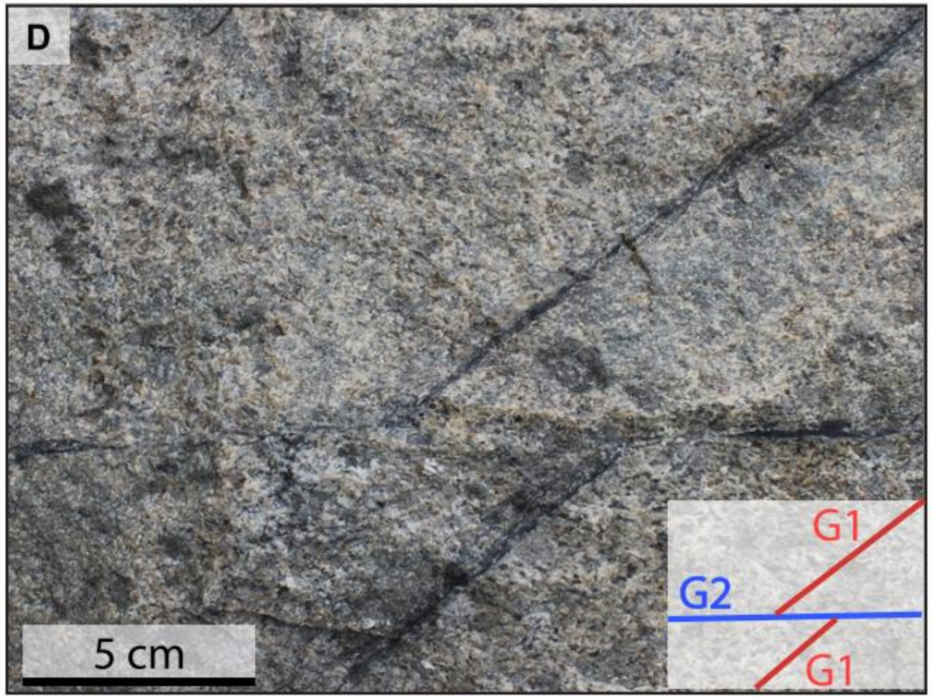
Poster Monday afternoon Hall X2.106

4. Case study: pseudotachylyte

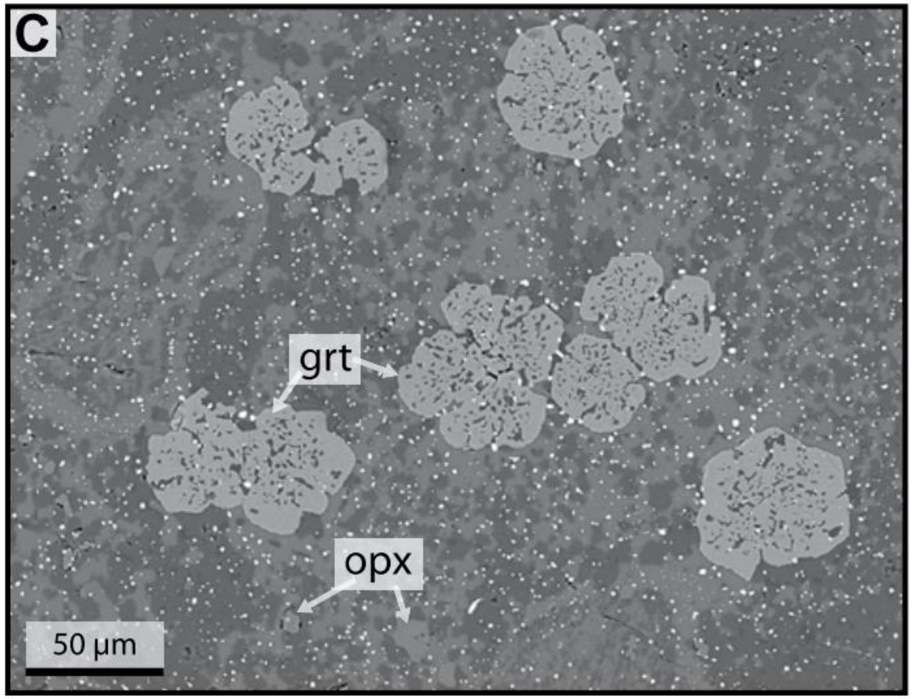
Difficult to study frictional melt pressure during or immediately after earthquakes.

Case one: Lofoten, northern Norway.

Pseudotachylyte vein



“Cauliflower” garnet



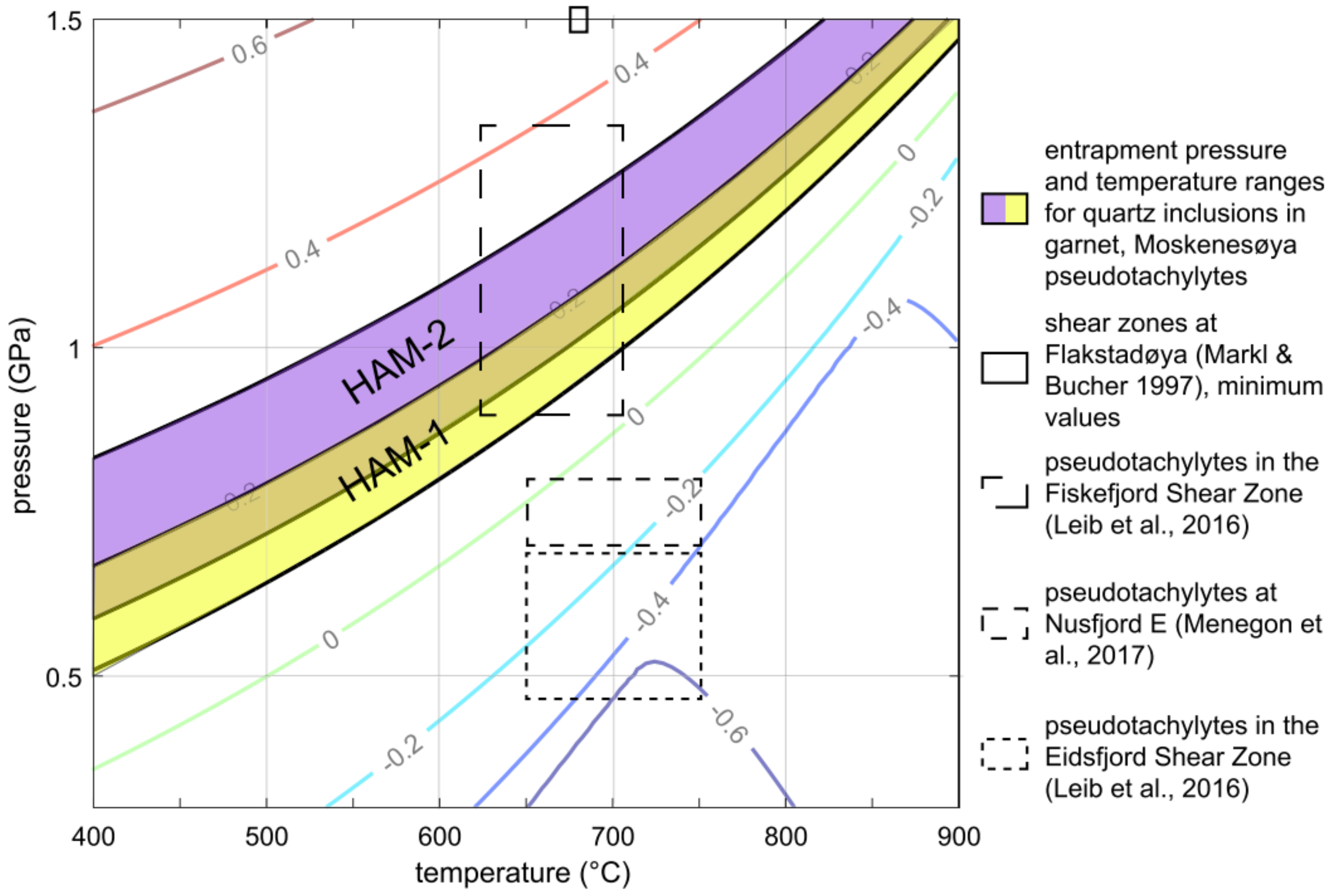
Dunkel, Zhong, Arnestad, Valen, Jamtveit 2020 Geology

4. Case study: pseudotachylyte

Difficult to study frictional melt pressure during or immediately after earthquakes.

Case one: Lofoten, northern Norway.

Independent constraint of melt pressure.

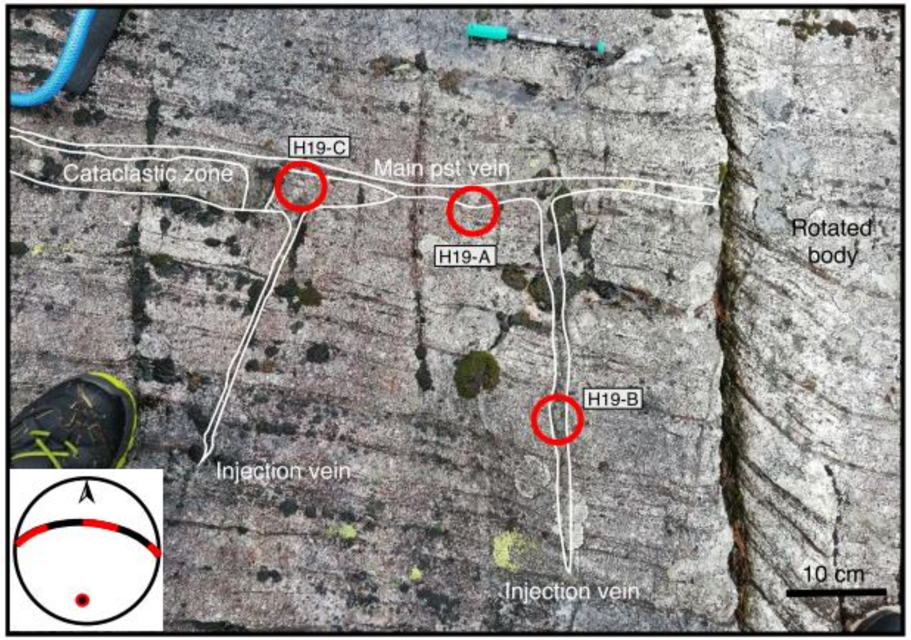


Dunkel, Zhong, Arnestad, Valen, Jamtveit 2020 Geology

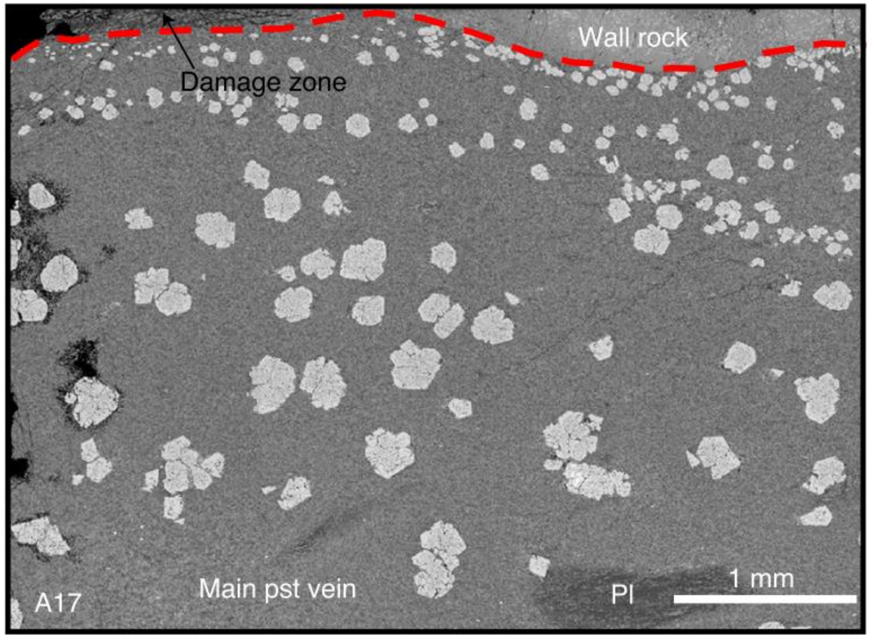
4. Case study: pseudotachylyte

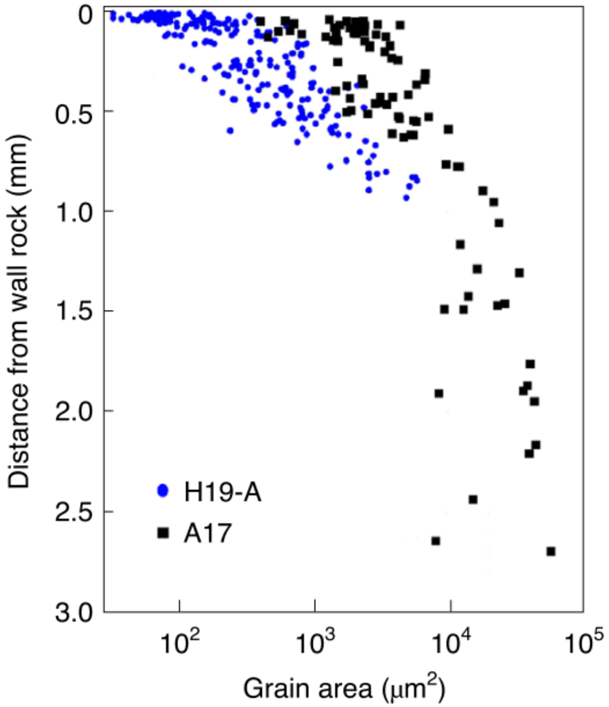
Case two: Holsnøy Island, western Norway.

Pseudotachylyte injection vein



"Dandelion-like" garnet from rock-melt interface



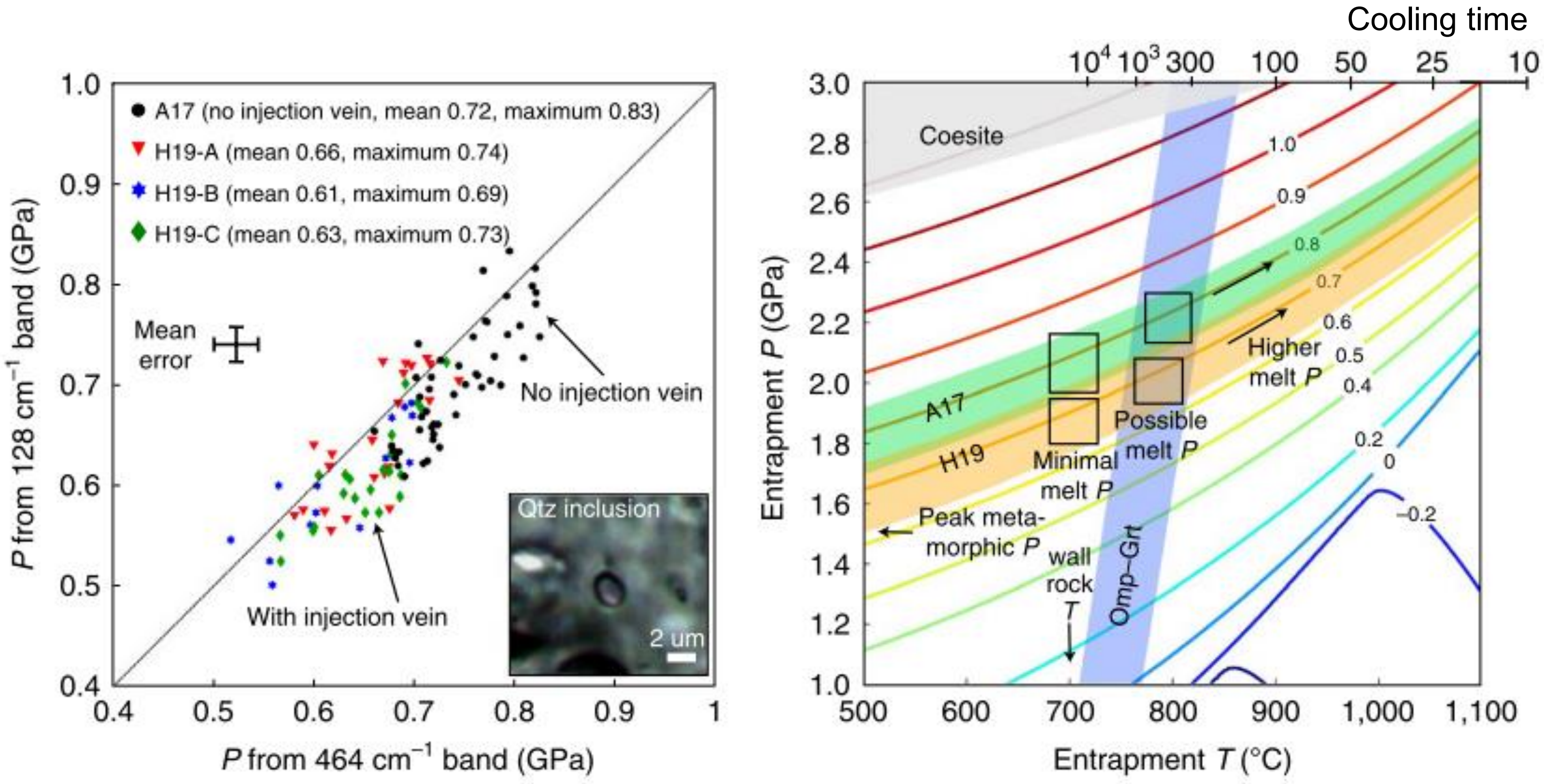


Zhong, Petley-Ragan, Incel, Dabrowski, Andersen, Jamtveit, 2021, Nat. Geo.

4. Case study: pseudotachylyte

Case two: Holsnøy Island, western Norway.

Determination of frictional melt pressure immediately after earthquakes.

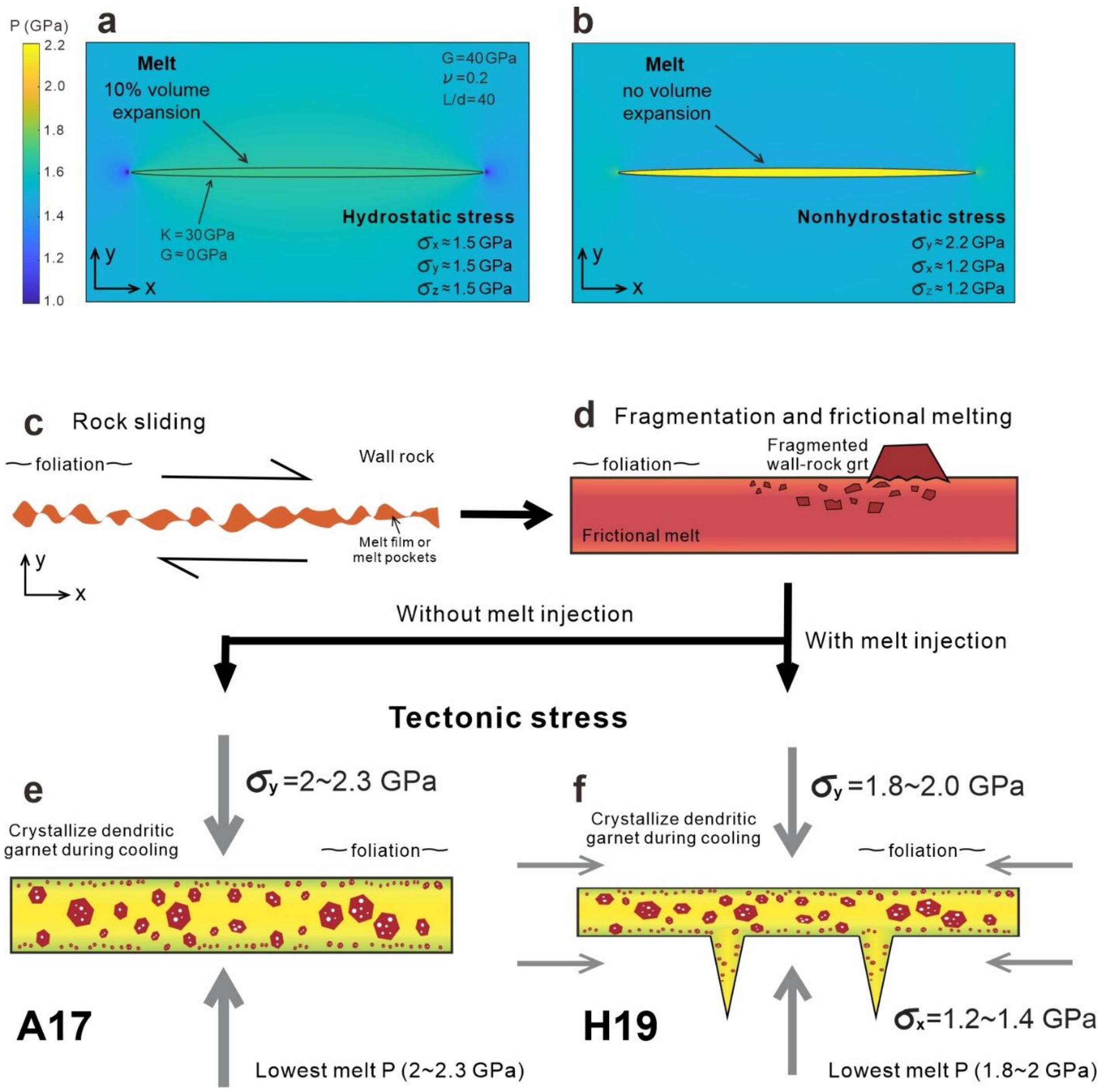


Zhong, Petley-Ragan, Incel, Dabrowski, Andersen, Jamtveit, 2021, Nat. Geo.

4. Case study: pseudotachylyte

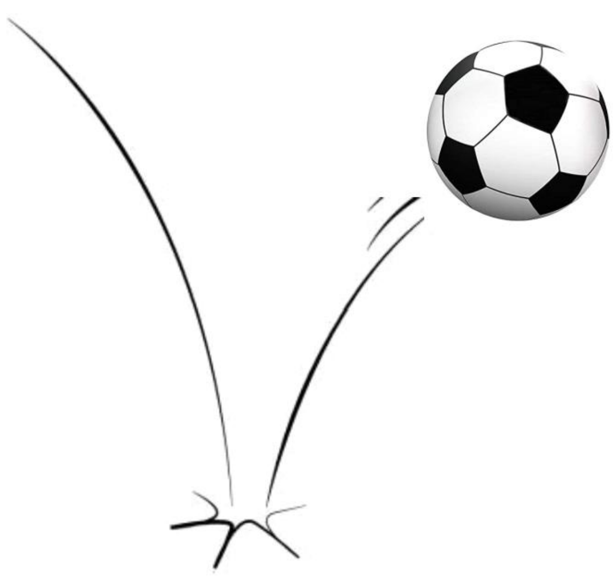
Case two: Holsnøy Island, western Norway.

- With elastic model applied to injection vein, it is possible to show an transient overpressure in the frictional melt.
- By applying the Eshelby's model, the overpressure is explained by a GPa-level differential stress in the lower crust.



Zhong, Petley-Ragan, Incel, Dabrowski, Andersen, Jamtveit, 2021, Nat. Geo.

5. Stress relaxation



Temperature and time

Elastic

- Reversible
- Nearly instantaneous

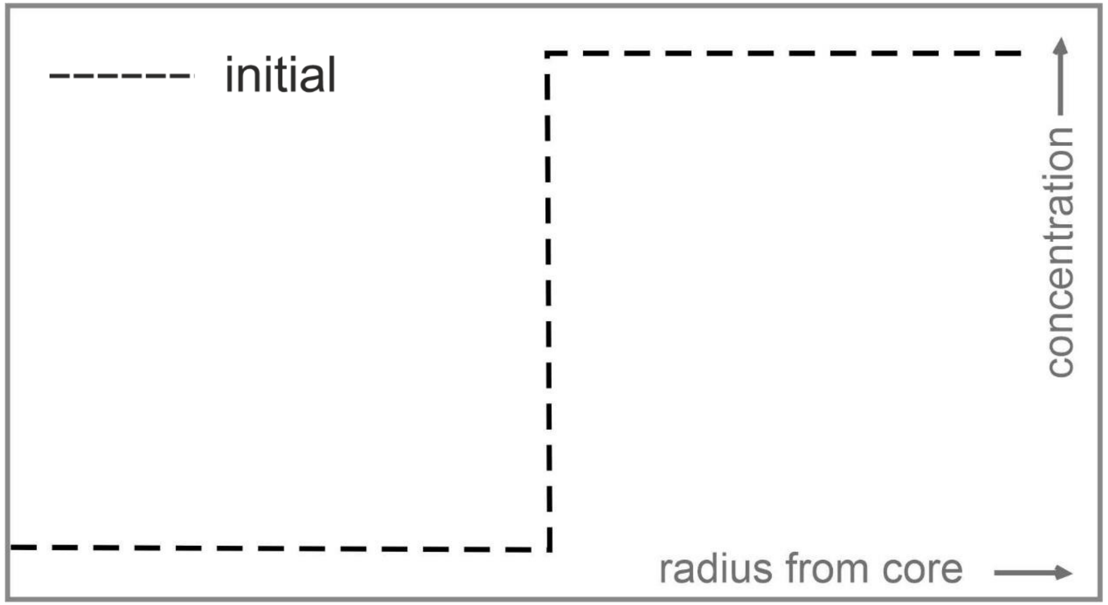
Viscous

- Irreversible
- Time dependent

5. Stress relaxation

At high temperature and given enough time

Diffusion homogenization



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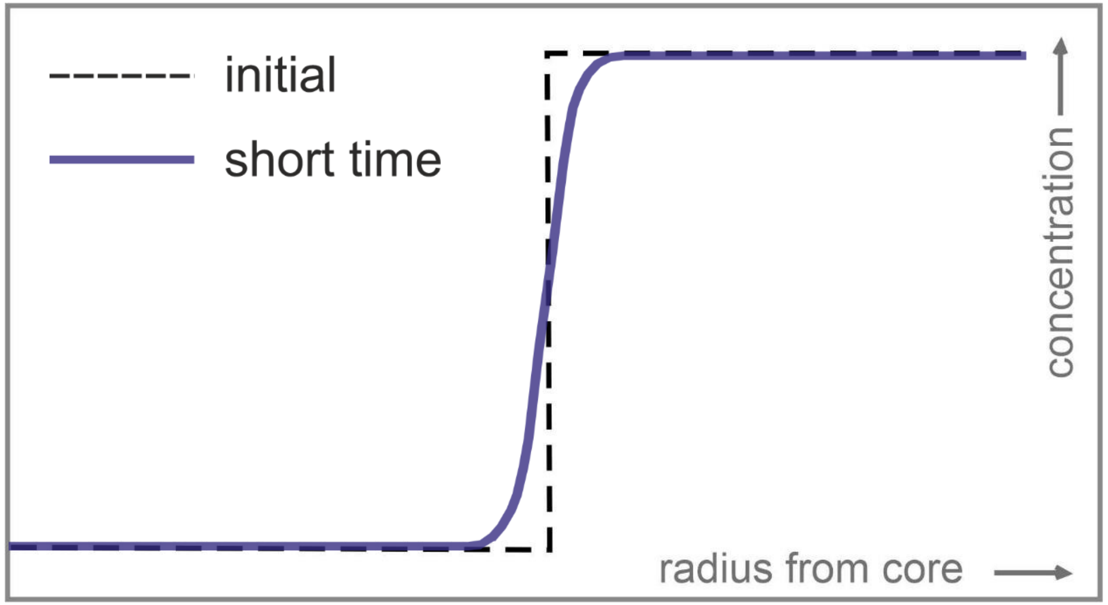
At high temperature and given enough time

Diffusion homogenization



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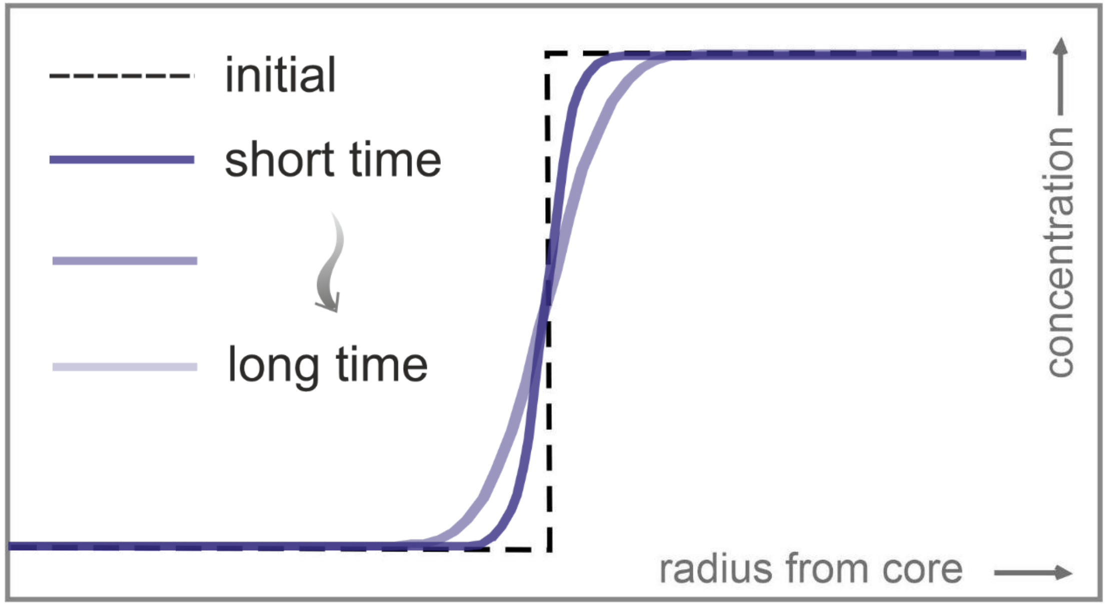

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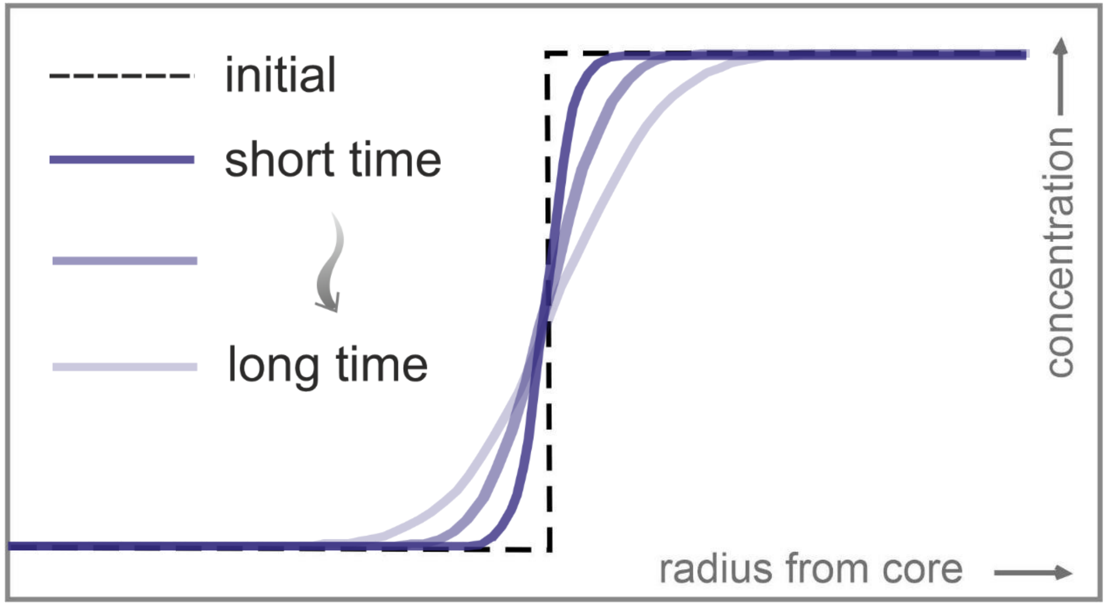

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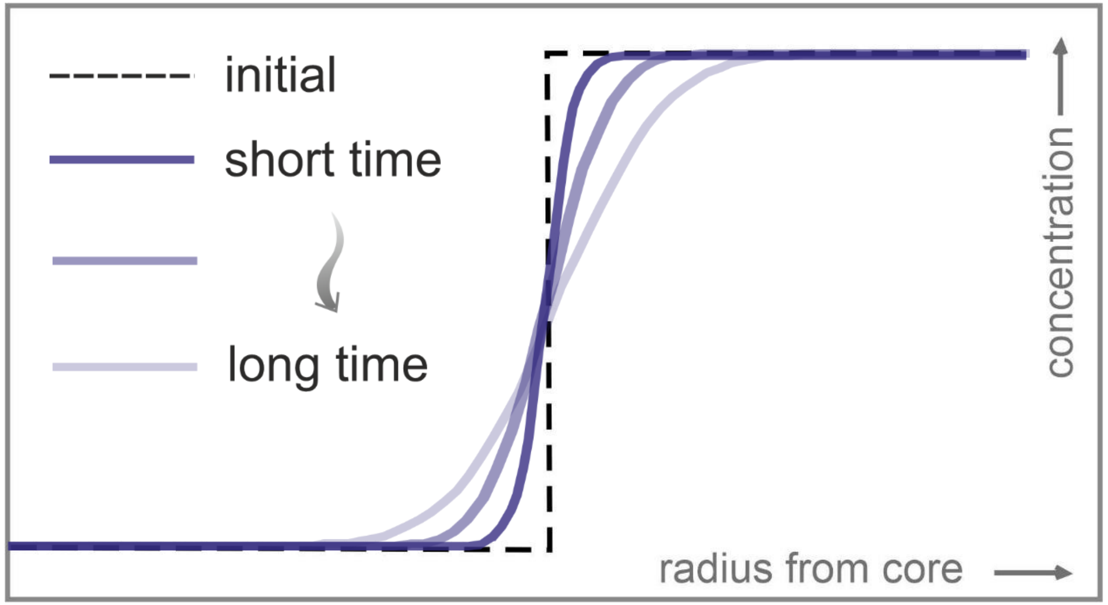
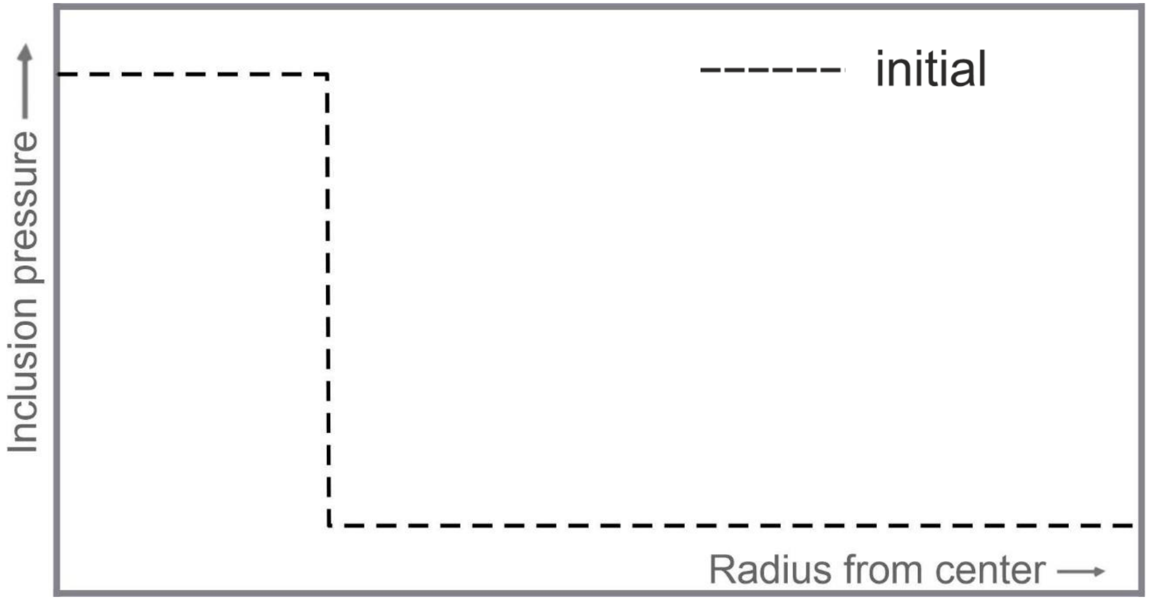
At high temperature and given enough time

Diffusion homogenization



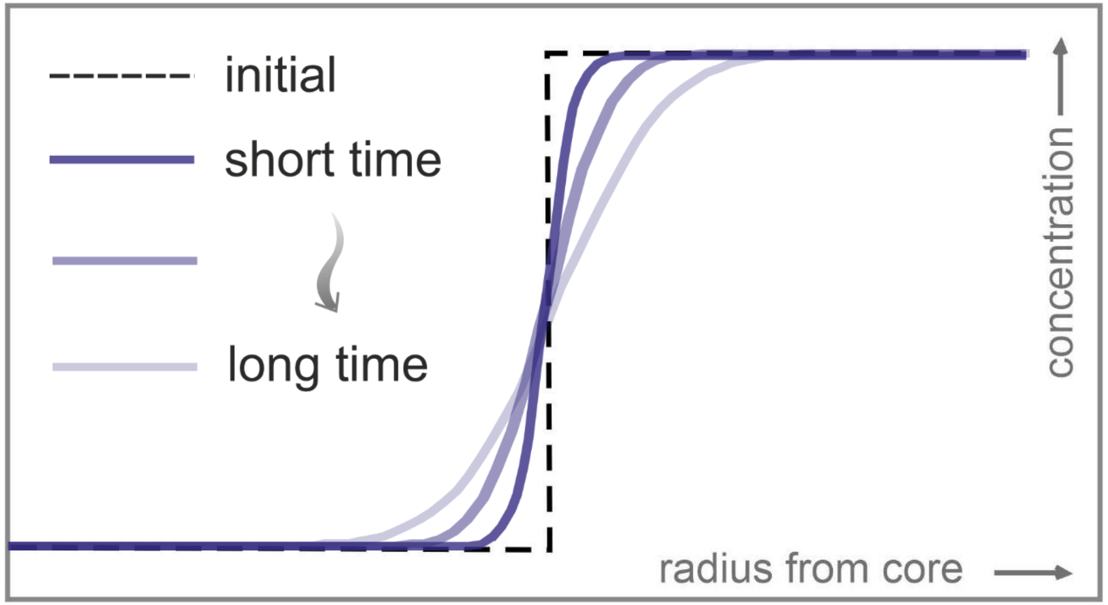
Viscous stress relaxation



5. Stress relaxation

At high temperature and given enough time

Diffusion homogenization



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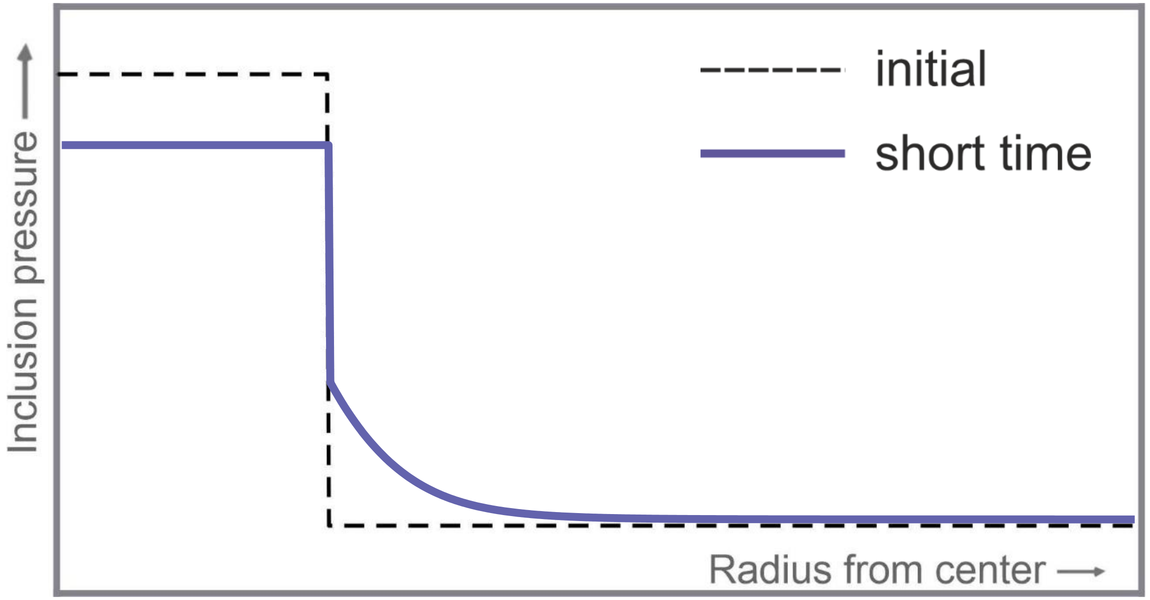

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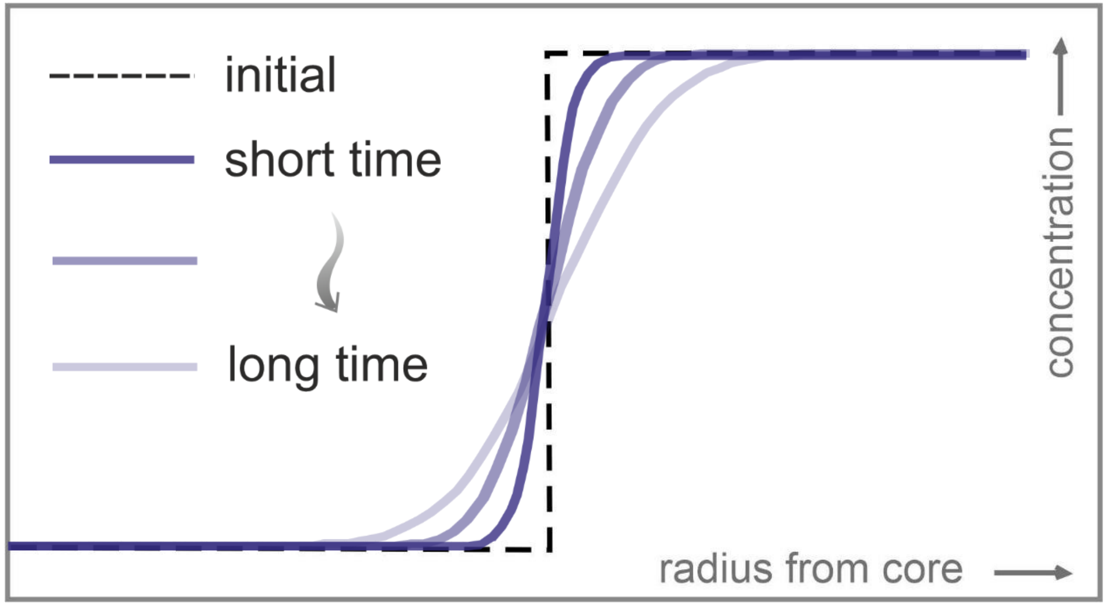
At high temperature and given enough time

Diffusion homogenization



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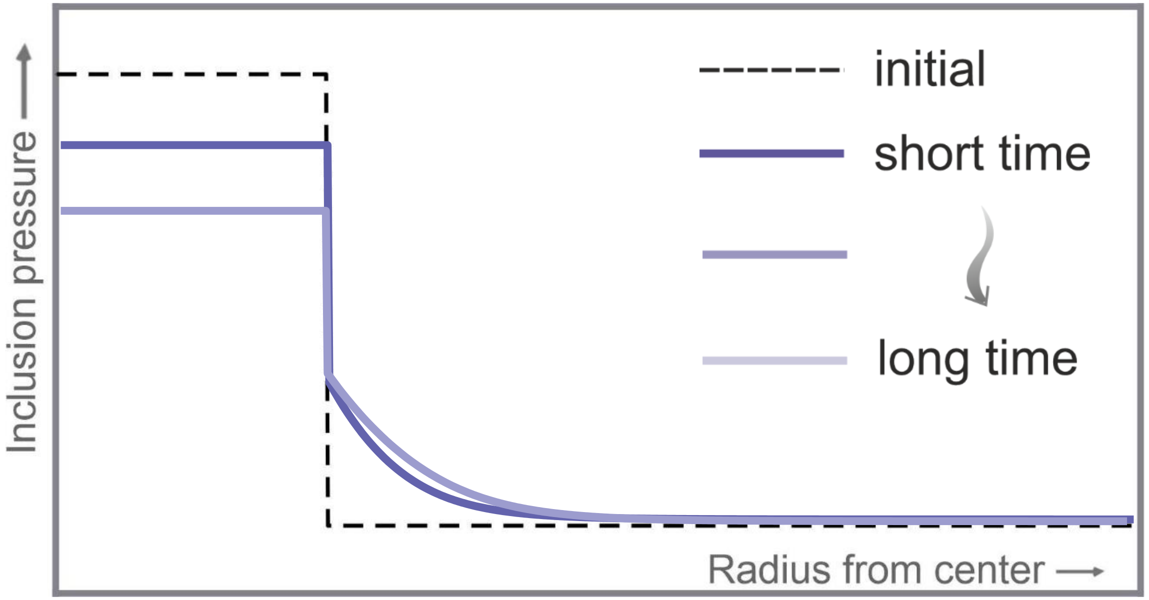

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At high temperature and given enough time

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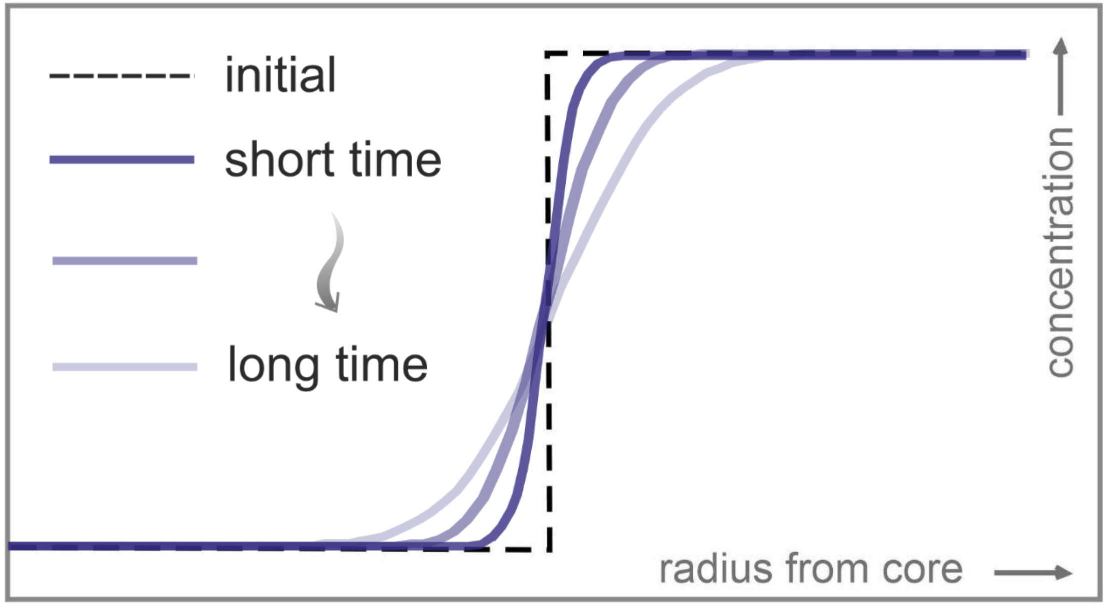

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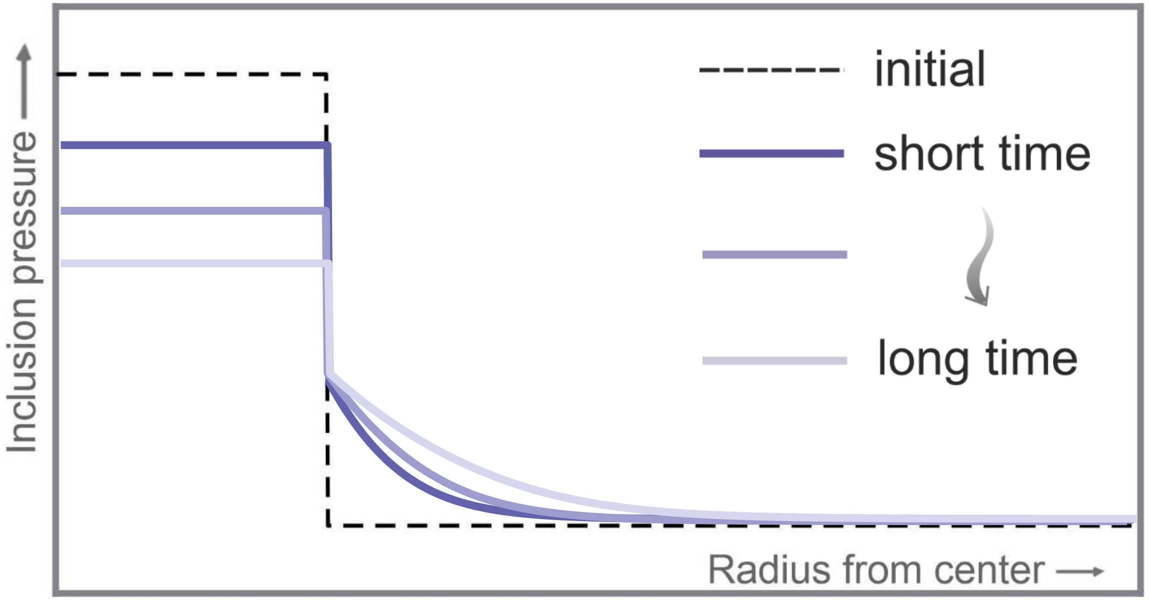
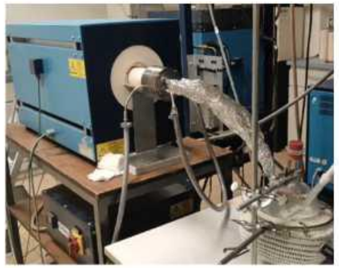
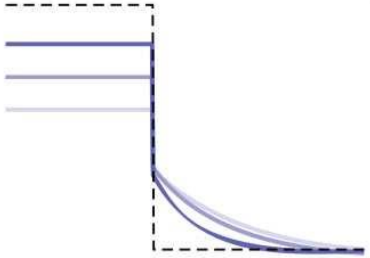


5. Stress relaxation

Field data



Experiment

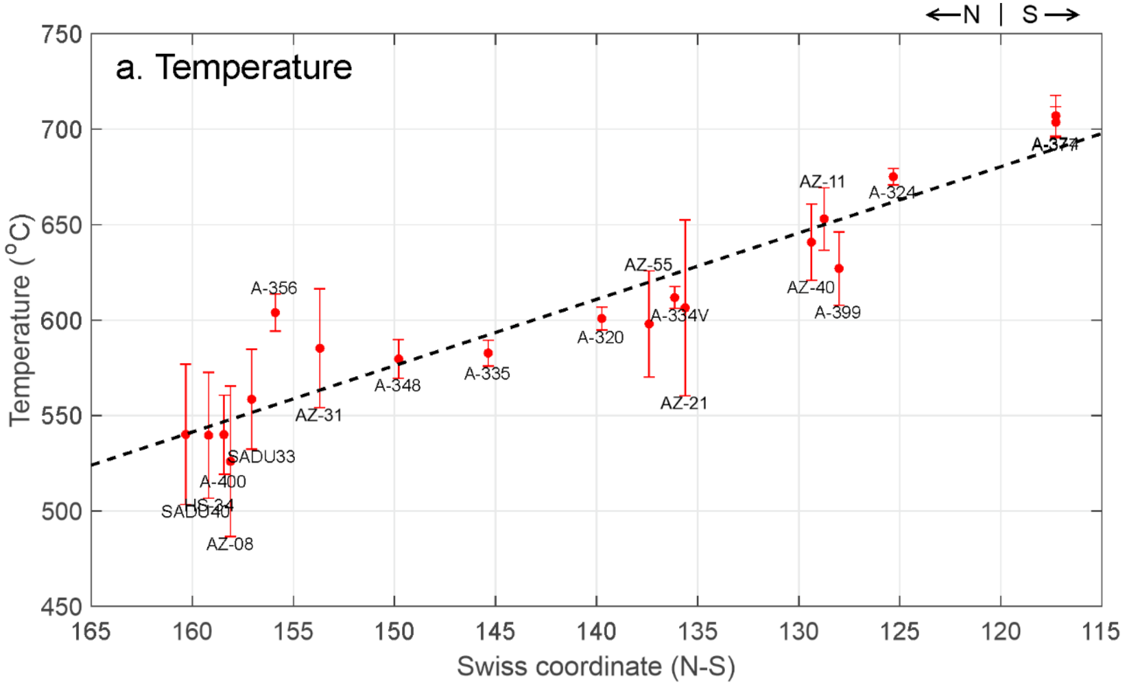


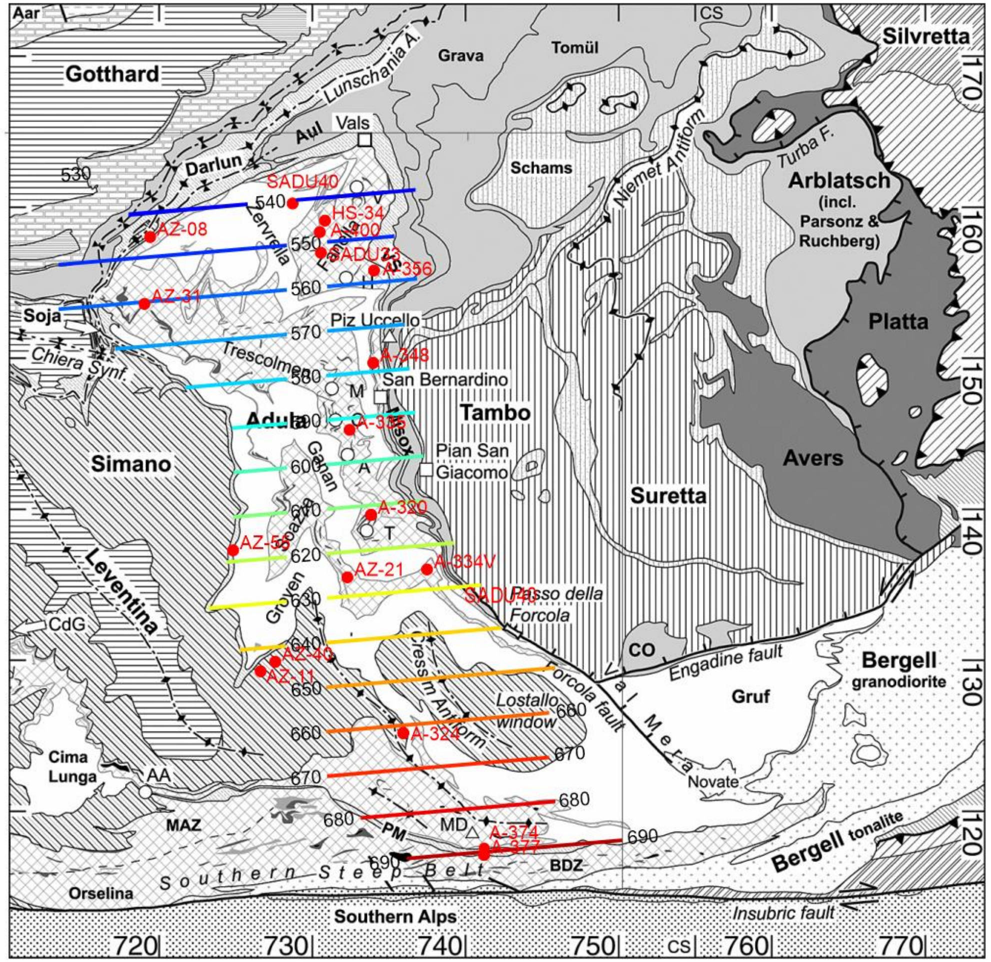
Modelling

5. Stress relaxation

Natural rock data (Adula nappe)

Zr-in-rutile thermometer

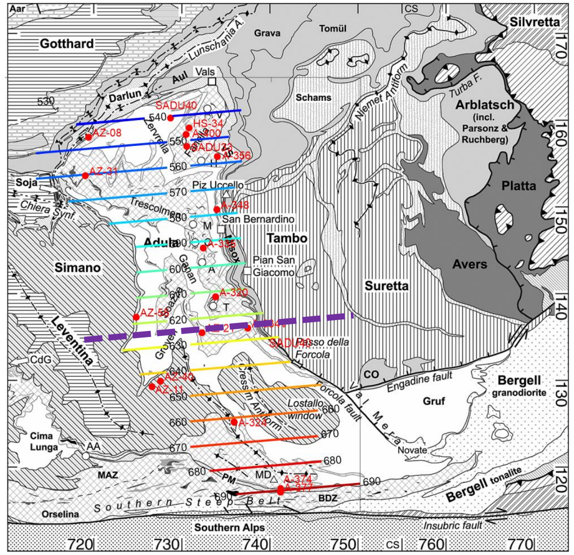




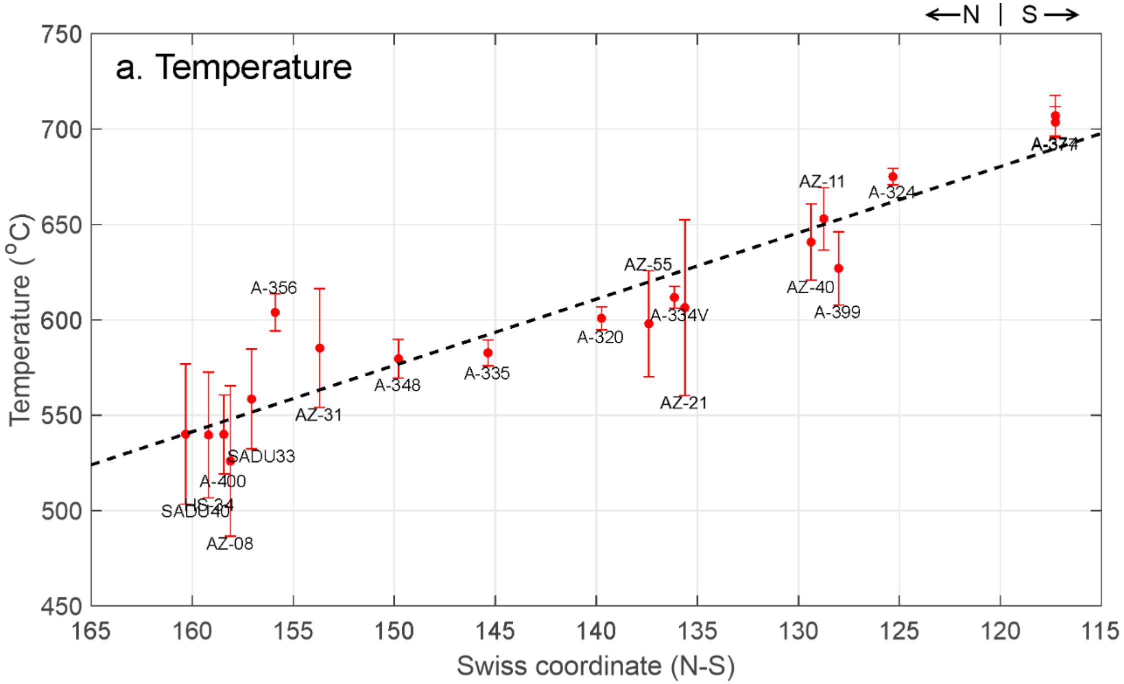
Adjusted from Pleuger and Podladchikov 2014

5. Stress relaxation

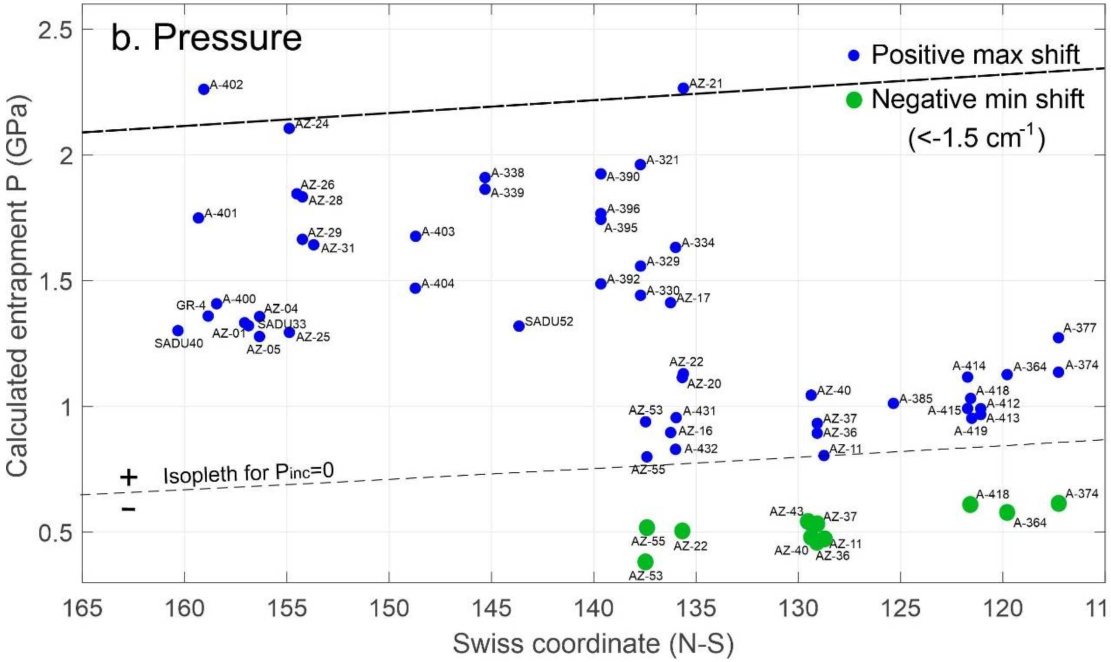
Natural rock data (Adula nappe)



Zr-in-rutile thermometer



Quartz-in-garnet elastic barometer



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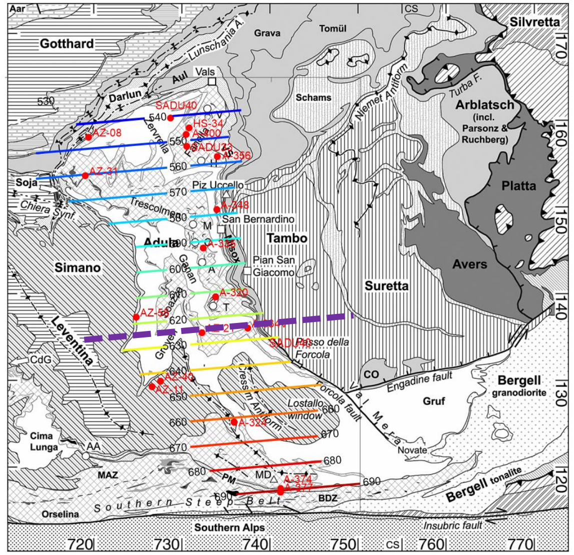

Natural rock data (Adula nappe)

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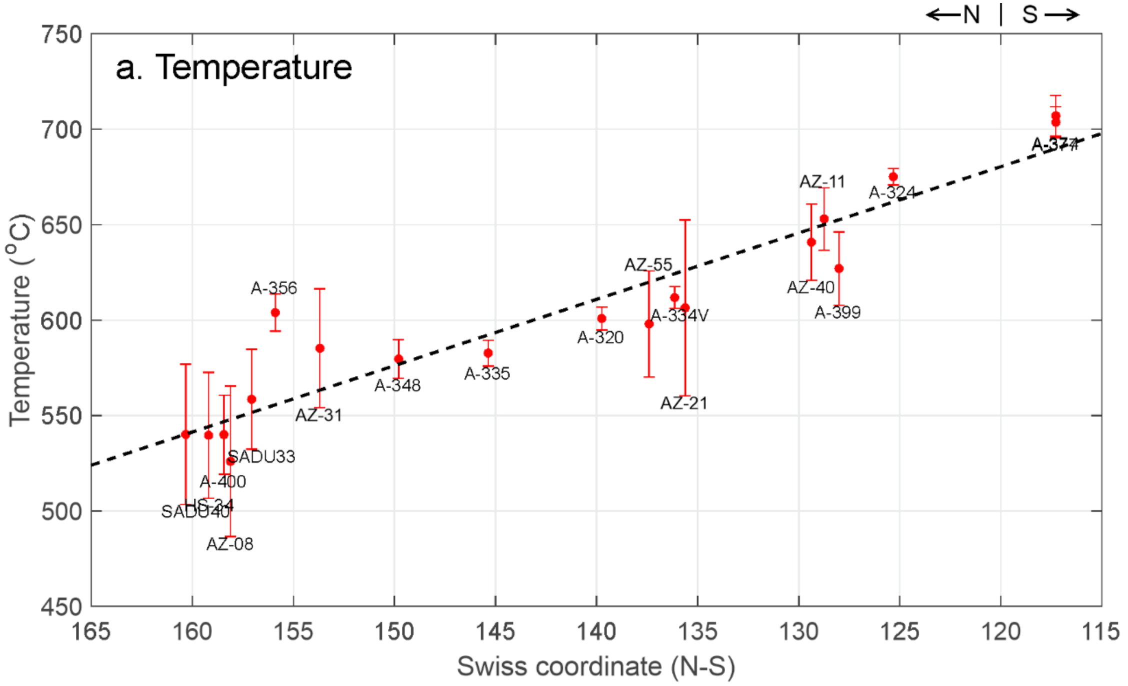

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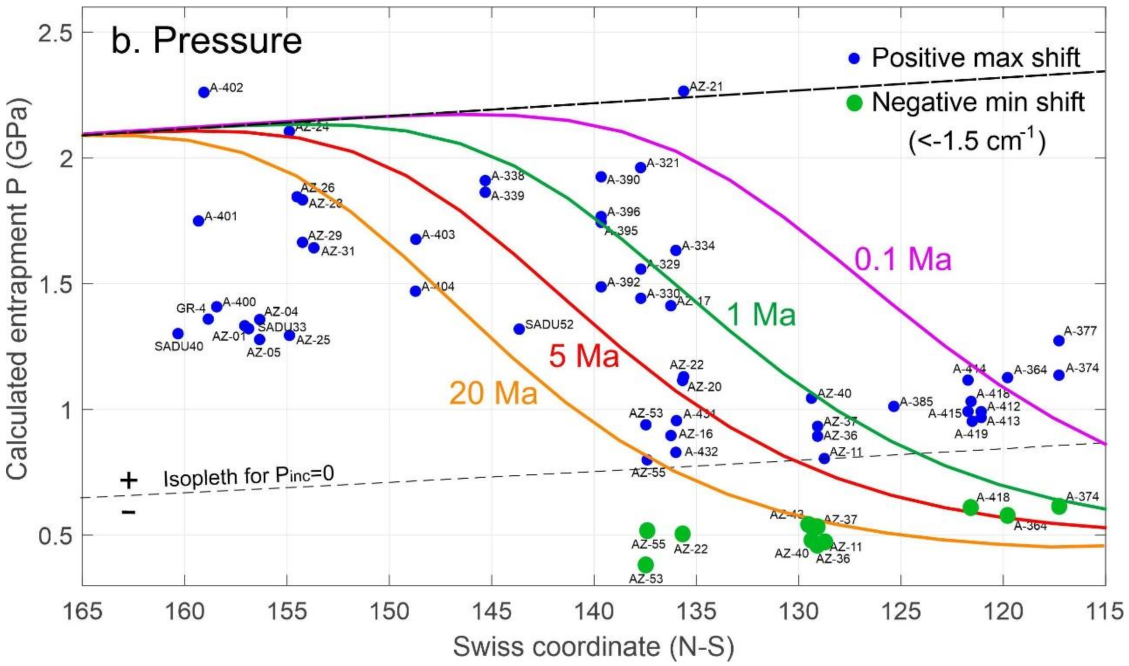

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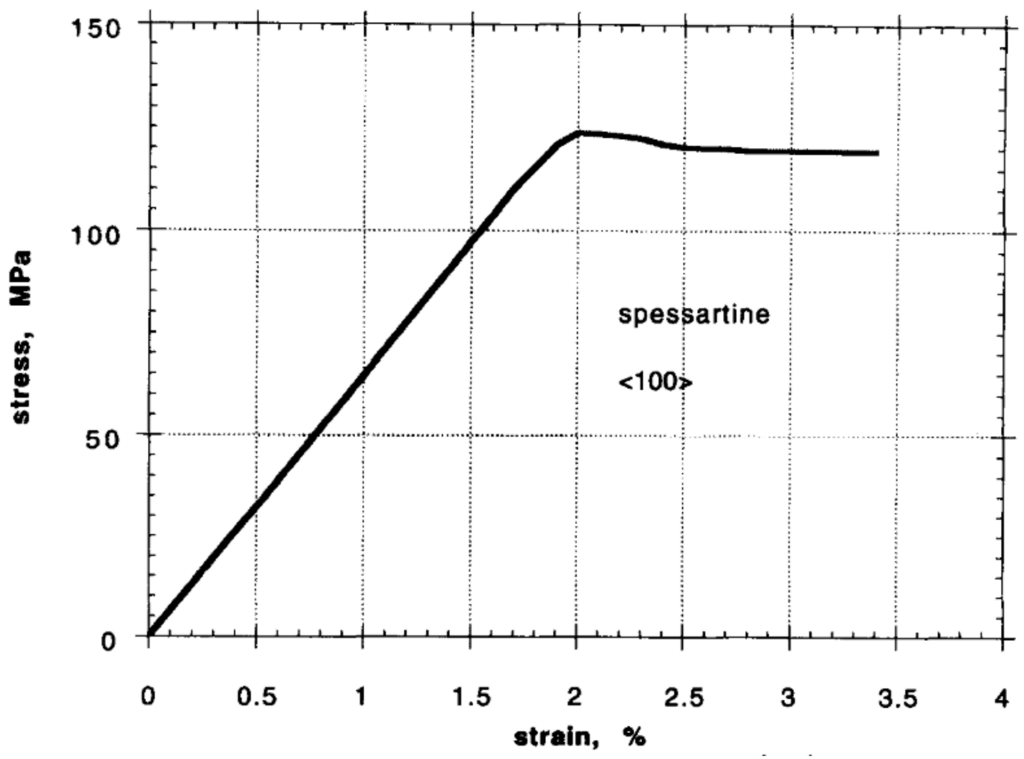
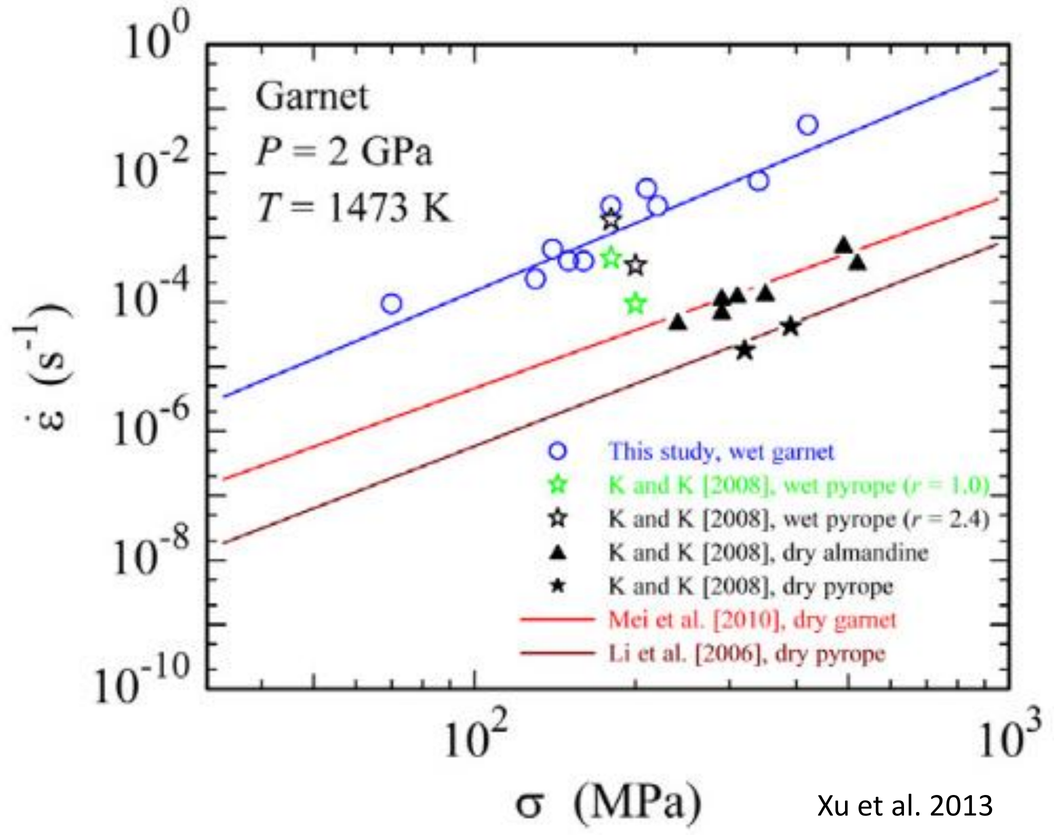
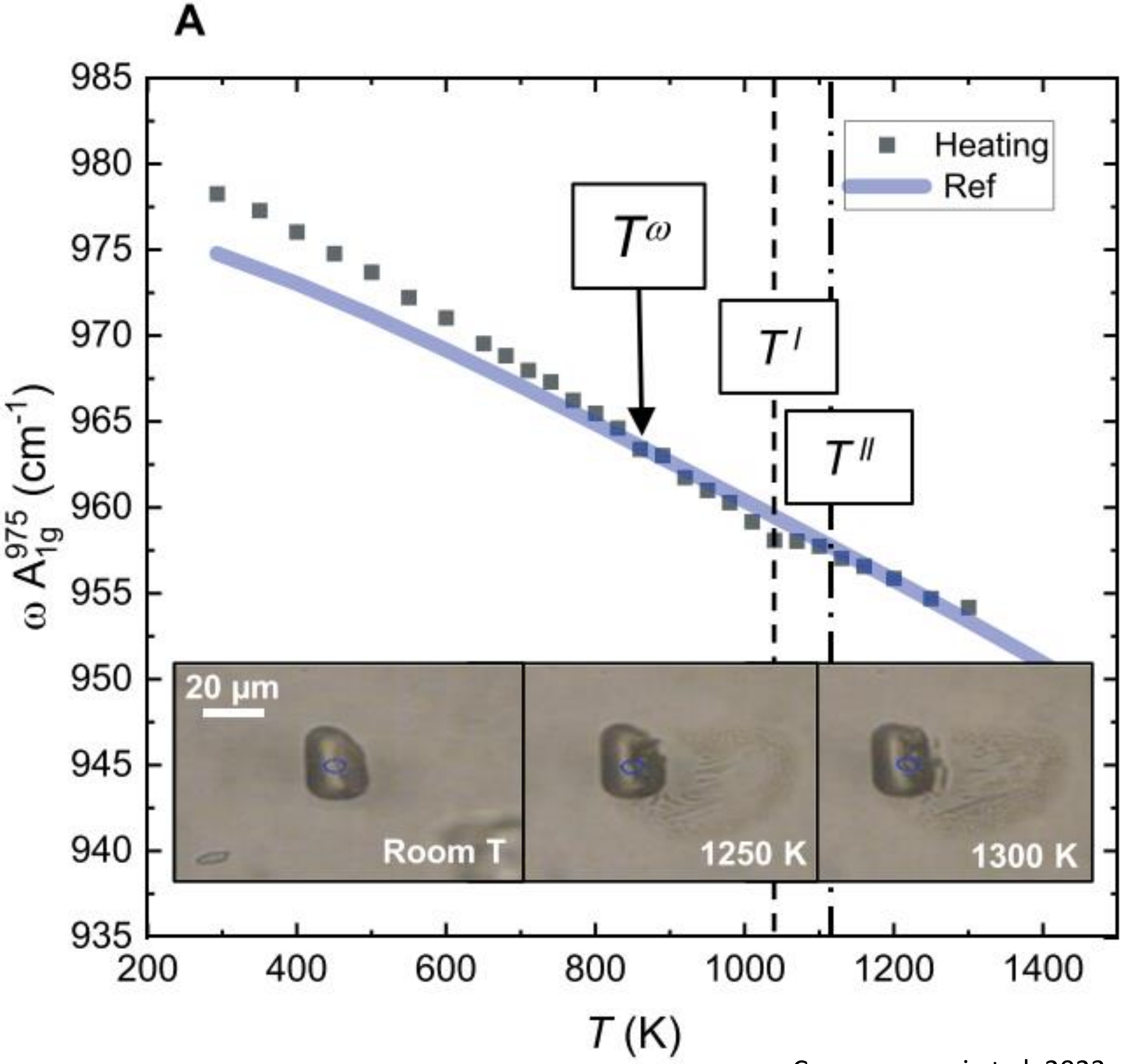


Karato et al. 1995



Xu et al. 2013

5. Stress relaxation



Campomenosi et al. 2023

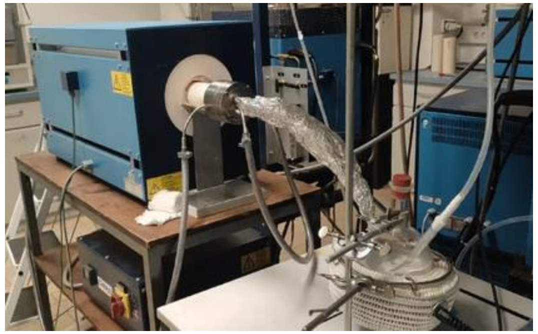
5. Stress relaxation

To quantify the rate of relaxation

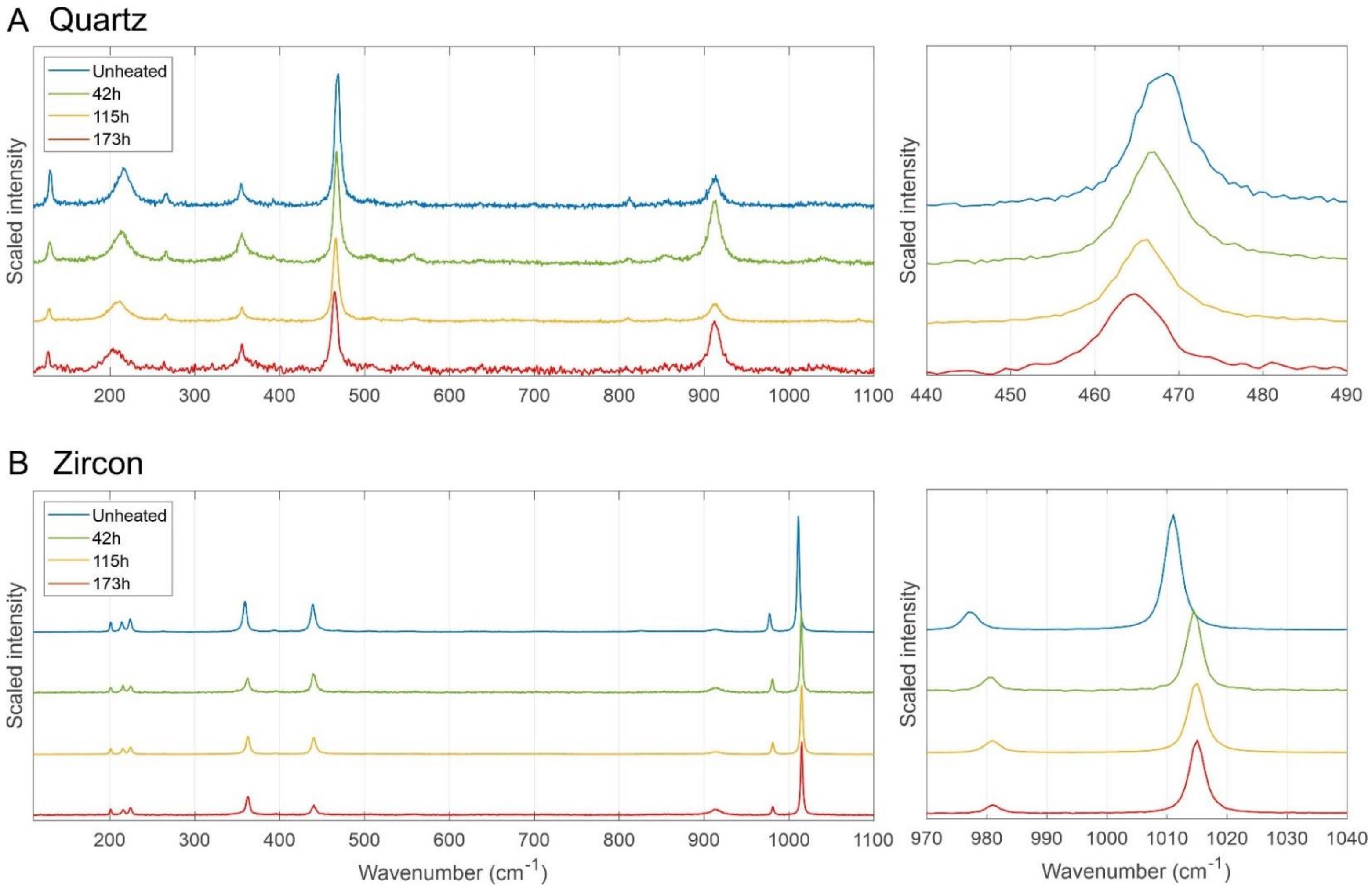
1. Measure Raman shift of inclusions
2. Send the sample to furnace
3. Heat it for a given time.
4. Take it out and remeasure.

Three buffering conditions tested:

1. Graphite buffered.
2. Water + Ar gas buffered.
3. Hydrogen + nitrogen buffered.



Water + Ar gas buffered experiment

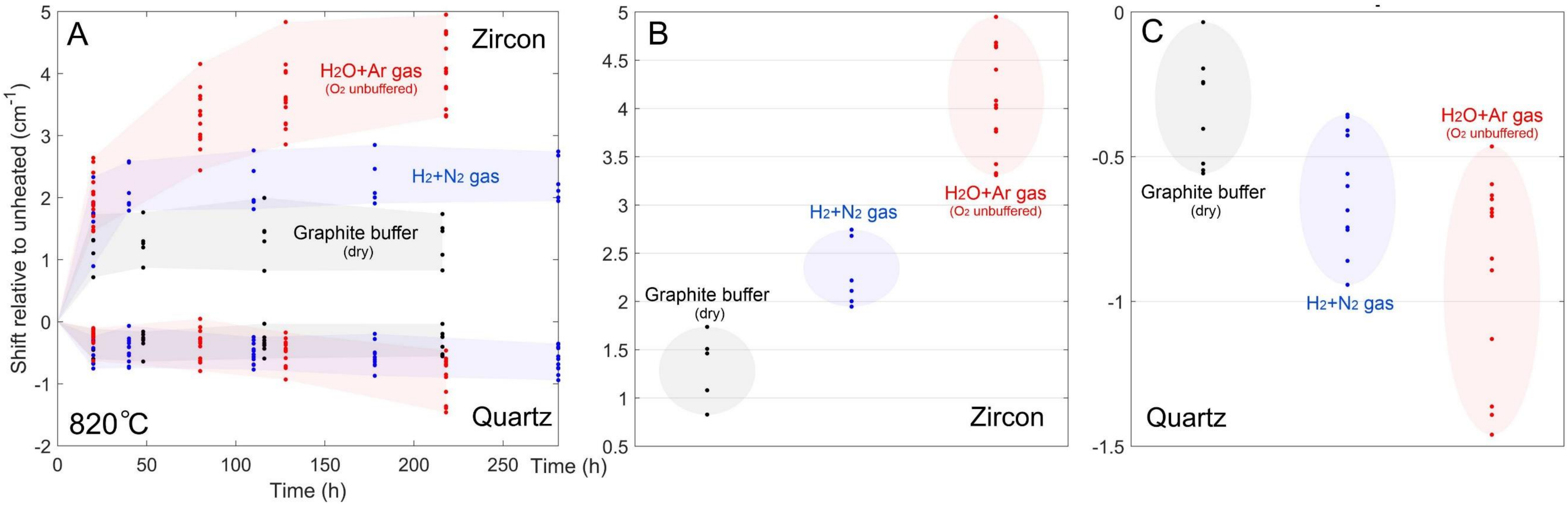


For details please visit Room D2, Friday, 08:40–08:50

Zhong; Wallis; Kingsbery; John. 2023, in-prep

5. Stress relaxation

The effect of adding water and hydrogen.



For details please visit Room D2, Friday, 08:40–08:50

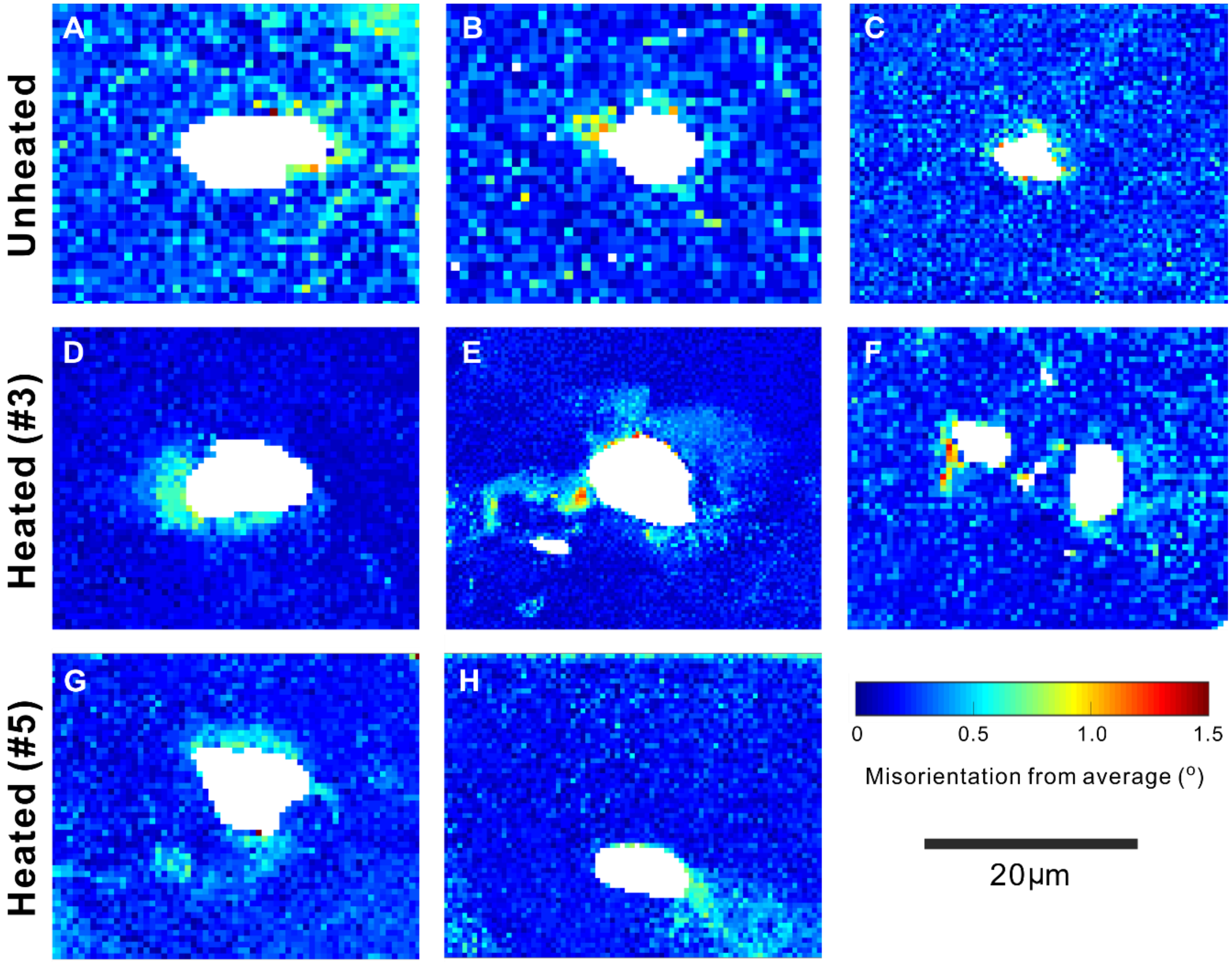
Zhong; Wallis; Kingsbery; John. 2023, in-prep

5. Stress relaxation

EBSD misorientation map

Water present condition

More dislocations?



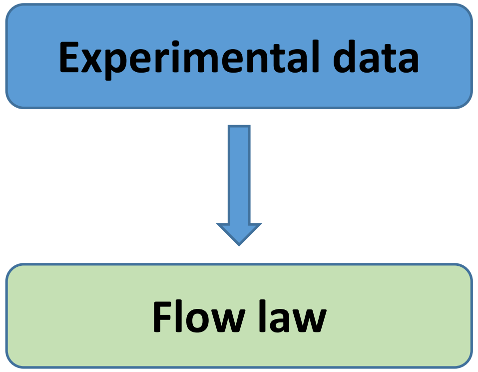
Zhong; Wallis; Kingsbery; John. 2023, in-prep

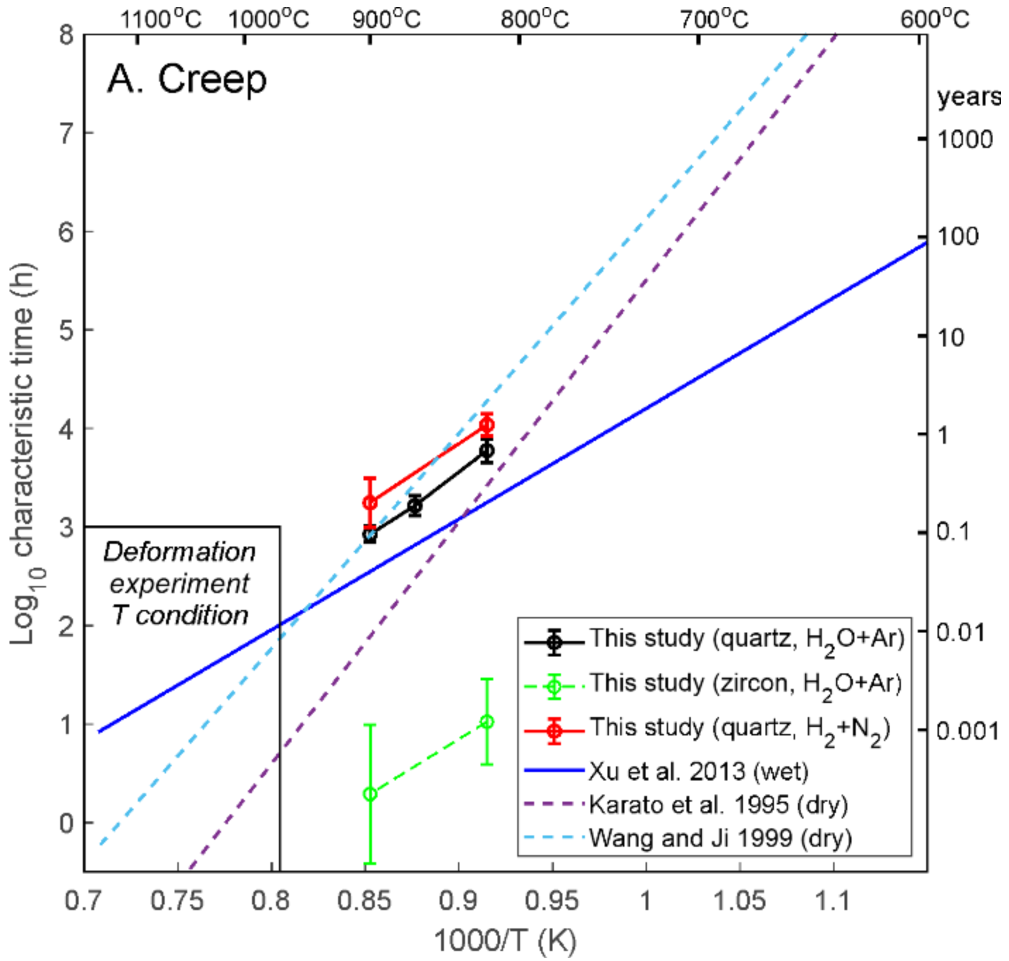
For details please visit Room D2, Friday, 08:40–08:50

5. Stress relaxation

- 1-D radially symmetric visco-elastic model
- Power-law creep (dislocation creep with *n*=3).
- Viscosity pre-factor to be fitted

Implications from experimental data



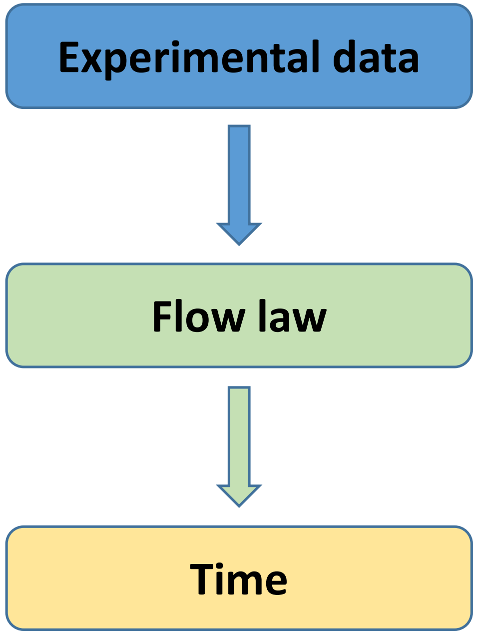


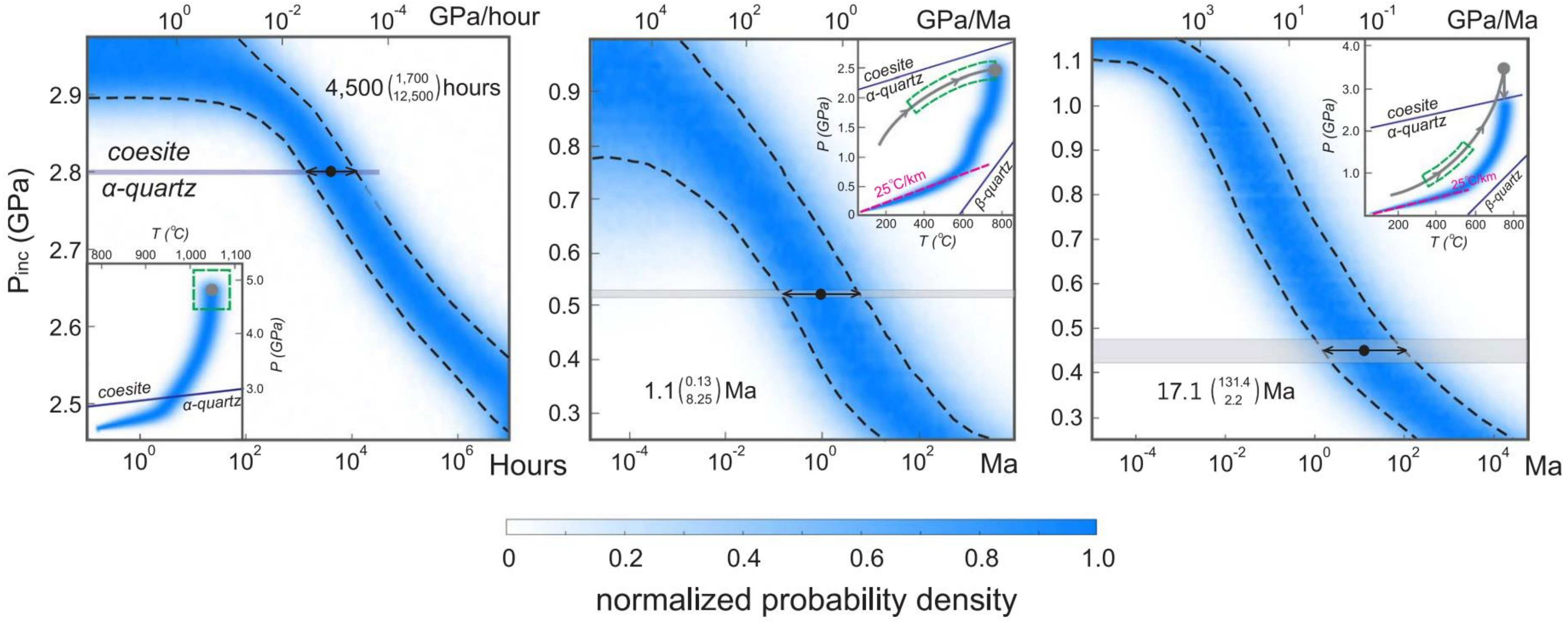
Zhong; Wallis; Kingsbery; John. 2023, in-prep

5. Stress relaxation

- 1-D radially symmetric visco-elastic model.
- Power-law creep from experiment Wang and Ji 1999, Karato et al. 1995.

Extrapolation to geological time scale



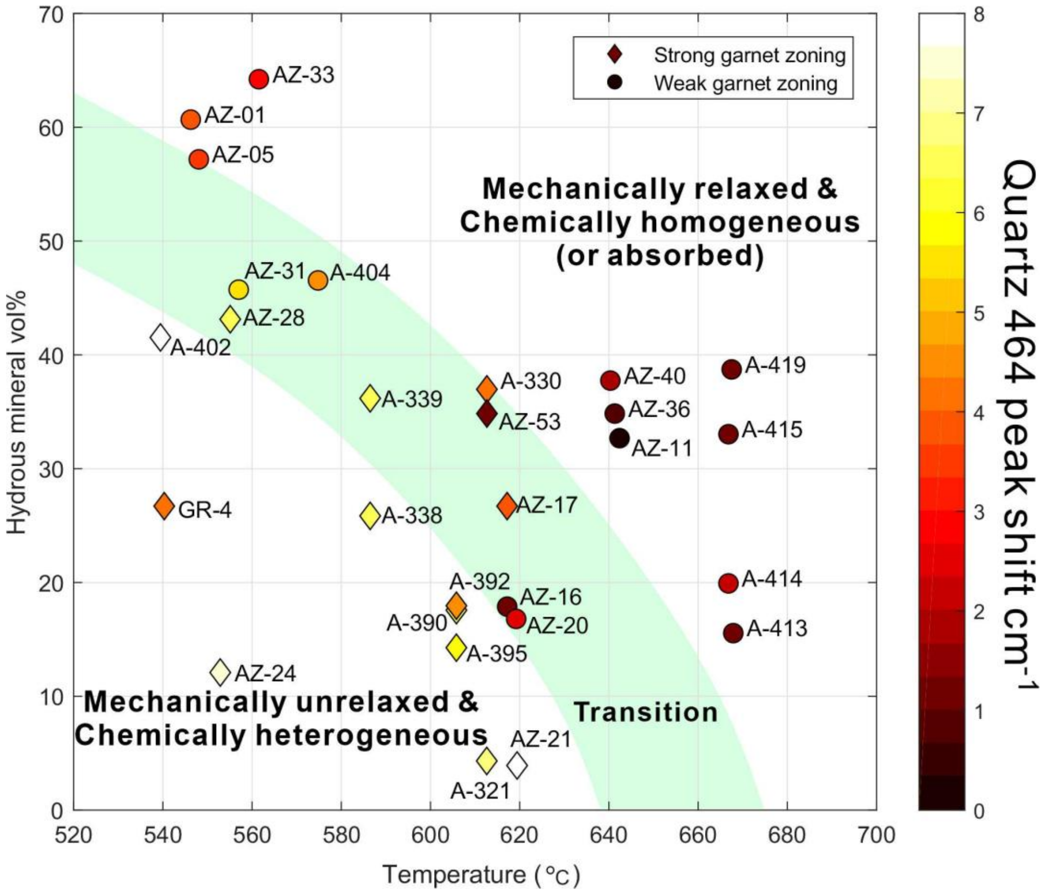


Zhong; Moulas, Tajčmanová, 2018. Sci. Report

6. Coming back from the lab to the field

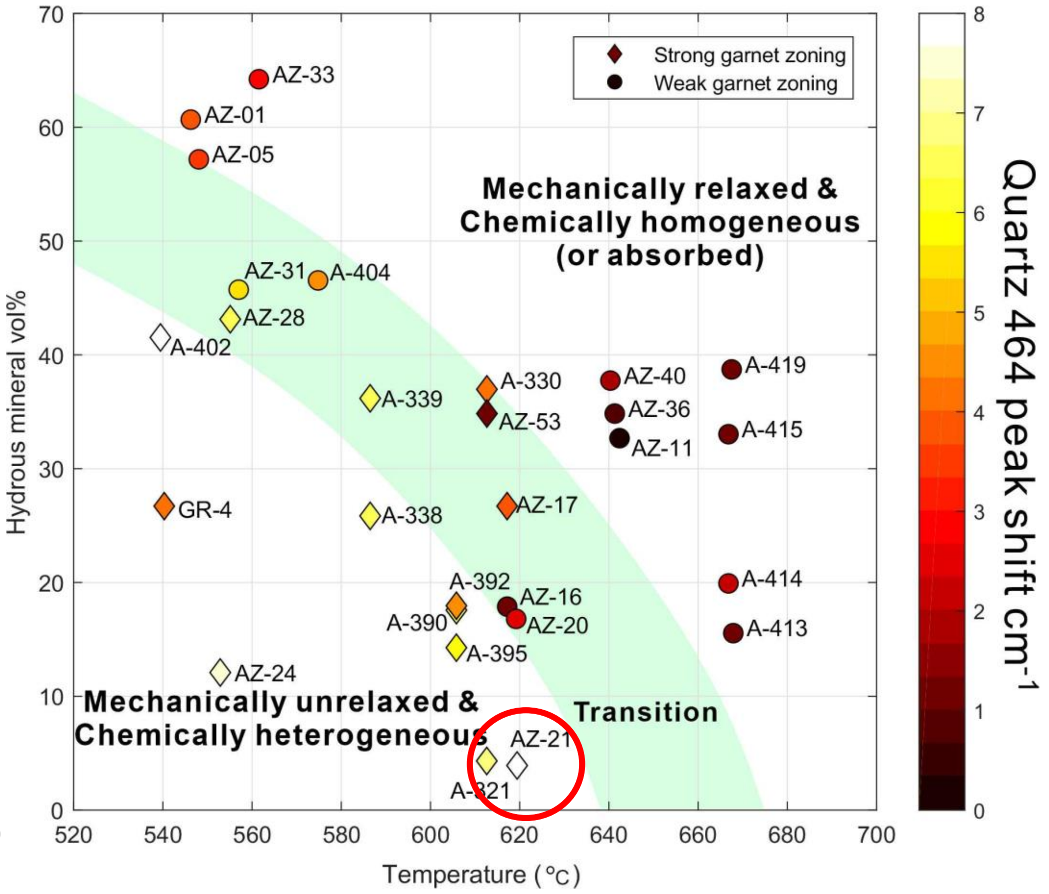
Compare factors including **hydrous minerals**, **temperature**, **inclusion pressure** and **garnet chemistry**.

6. Coming back from the lab to the field

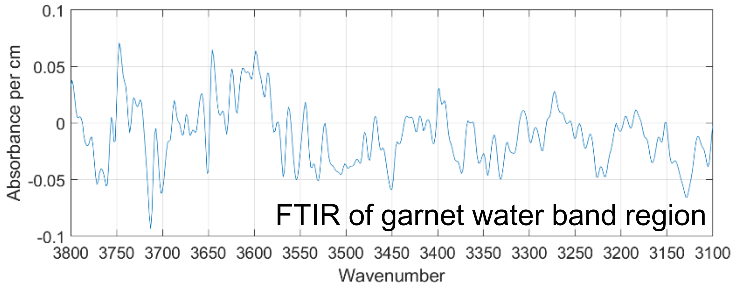


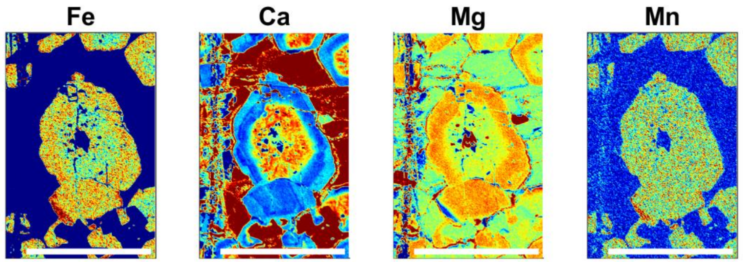
Data obtained with Mona Lüder and Julien Reynes

6. Coming back from the lab to the field



AZ-21 garnet

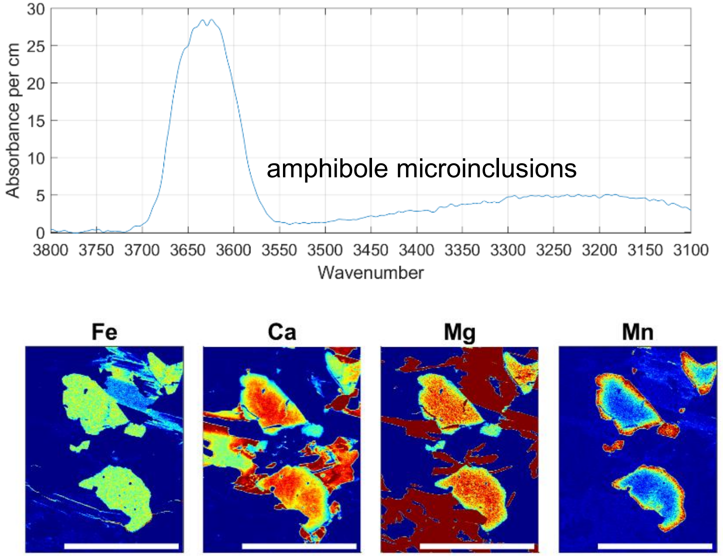


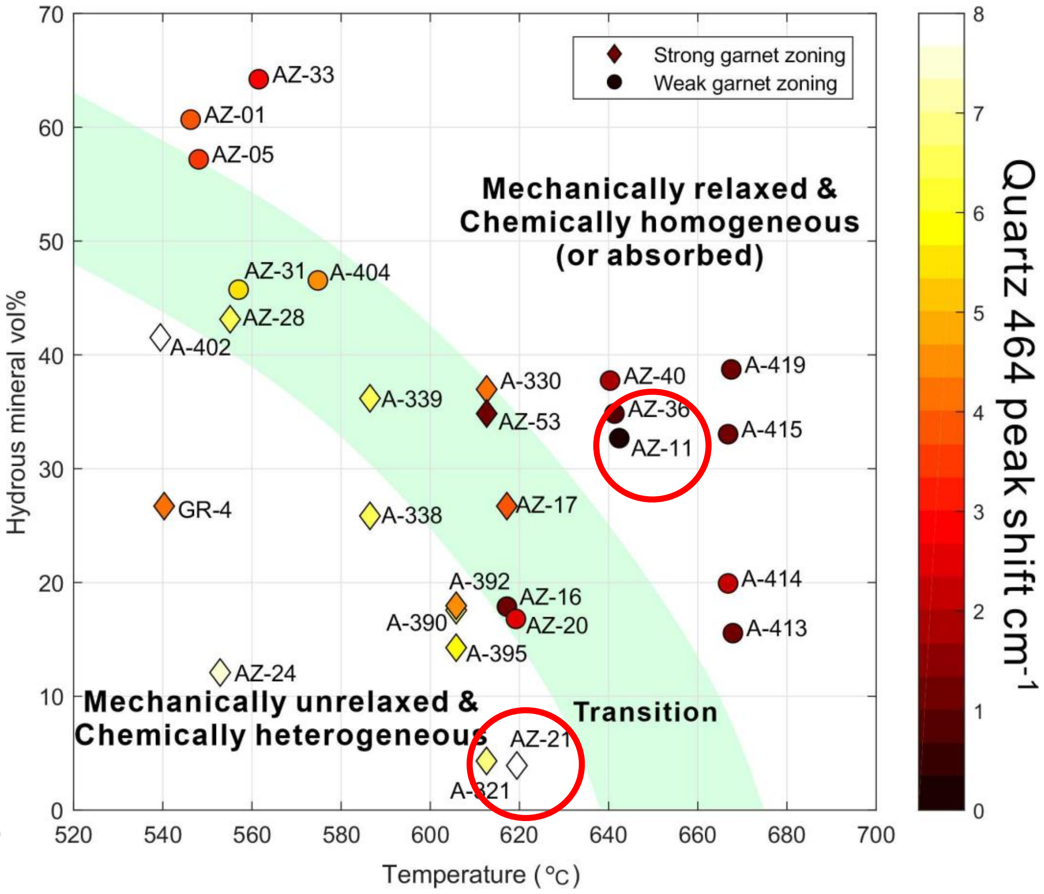


Data obtained with Mona Lüder and Julien Reynes

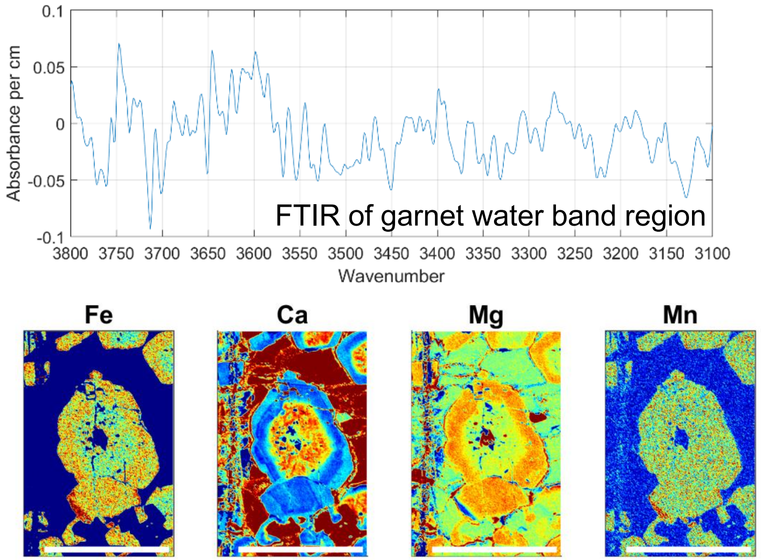
6. Coming back from the lab to the field

AZ-11 garnet





AZ-21 garnet



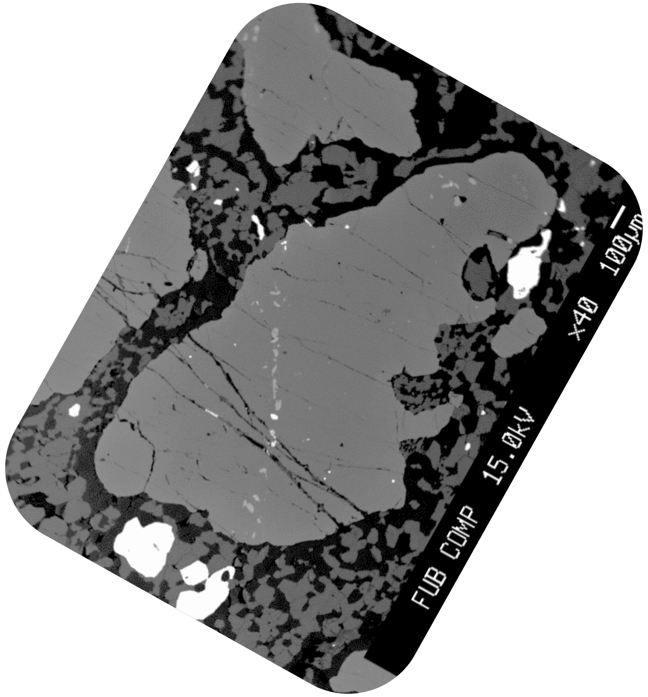
Data obtained with Mona Lüder and Julien Reynes

Summary

- Stress variations exist in metamorphic rocks upon formation or during exhumation.
- To generate stress (pressure) variation: change of P-T or application of far-field stress.
- A direct application is elastic thermobarometry in inclusion-host system.
- Case studies on frictional melt preserved in pseudotachylyte vein show the strength of the method.

However, things become complicated with viscous relaxation...

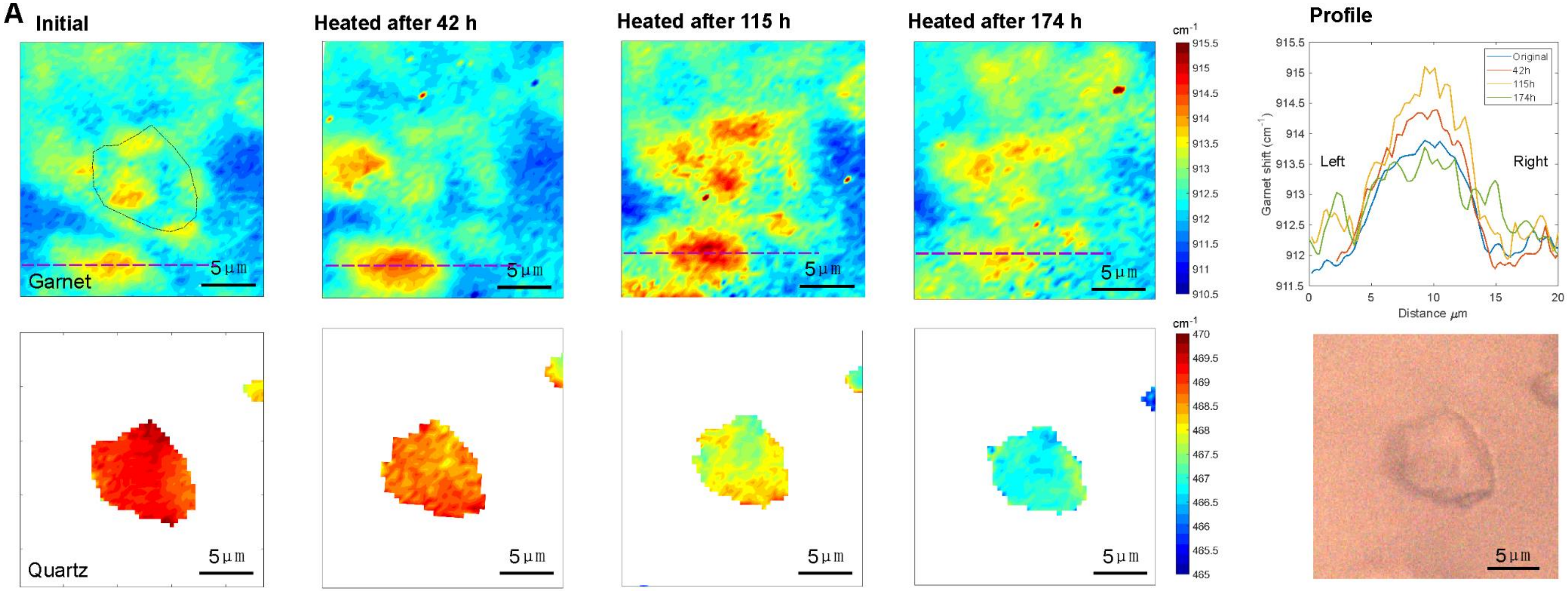
- Field-based study show a drastic drop of quartz inclusion pressure in the Adula nappe. Two factors, i.e. T and water, are systematically tested.
- Water can be critical in changing the preserved stress variation in garnet.
- Diffusion and deformation seem to be closely linked for garnet. When water is abundant (hydrous minerals), chemical zonation and stress variations disappear at the same time.



Thank you!

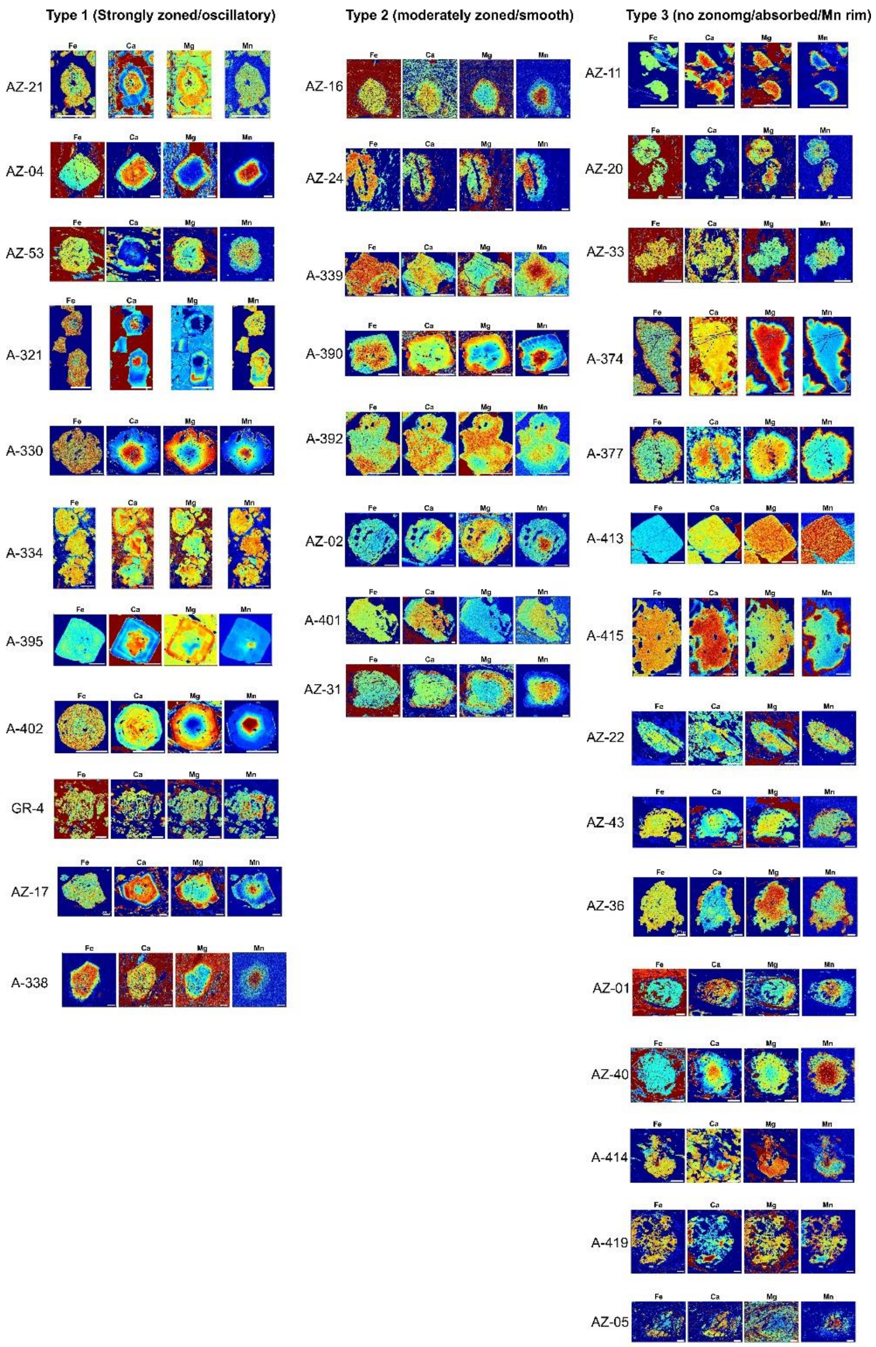
Xin Zhong
Freie Universität Berlin
Email: xinzhong0708@gmail.com

Extra slides from below

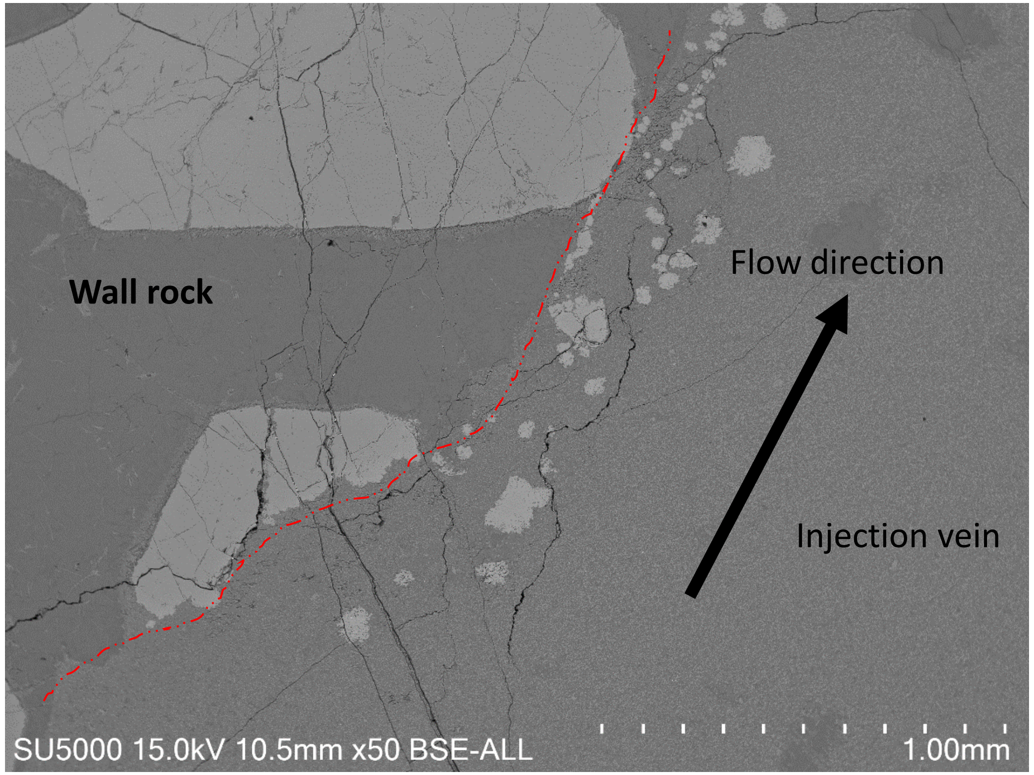


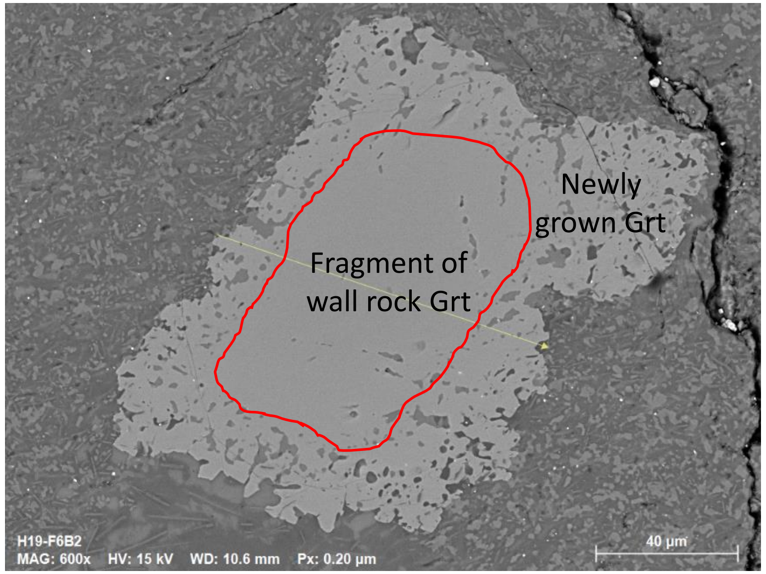
Extra slides

All garnet mapping data



Extra slides





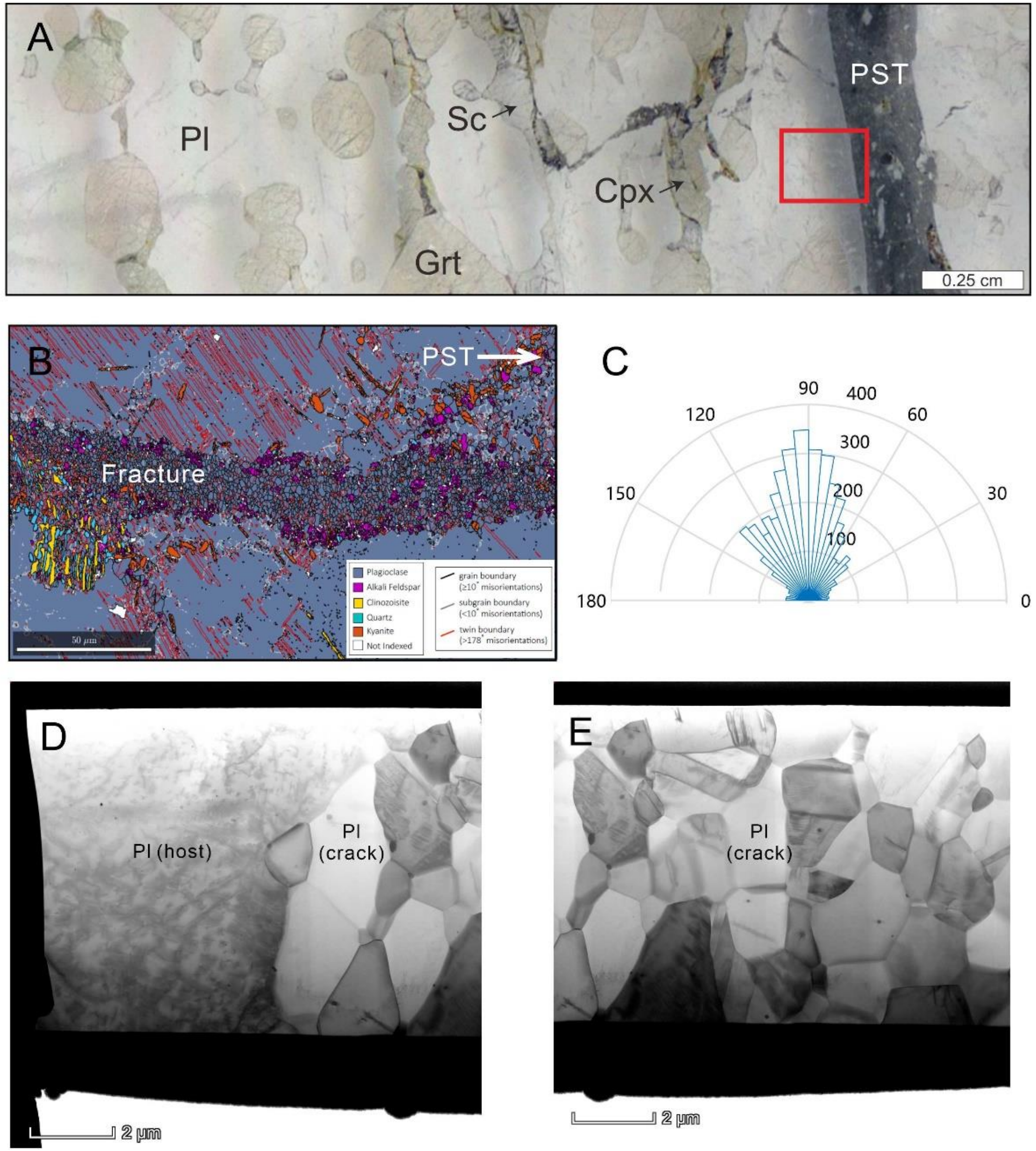
Extra slides

<u>Strong SPO</u>

<u>(EBSD)</u>

<u>Dislocation free</u>

<u>(TEM)</u>



Extra slides

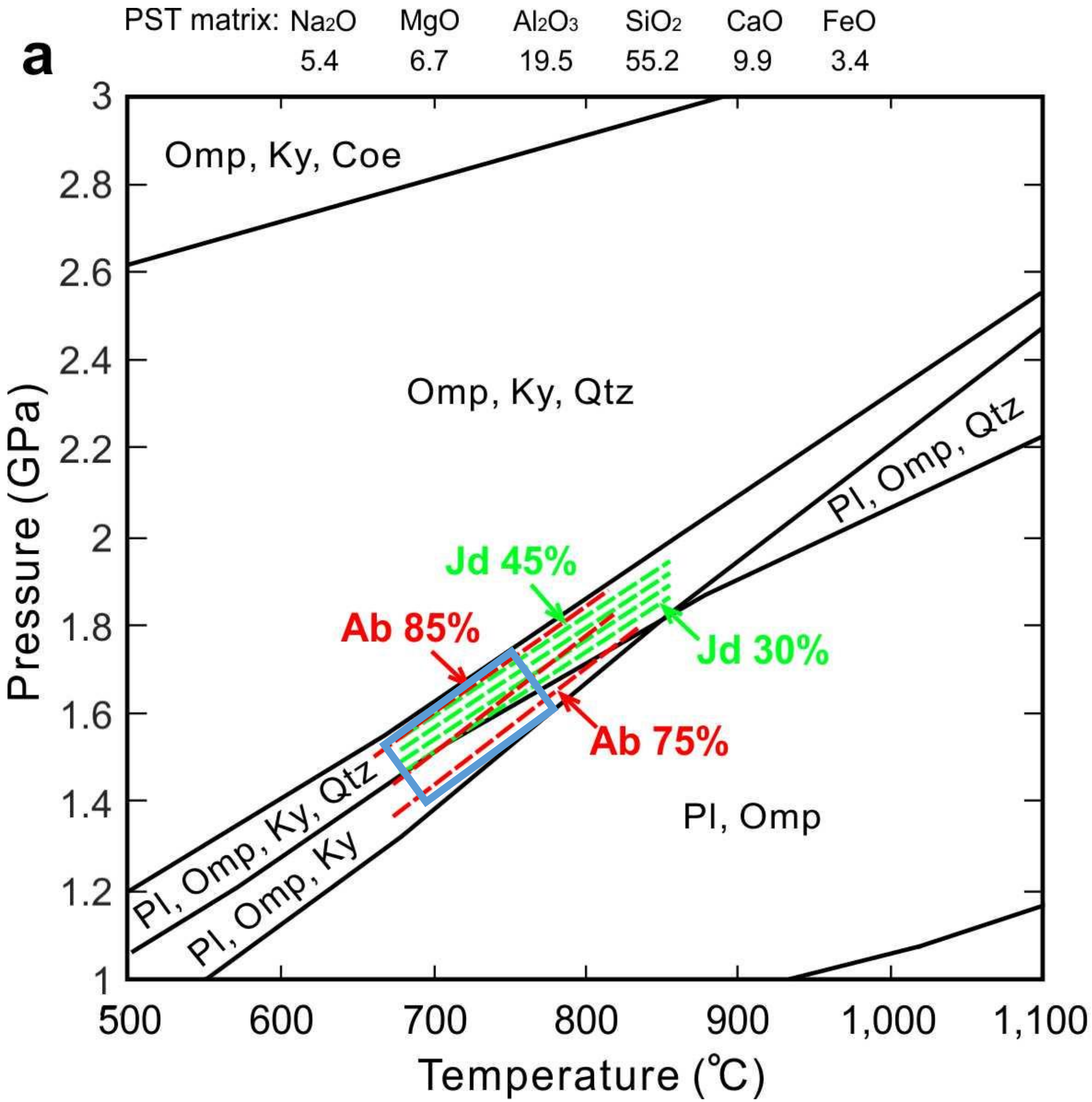
Phase equilibria model (Perple_X)

Wall rock T ca. 700ºC.

Under equilibrium,

PST matrix forms at ca. **1.5-1.7 GPa**

Consistent with previous studies (Bhowany 2018)



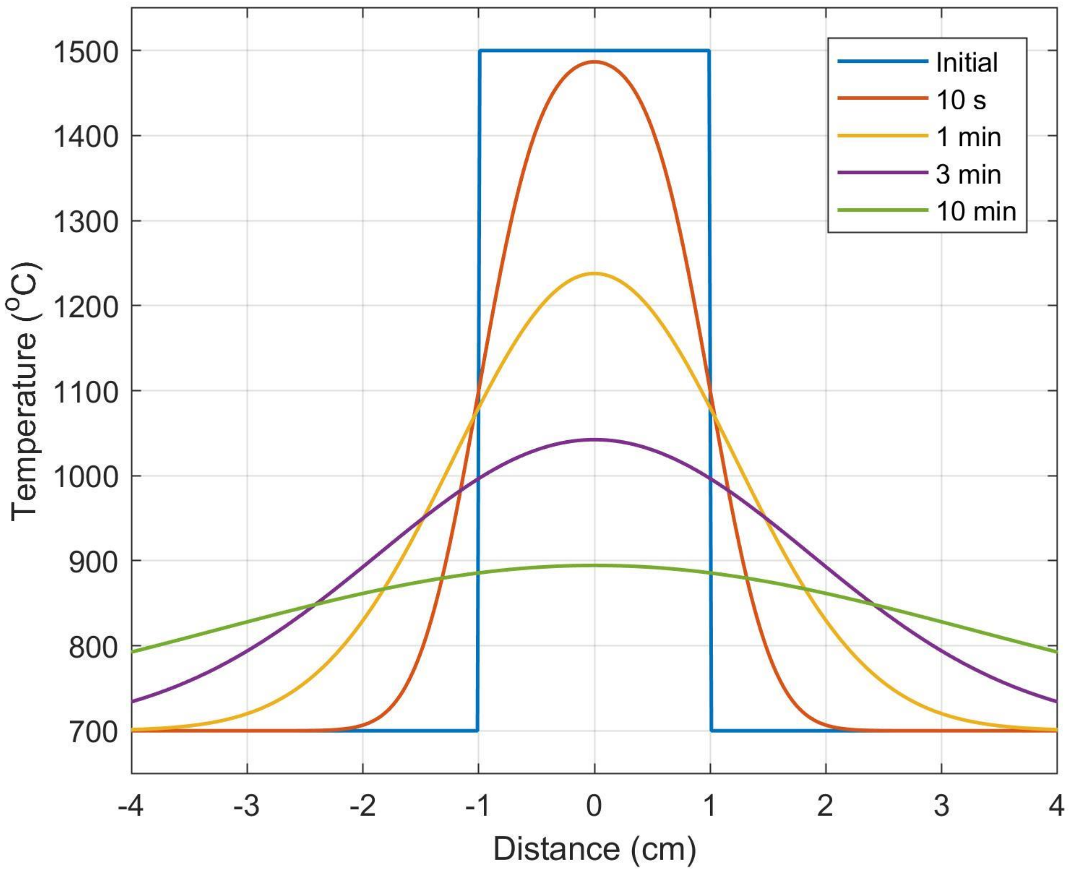
Extra slides

1D thermal conduction

Quenching of a 2 cm thick vein (A17) takes more than at least ca. 3 minutes.

This is longer than the duration of dynamic stress (seconds).

High tectonic differential stress?



Extra slides

Strike and dip are similar