Recent development in the experimental study of plastic deformation of deep mantle minerals

Shun-ichiro Karato

Yale University

Department of Geology & Geophysics

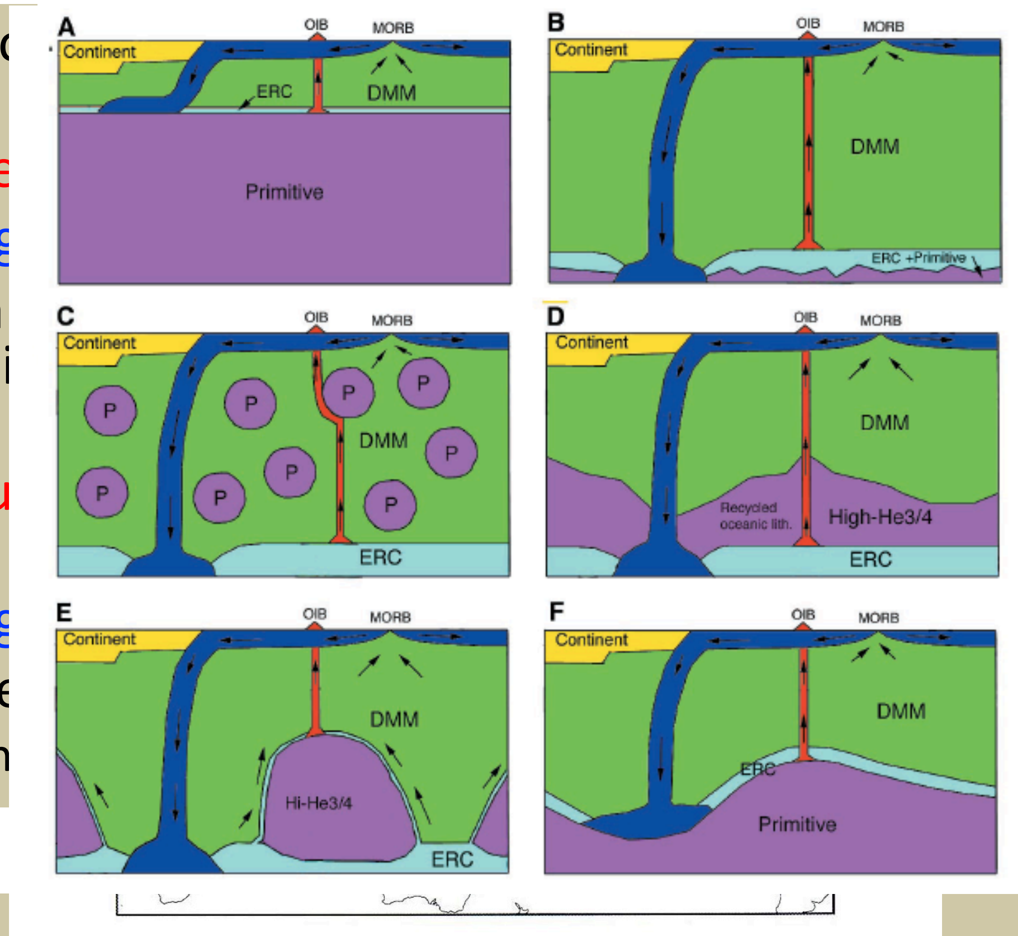
New Haven, CT 06520, USA

In collaboration with

George Amulele, Robert Farla, Jennifer Girard, Anwar Mohiuddin, Kazuhiko Otsuka, Noriyoshi Tsujino

Geodynamic questions related to rheological properties

- Seismic tomo … the transition zone.
  - → How doe
  - (how strong … ?)
- Geochemica … ical reservoirs" (i … ng time (~2 Gyrs or more)
  - → How cou … in a convecting
  - (how strong … ?)
- Does water e
  - Water-con

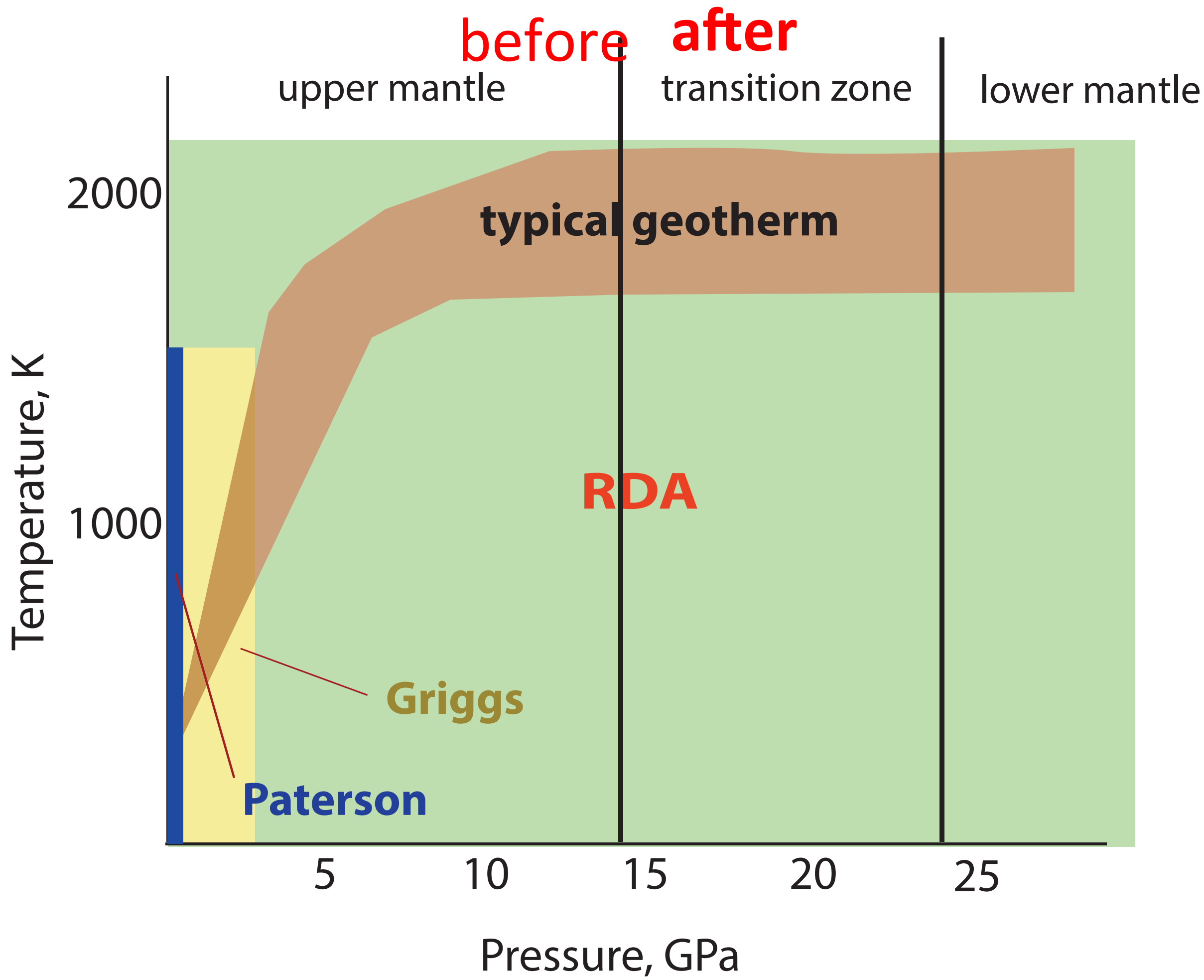


→ Needs experimental studies at high P-T (slow strain-rate, large strain) and studies on grain-size. (+ water effect?)

A brief history of technical development

- Griggs (1936): A gas-medium apparatus
- Griggs (1965): A solid-medium apparatus, low resolution (<3 GPa)
- Paterson (1970): A gas-medium apparatus (internal load cell, high resolution) (<0.3 GPa)
- Sung, Goetze, Mao (1977): High-P (<20 GPa) deformation experiments using DAC at low T
- Green (1989-): A modification to Griggs apparatus (high-resolution stress measurements, P to ~4 GPa)
- Singh (1993): A theory of x-ray stress measurement
- Karato-Rubie (1997): Multi-anvil shear deformation experiments (~15 GPa) (stress relaxation test)
- Weidner (1998-): Synchrotron *in-situ* stress, strain measurements (stress relaxation tests)
- Paterson (2000): A low-P (gas-medium) torsion apparatus
- Karato group (2001-): RDA (a high-P torsion apparatus)
- Wang, Weidner, Durham group (2003-): DDIA
- Karato (2009): A modified theory of x-ray stress measurement
- Girard et al. (2016): The first quantitative deformation experiments under the lower mantle conditions

Conditions for quantitative deformation experiments



- ✓ needs for deformation experiments at higher P
- ✓ deformation experiments need to be conducted in the right regime (in order for geological applications)

Extending rheological studies to higher P
quantitative deformation experiments under the whole mantle conditions

Key points in the design of a high-P deformation apparatus

- high P and **T**
- controlled strain-rate (stress)
- large strain
- *In-situ* stress-strain measurements

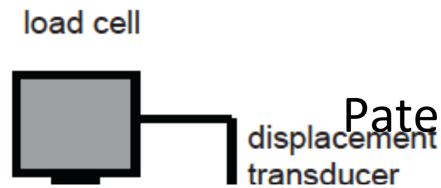
torsion tests→ good support (high P), large strain

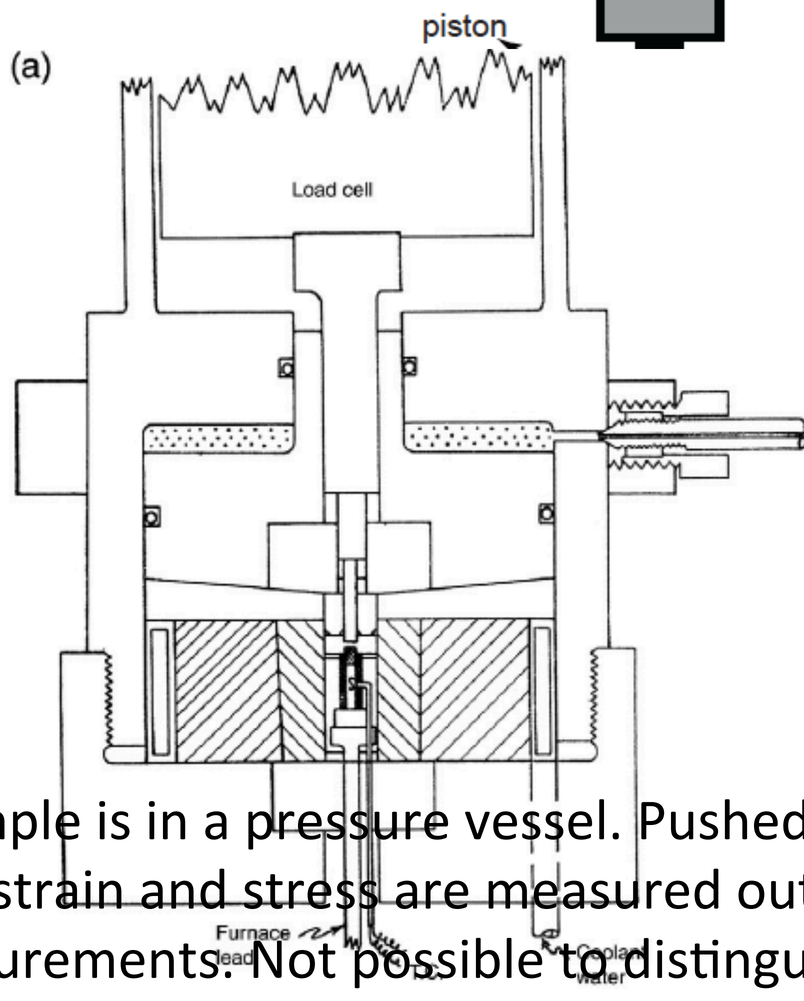
(strain gradient: evolution of microstructure)

(pressure gradient: precise P-dependence)

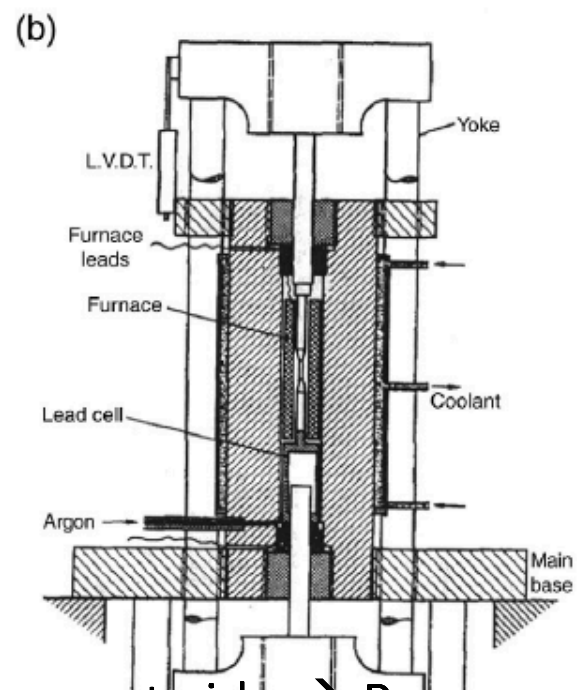
Conventional deformation experiments

Griggs apparatus





Paterson apparatus

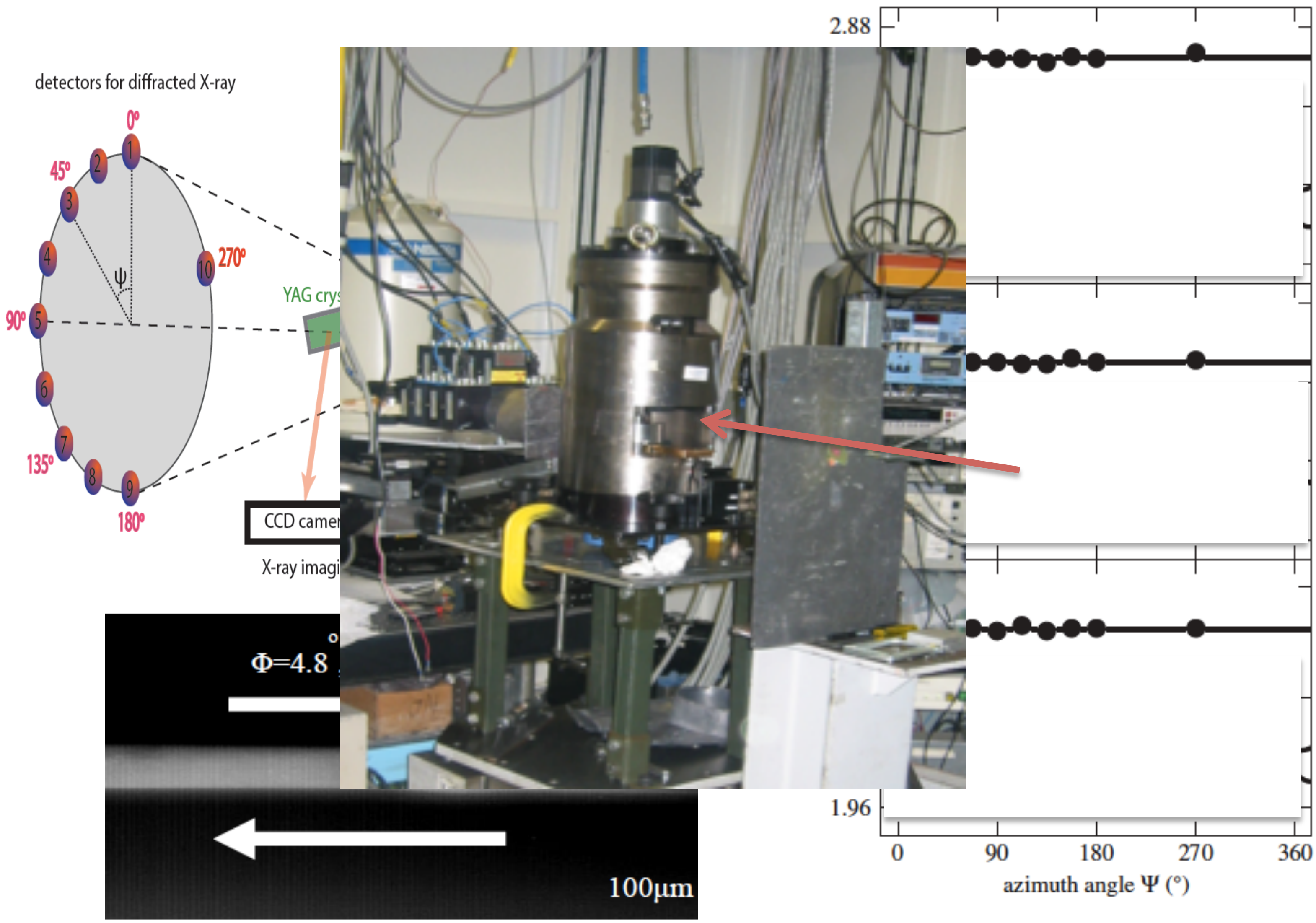


A sample is in a pressure vessel. Pushed from out-side → Pressure limit.
Both strain and stress are measured out-side. → Problems with the stress measurements. Not possible to distinguish stress in different phases.

Advantages of synchrotron experiments

- Synchrotron radiation: high intensity X-ray
  → penetrate through pressure medium
  → P-T estimates (from equations of state)
- *In-situ* measurements of stress and strain
  → no issue of friction
  → need a theory to calculate stress from X-ray diffraction
- Stress can be measured for co-existing minerals separately
  → strength contrast of co-existing minerals

X-ray stress, strain measurements



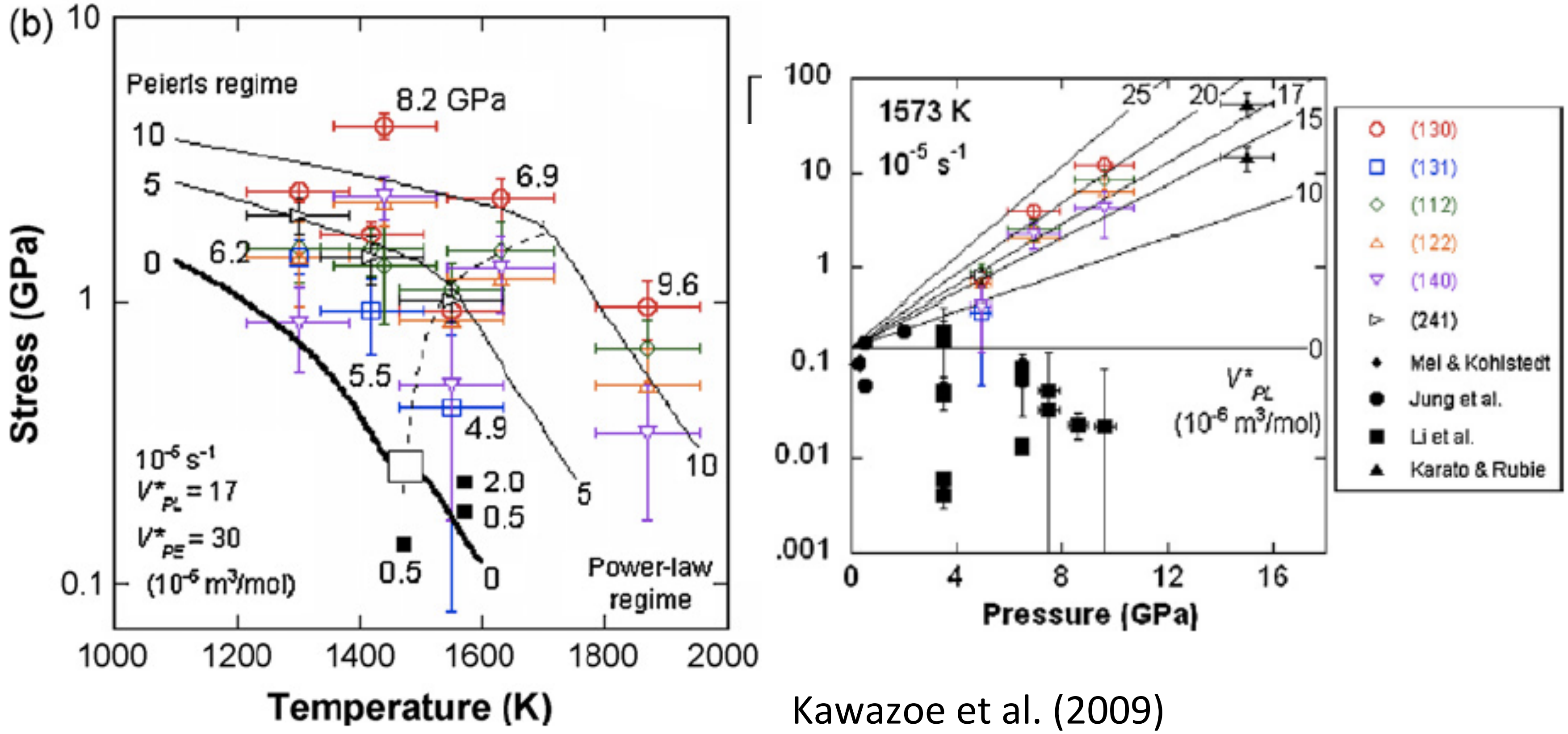
static
(room P, T)

during
deformation
P=15 GPa
T=2100 K

Applications of RDA

- Pressure effects (V*) on deformation of olivine
- Plastic deformation of transition zone minerals (wadsleyite, ringwoodite)
- **Deformation experiments under the lower mantle conditions**
  - Mantle convection, geochemical mixing

Pressure dependence of creep of dry olivine

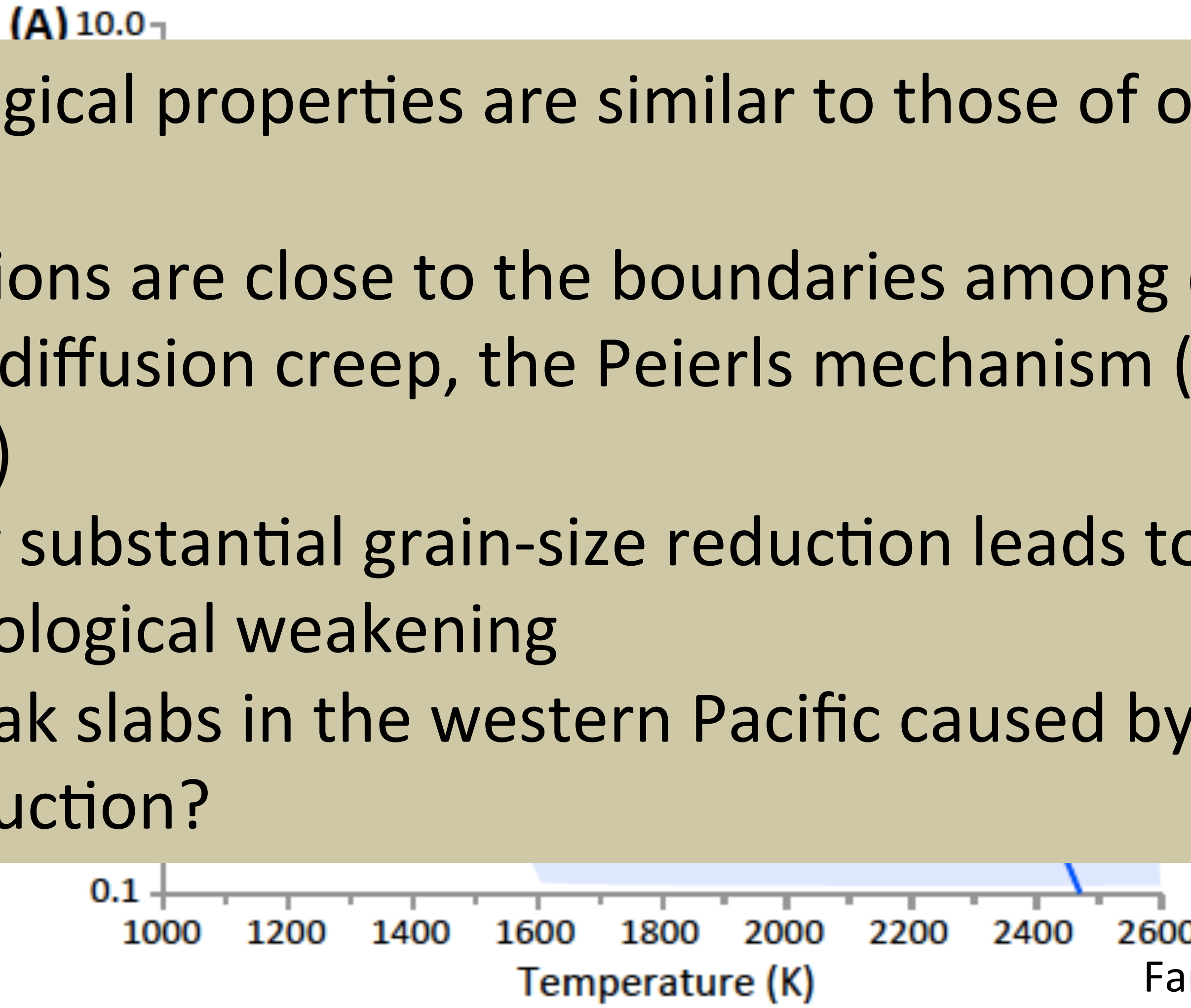


Kawazoe et al. (2009)

P effect is large for both “power-law” creep (high-T mechanism) and the Peierls mechanism (low T mechanism).

wadsleyite-ringwoodite

(transition zone minerals)



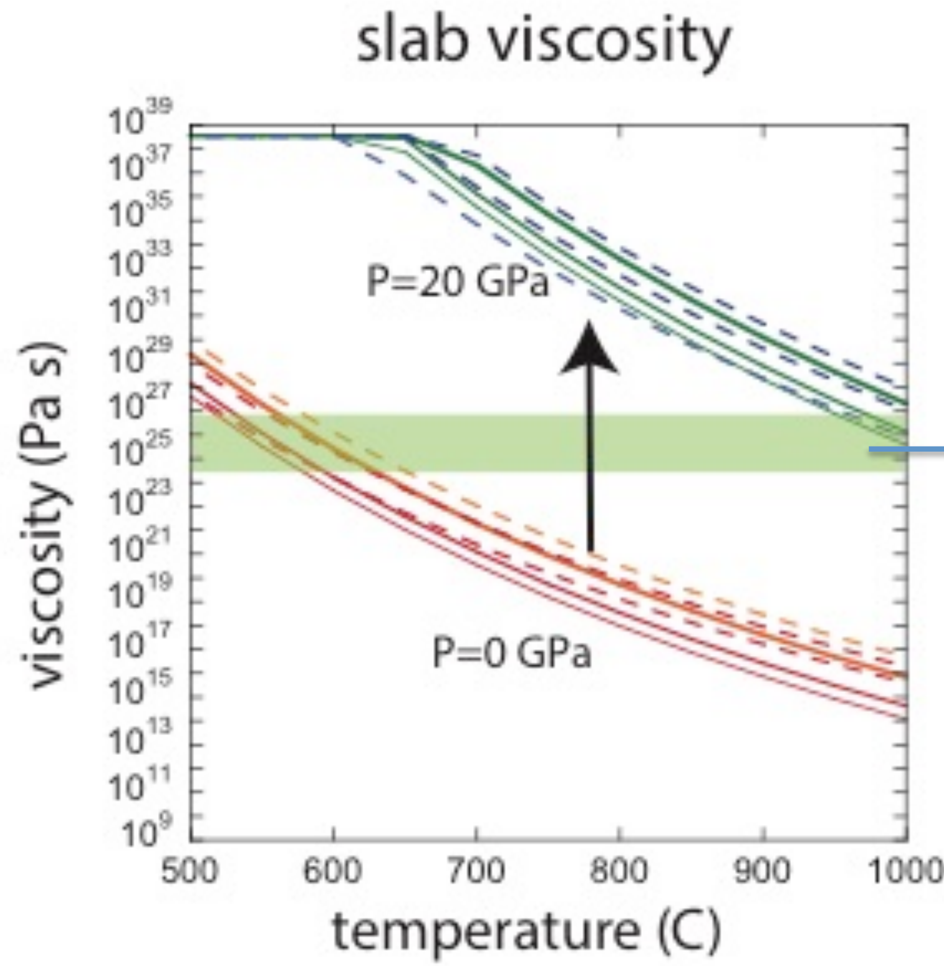
Rheological properties are similar to those of olivine at high P.

Conditions are close to the boundaries among dislocation creep, diffusion creep, the Peierls mechanism (similar to olivine)

→ Any substantial grain-size reduction leads to rheological weakening

→ Weak slabs in the western Pacific caused by grain-size reduction?

Farla et al. (2015)



threshold stress
for slab deformation
needed for slab
deformation
(assumed by geodynamicists)

When grain-size effect is ignored, the predicted strength far exceeds the strength needed to deform the subducted slabs.

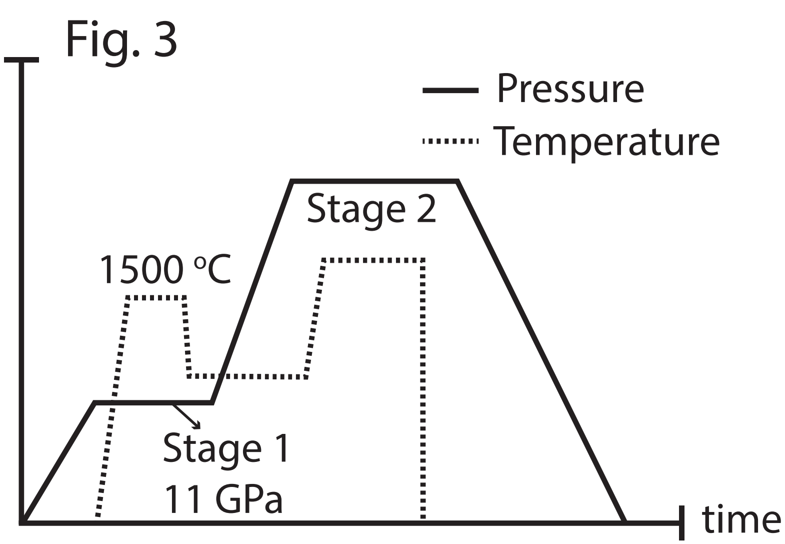
Dislocation creep (or diffusion creep with mm size)

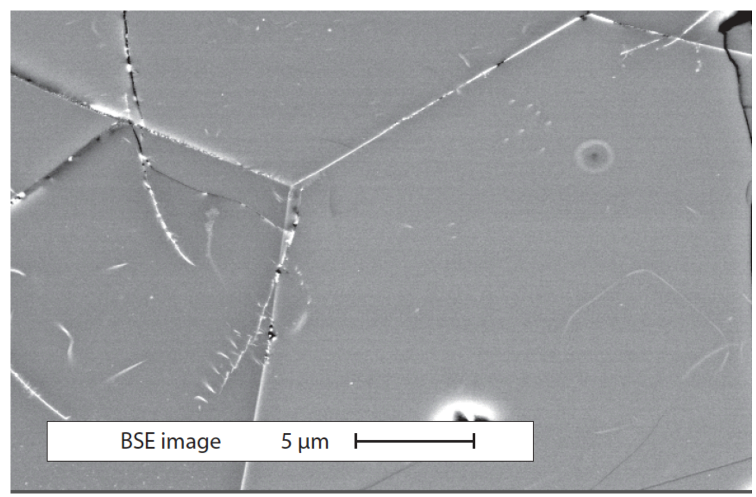
→ too high viscosity

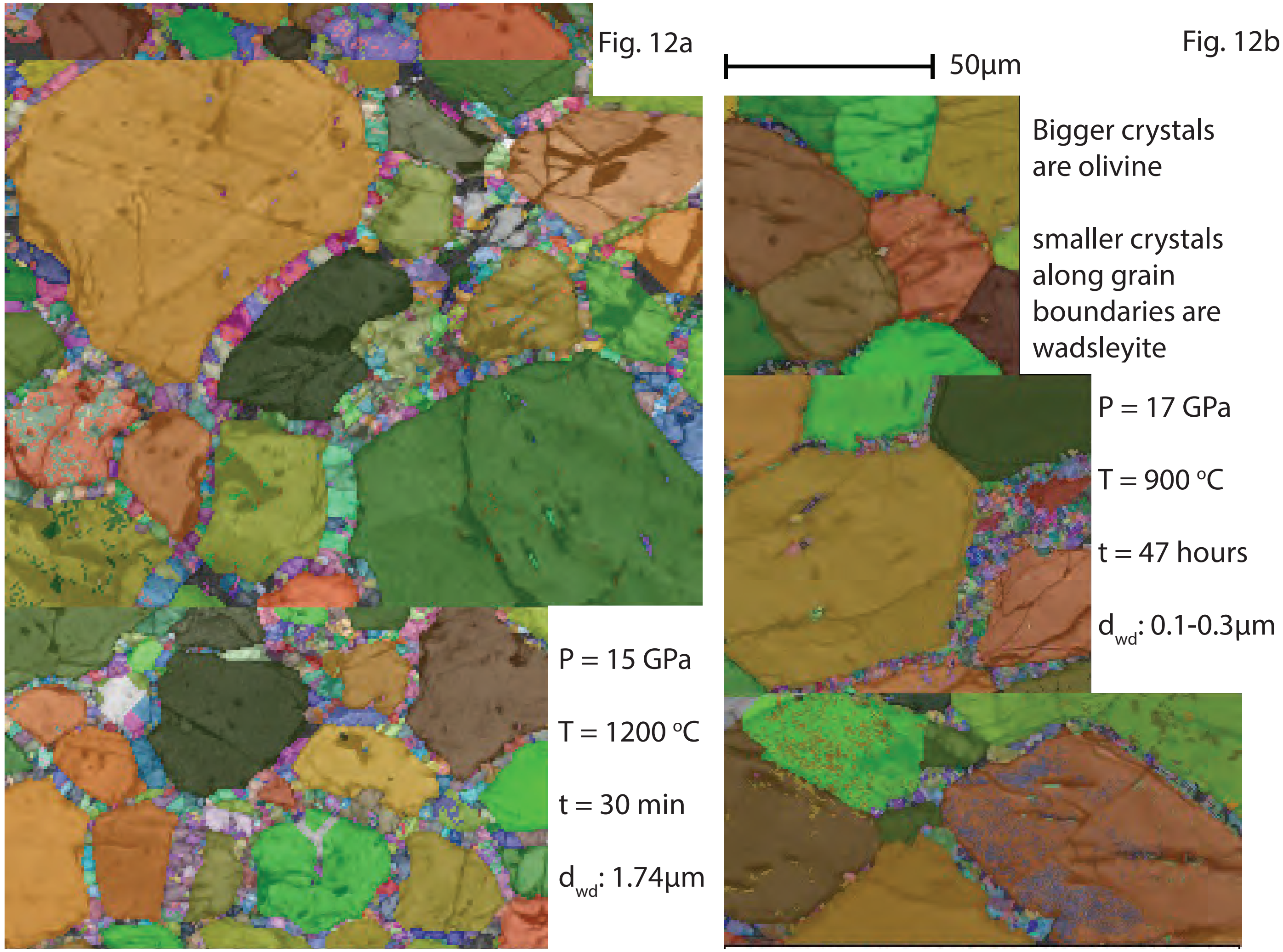
(need to reduce the viscosity by ~10 order of magnitude)

→ grain-size reduction from mm to micron can do the job:

→ an experimental study on the degree of grain-size reduction upon a phase transformation at various conditions

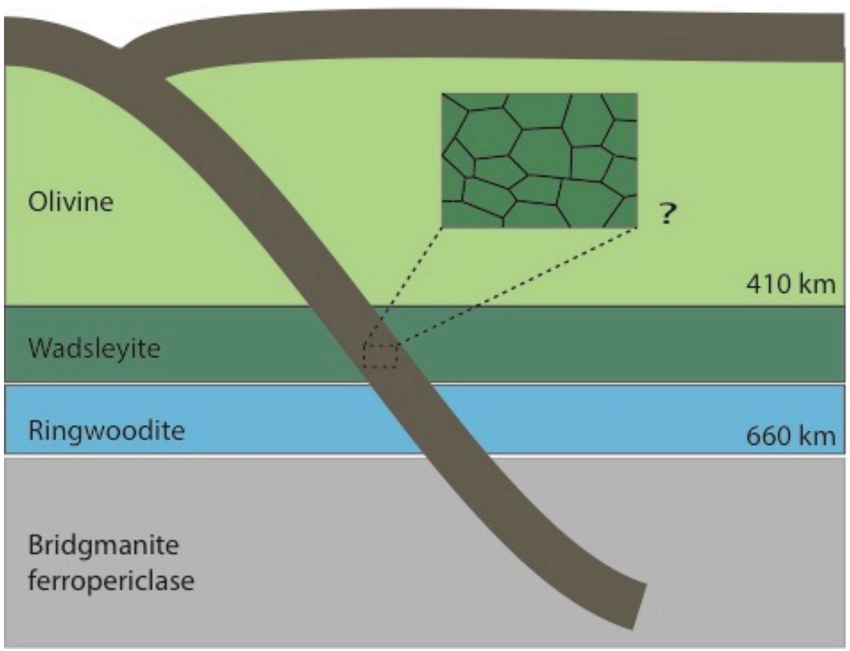




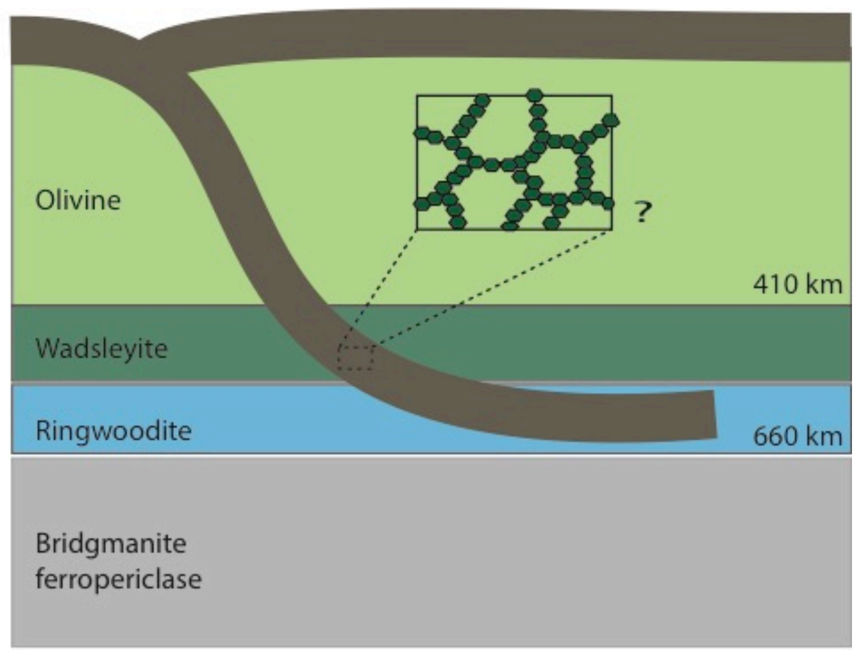


- A strong effect of T on grain-size (mostly grain-growth control)

Grain size evolution and its influenvce on slab deformation in the transition zone

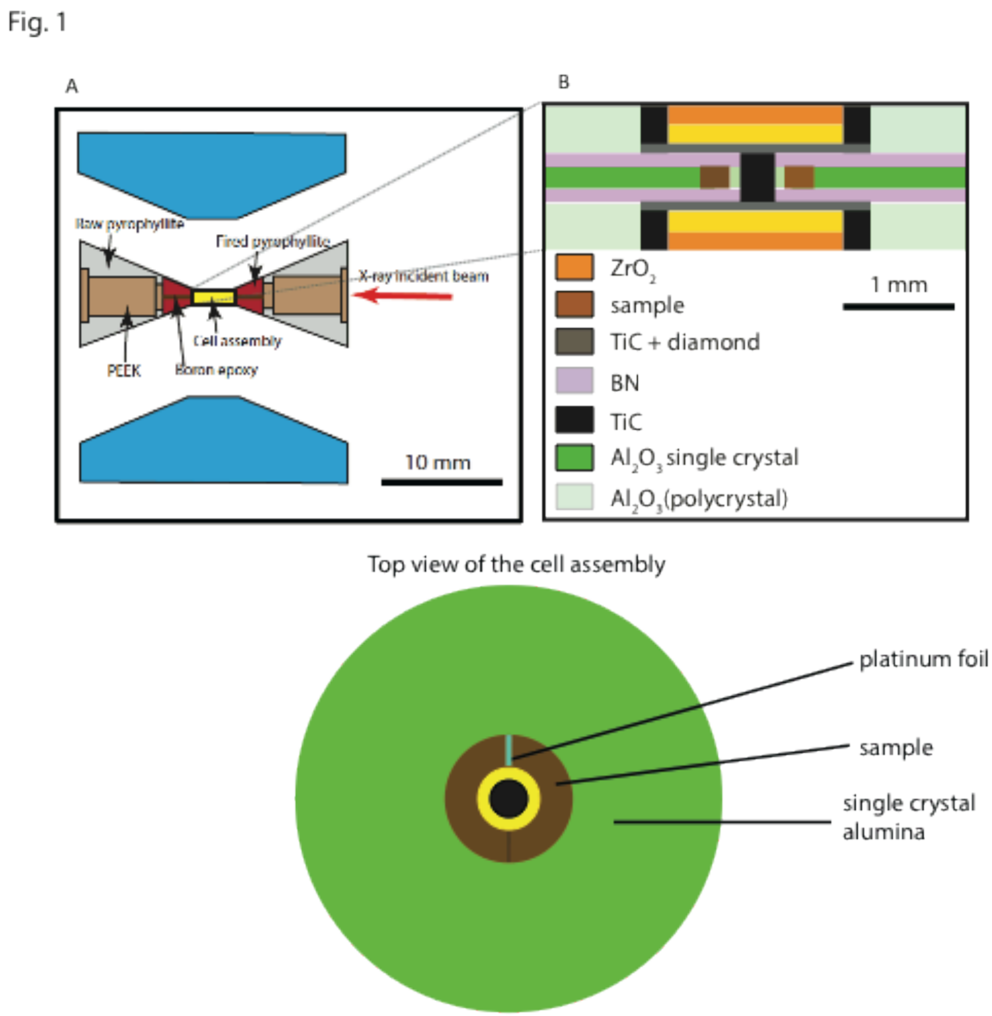


Warm/young slabs



Cold/old slabs

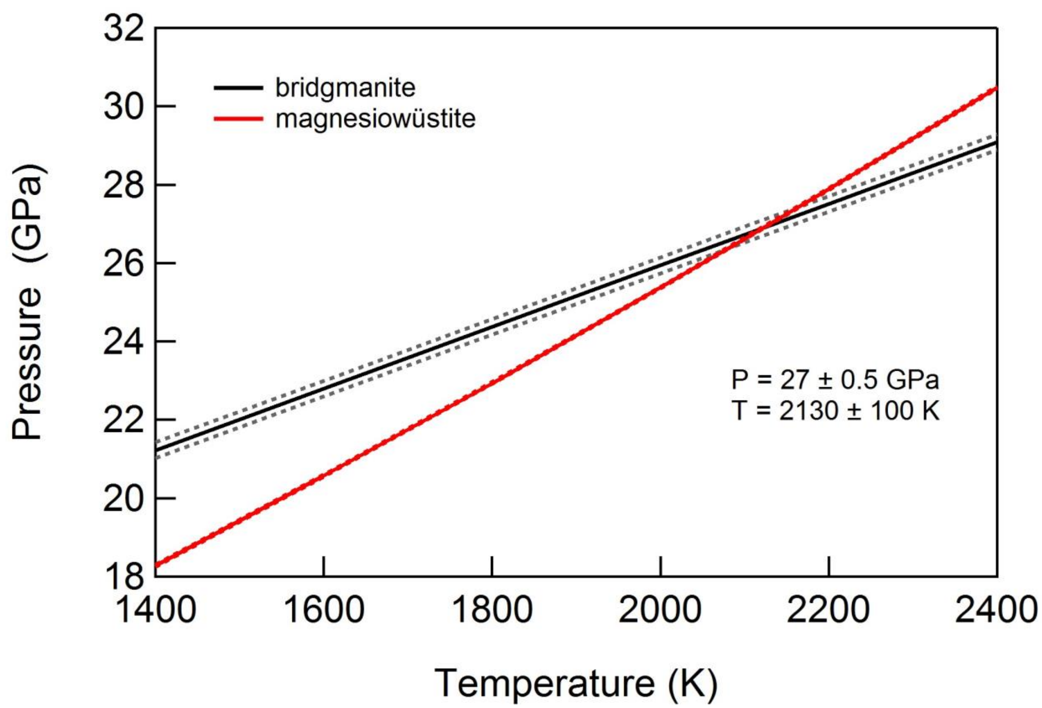
Deformation experiments under the lower mantle conditions



Girard et al. (2016)

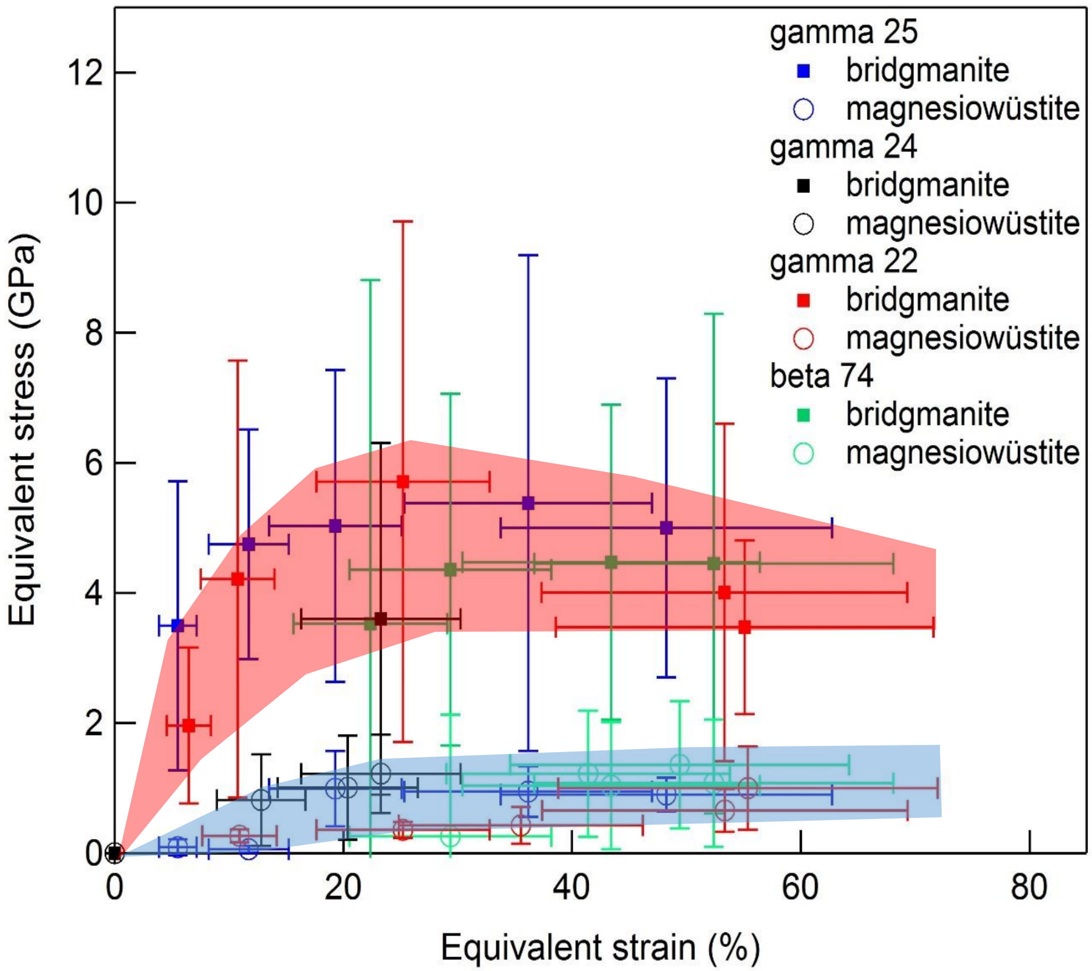
Advantages of a two-phase specimen in synchrotron *in-situ* deformation experiments

1. In-situ P-T measurements
2. Direct measurements of strength contrast



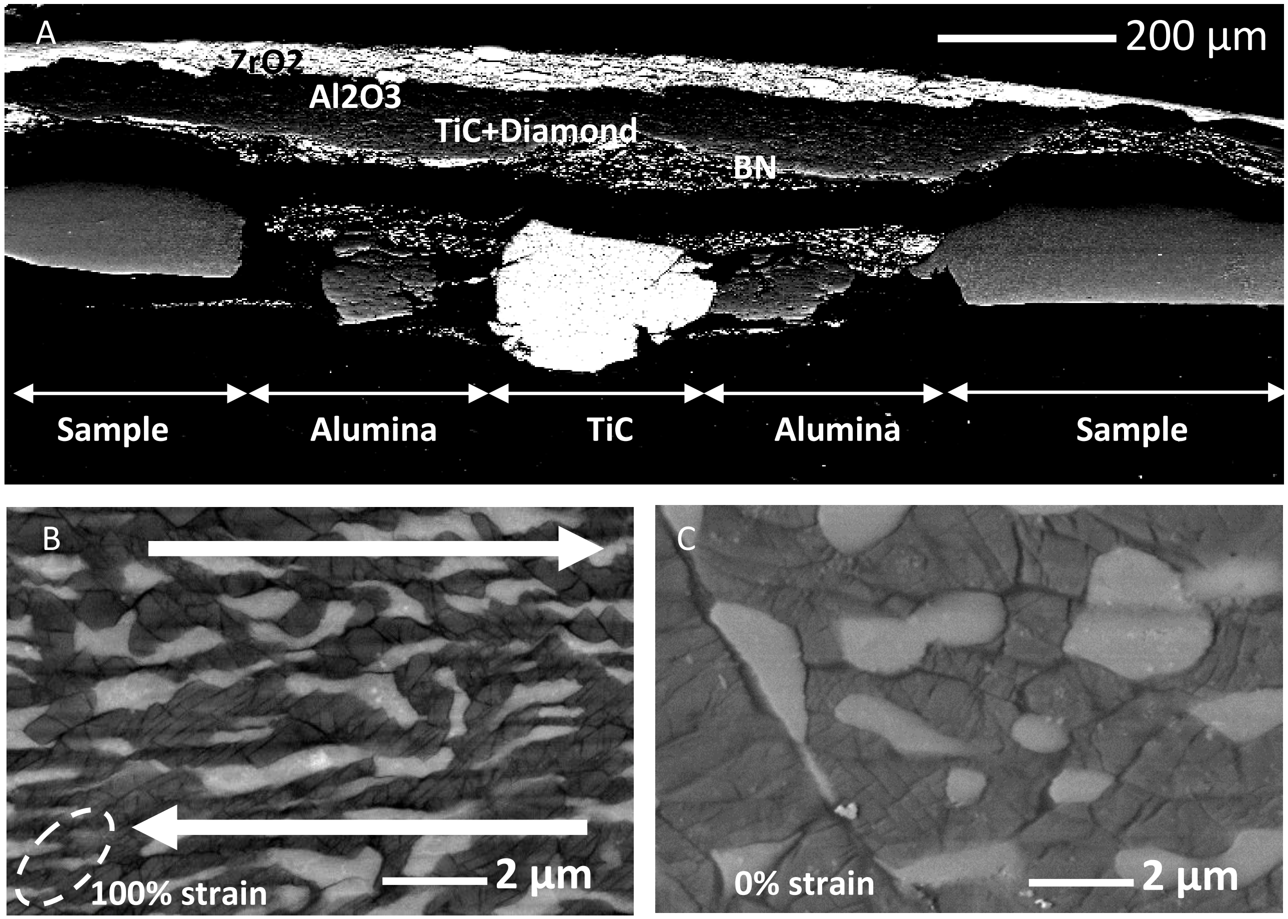
Girard et al. (2016)

Bridgmanite (perovskite) is much stronger than (Mg,Fe)O.



Girard et al. (2016)

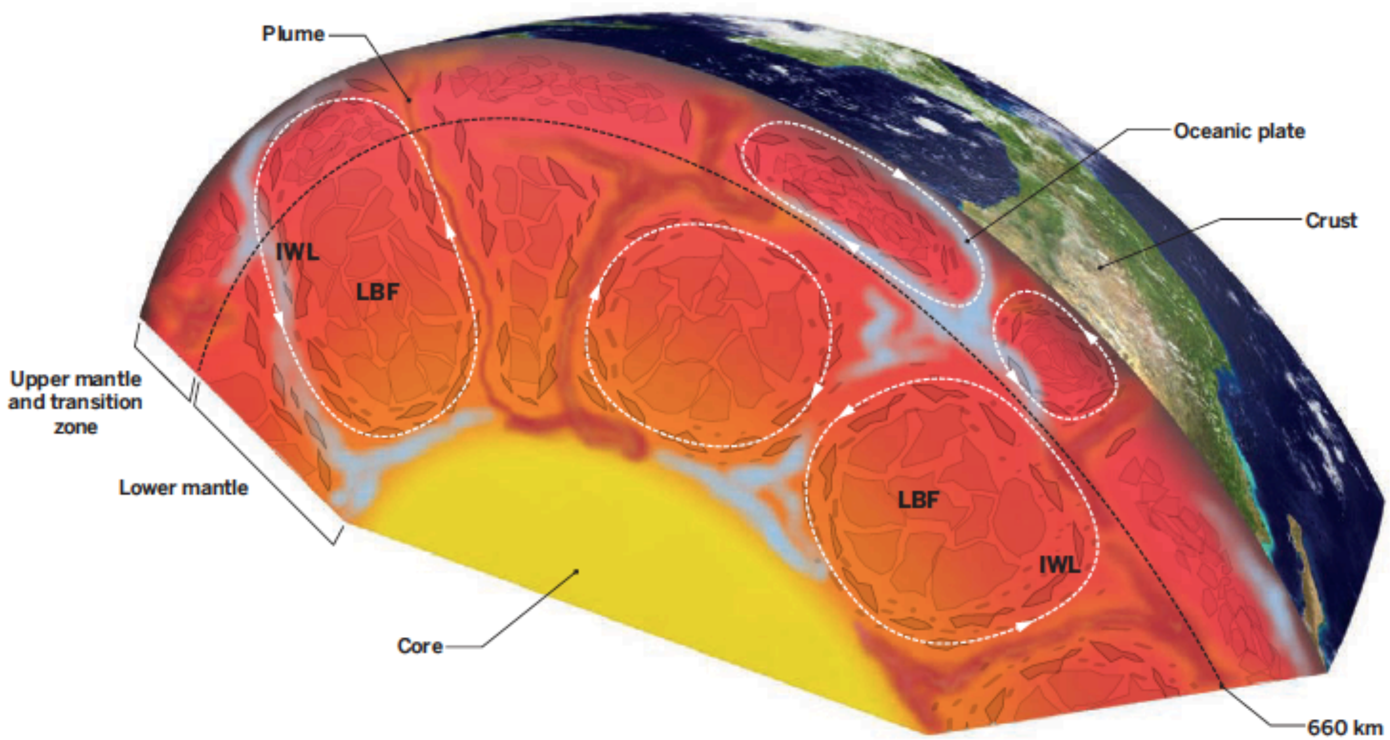
Strain of (Mg,Fe)O is more than the macroscopic strain.



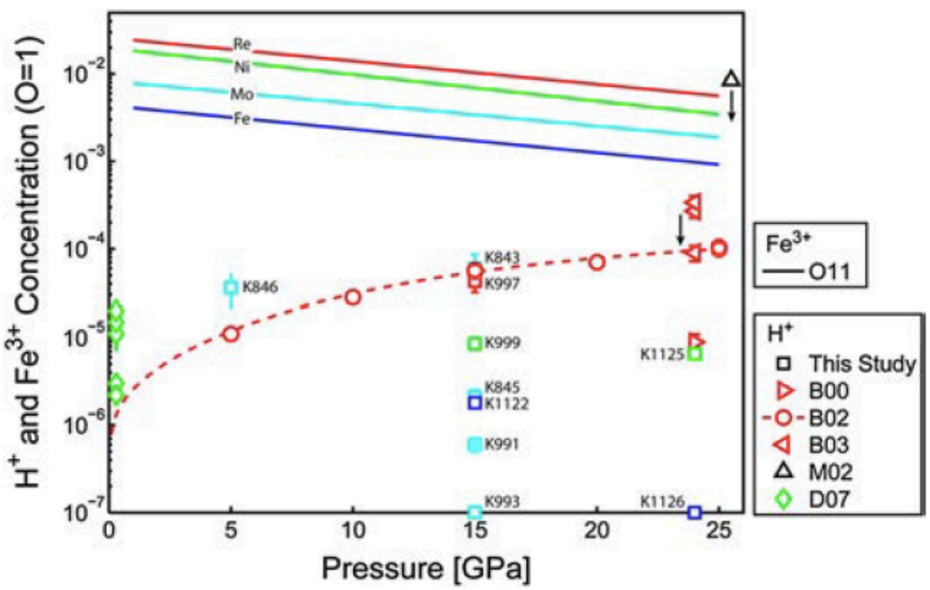
after deformation

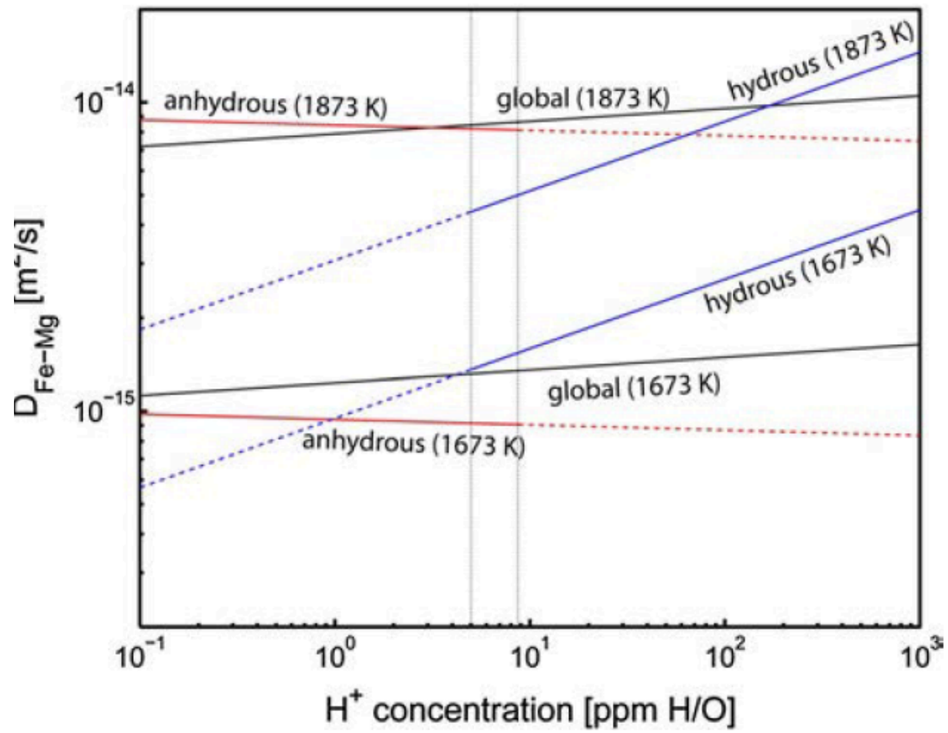
before deformation

Deformation of a two-phase with large strength contrast
→ strain weakening
→ localized deformation
→ Majority of the lower mantle may not be deformed
  → Preservation of geochemical reservoirs?
  → Lack of seismic anisotropy?



Water effects on diffusion are small in (Mg,Fe)O.





Otsuka-Karato (2015)

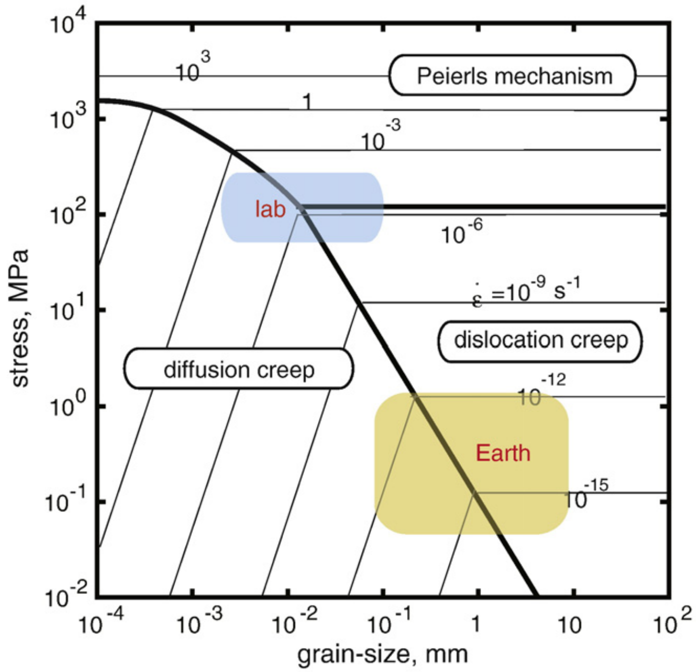
Summary I

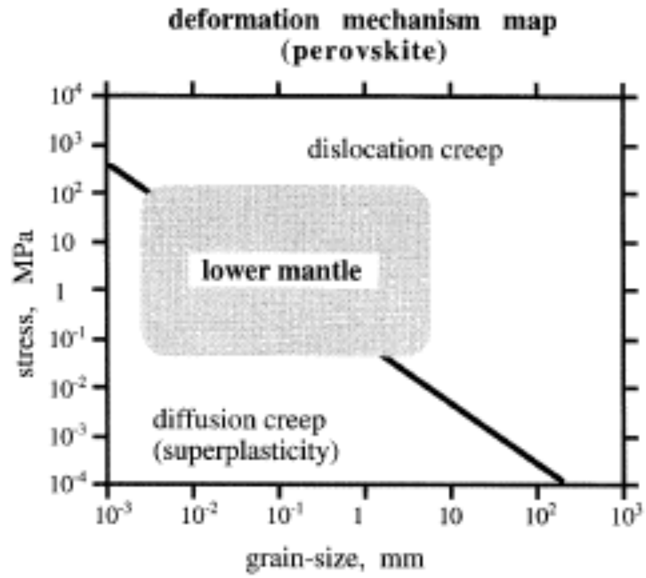
- Quantitative deformation experiments to P~28 GPa, T~2200 K using the **RDA** (rotational Drickamer apparatus).
- Deformation mechanisms in the laboratory and in a slab are close to the boundary among three mechanisms (power-law dislocation creep, Peierls mechanism, diffusion creep).
- Both power-law creep and Peierls mechanism are highly sensitive to P.
  - → Cold slab cannot deform if only these mechanisms are considered.
  - → **Grain-size** reduction will lead to substantial weakening (via diffusion creep).
- Two dominant minerals in the lower mantle (bridgmanite ((Mg,Fe)SiO_3) and ferropericlase ((Mg,Fe)O) have largely different strength: bridgmanite is much stronger than (Mg,Fe)O.
  - → shear localization?
    - → preservation of geochemical reservoirs?
  - → absence of anisotropy in the majority of the lower mantle?
- **Water** has almost no effect on diffusion in (Mg,Fe)O

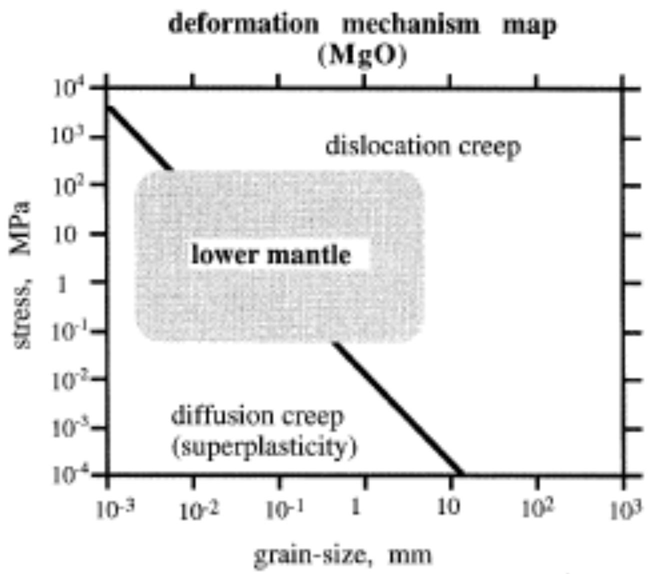
Summary II

What's next in the study of deep Earth rheology?

- More quantitative flow laws for each mechanism (deformation mechanism maps) → e.g., grain-size effects
  deformation of deep slabs
- Does water enhance deformation of lower mantle minerals?
  - evolution of water (water-convection feedback)
- Deformation of (Mg,Fe)O
  - Does dominant slip system change with P?
- How to interpret seismic anisotropy in the deep mantle? (LPO can be complex as shown for olivine)
  flow pattern around the transition zone, in the D" layer

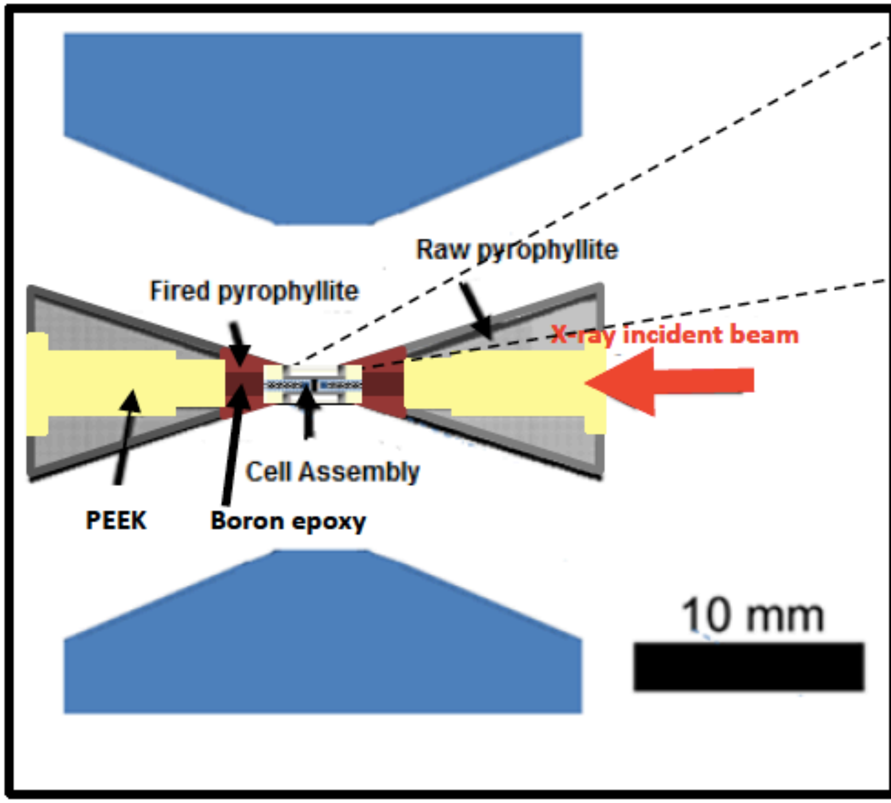

Peierls mechanism
lab
dislocation creep
diffusion creep
Earth
stress, MPa
grain-size, mm


deformation mechanism map
(perovskite)
dislocation creep
lower mantle
diffusion creep
(superplasticity)
stress, MPa
grain-size, mm

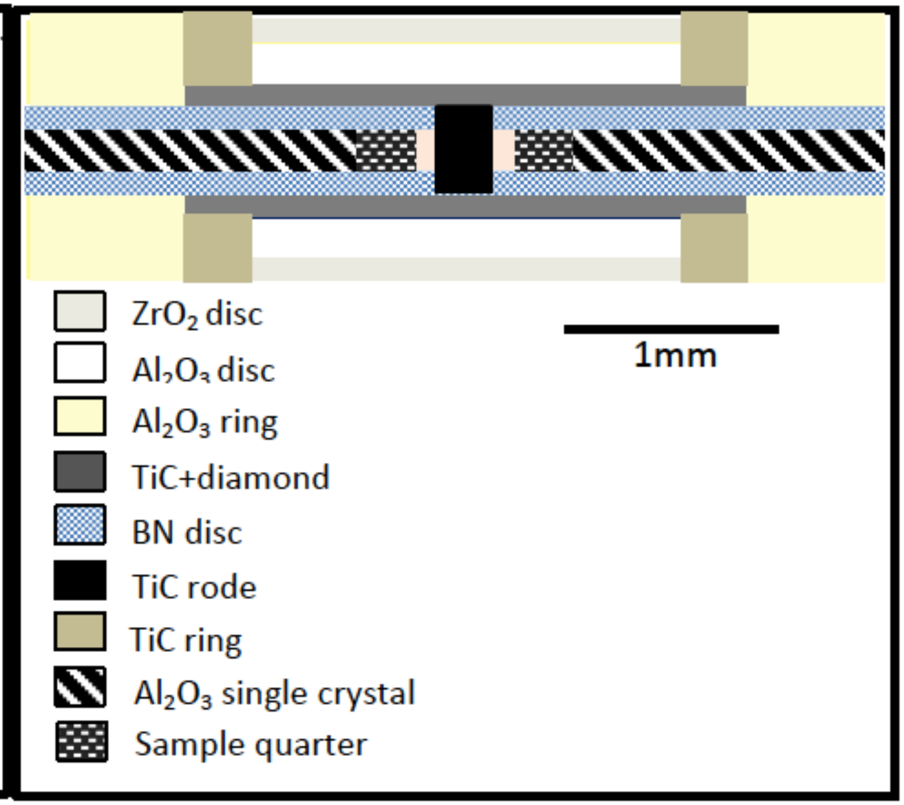

deformation mechanism map
(MgO)
dislocation creep
lower mantle
diffusion creep
(superplasticity)
stress, MPa
grain-size, mm

Sample assembly of RDA

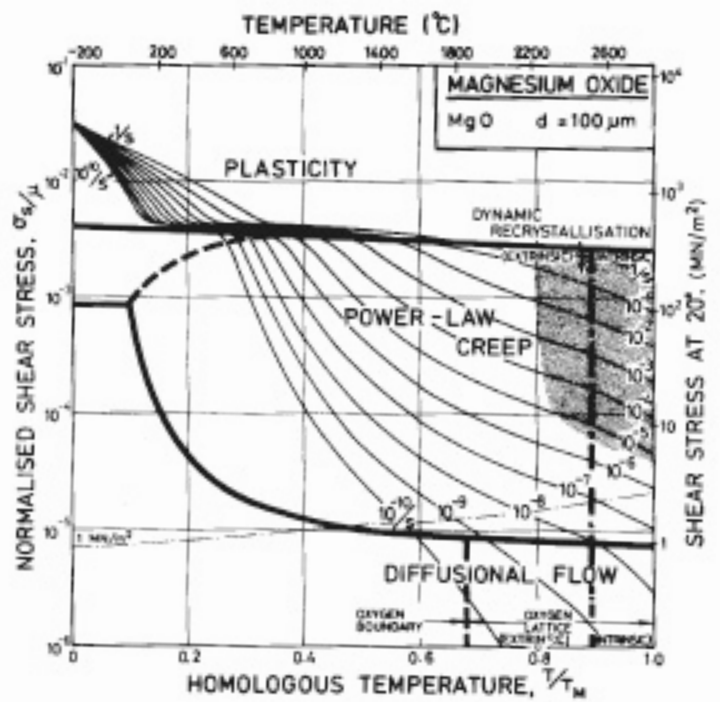
1)

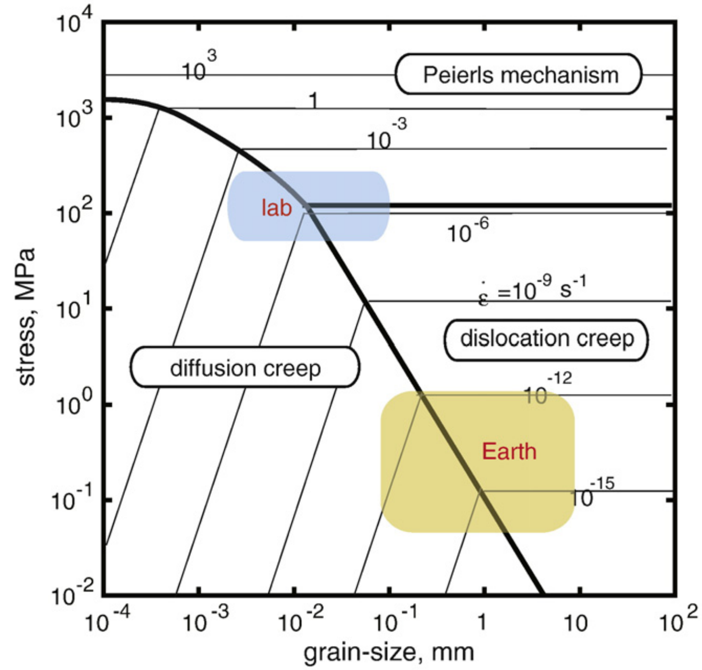


2)

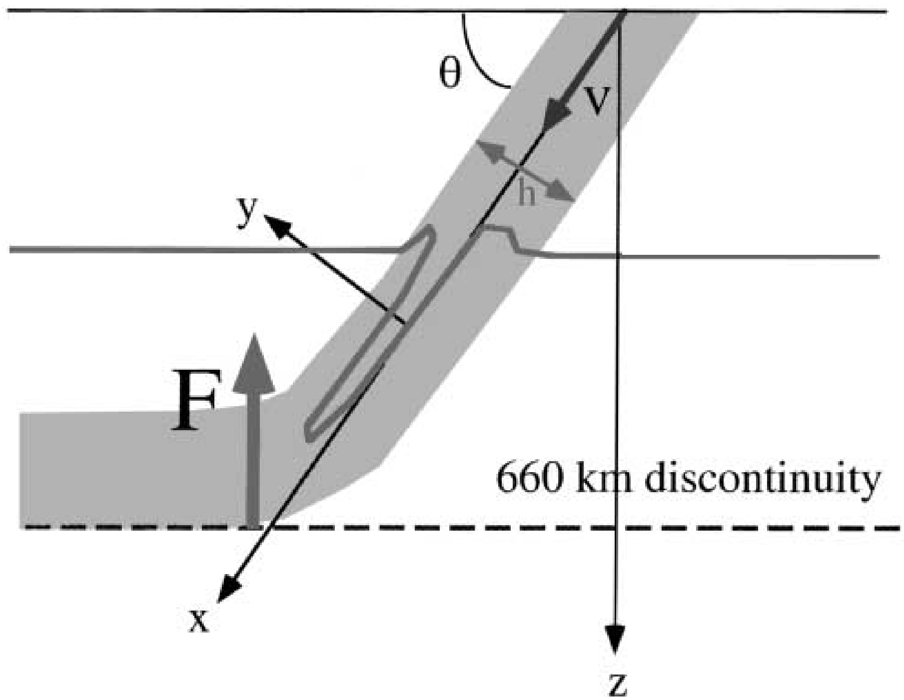


olivine


TEMPERATURE (°C)
MAGNESIUM OXIDE
MgO d = 100 μm
PLASTICITY
DYNAMIC RECRYSTALLISATION
POWER - LAW CREEP
DIFFUSIONAL FLOW
OXYGEN BOUNDARY
OXYGEN LATTICE
NORMALISED SHEAR STRESS, σs/μ
SHEAR STRESS AT 20°, (MN/m²)
HOMOLOGOUS TEMPERATURE, T/TM


Peierls mechanism
lab
Earth
dislocation creep
diffusion creep
stress, MPa
grain-size, mm

Slab deformation in the transition zone

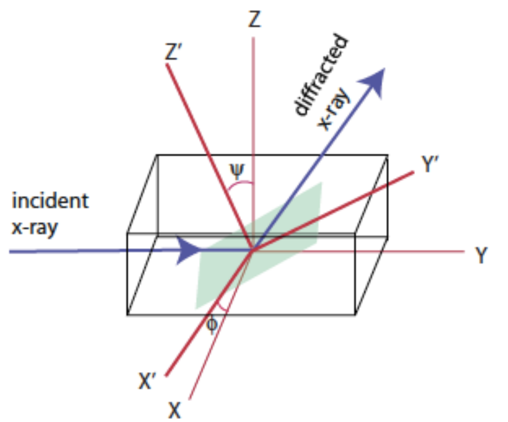


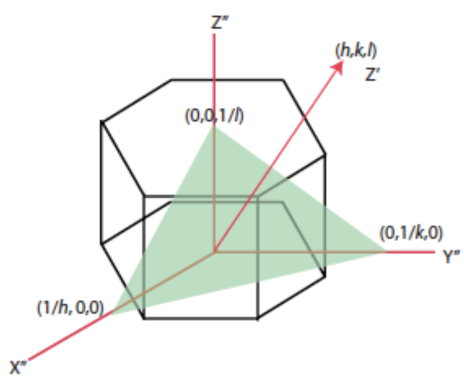
$$M = \int_{-h/2}^{h/2} \sigma y \, \mathrm{d}y = -4 \int_{-h/2}^{h/2} \eta \dot{\varepsilon} y \, \mathrm{d}y$$

PHYSICAL REVIEW B 79, 214106 (2009)

Theory of lattice strain in a material undergoing plastic deformation: Basic formulation and applications to a cubic crystal

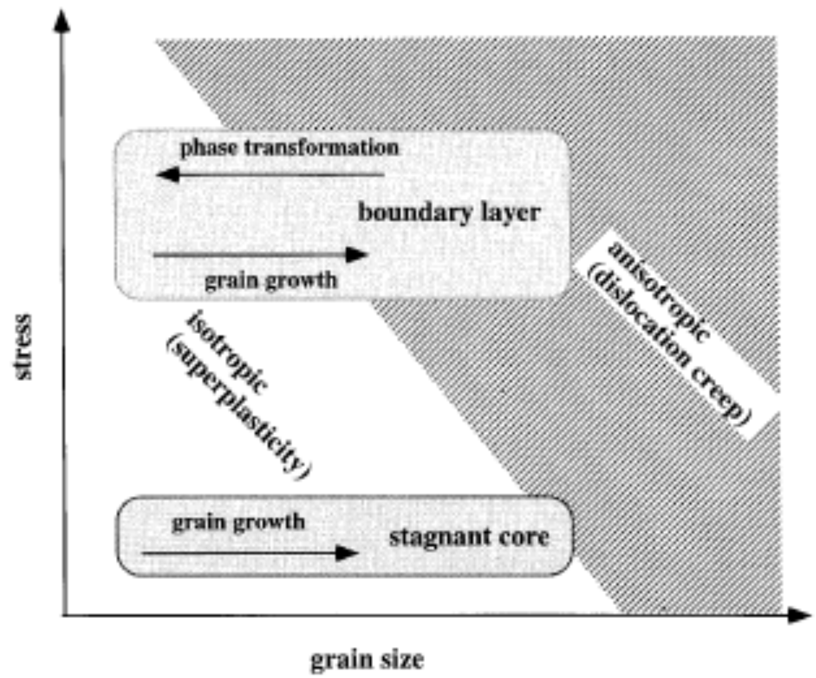
Shun-ichiro Karato
Department of Geology and Geophysics, Yale University, New Haven, Connecticut 06520, USA

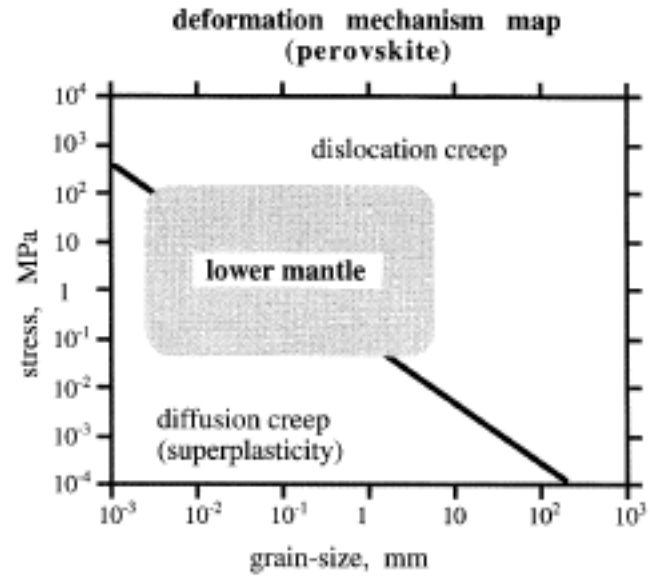


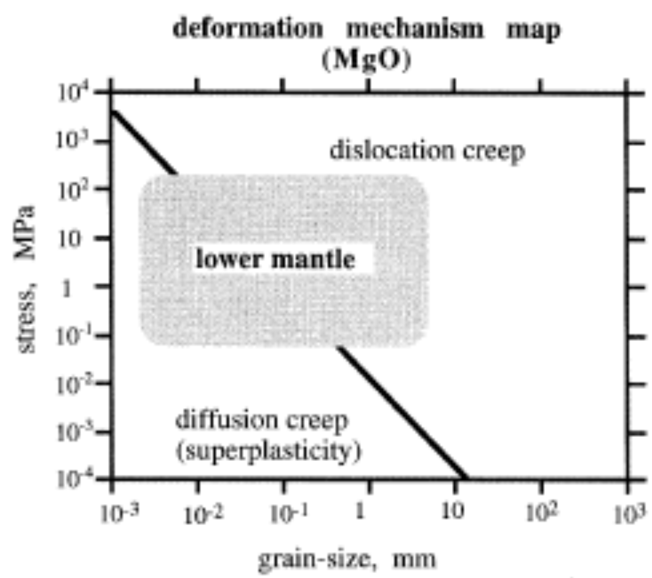


$$\left(\frac{\Delta d}{d}\right)^{hkl} = G\left(\psi, hkl \| \Sigma_{ij}\, S''_{ijpq}\, \frac{\bar{\eta}''_{ijpq}}{\langle H \rangle}\, \alpha, \beta\right)$$

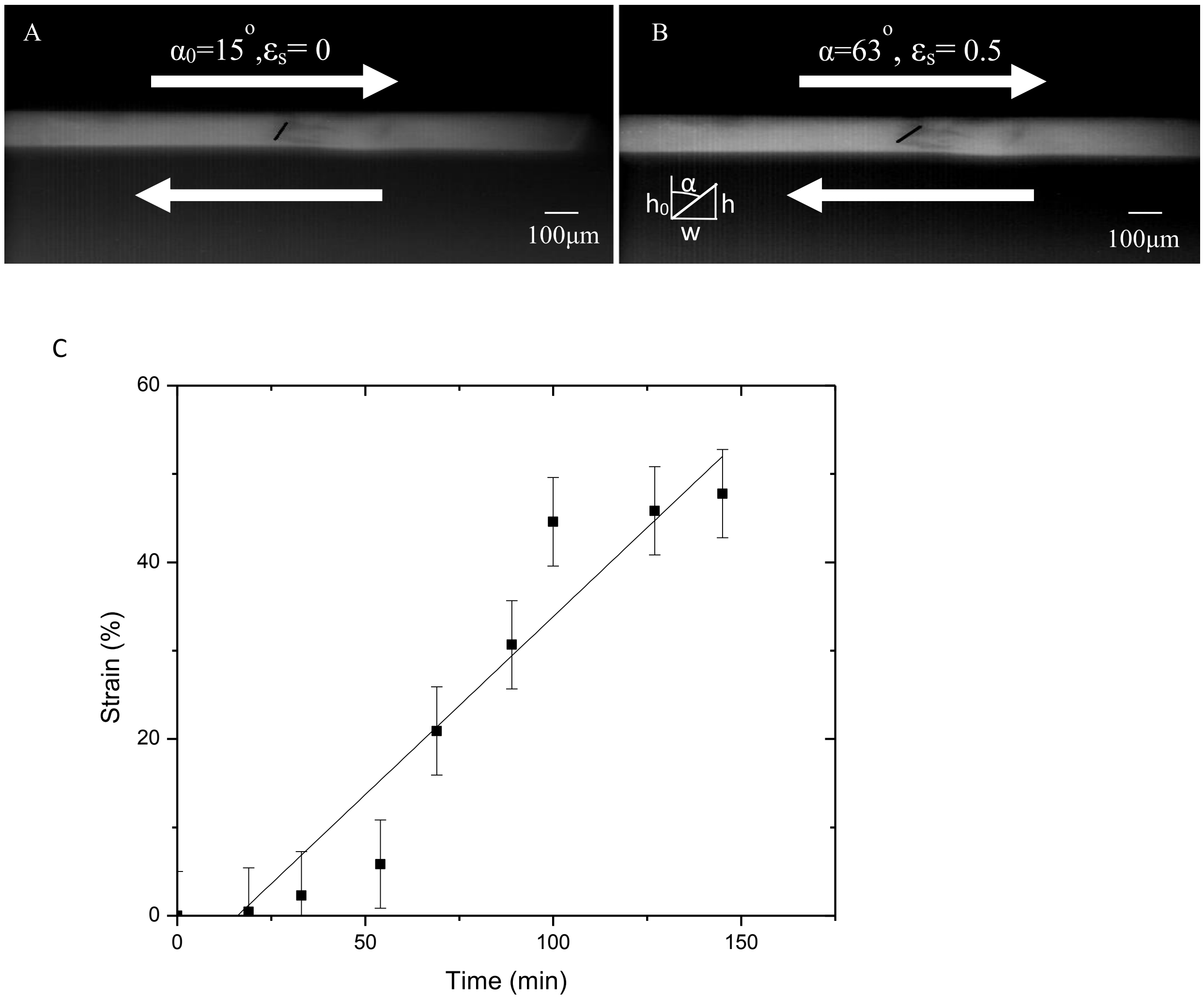
X-ray diffraction
→ strength
→ plastic anisotropy


phase transformation
boundary layer
grain growth
anisotropic
(dislocation creep)
isotropic
(superplasticity)
grain growth
stagnant core
stress
grain size


deformation mechanism map
(perovskite)
dislocation creep
lower mantle
diffusion creep
(superplasticity)
stress, MPa
grain-size, mm

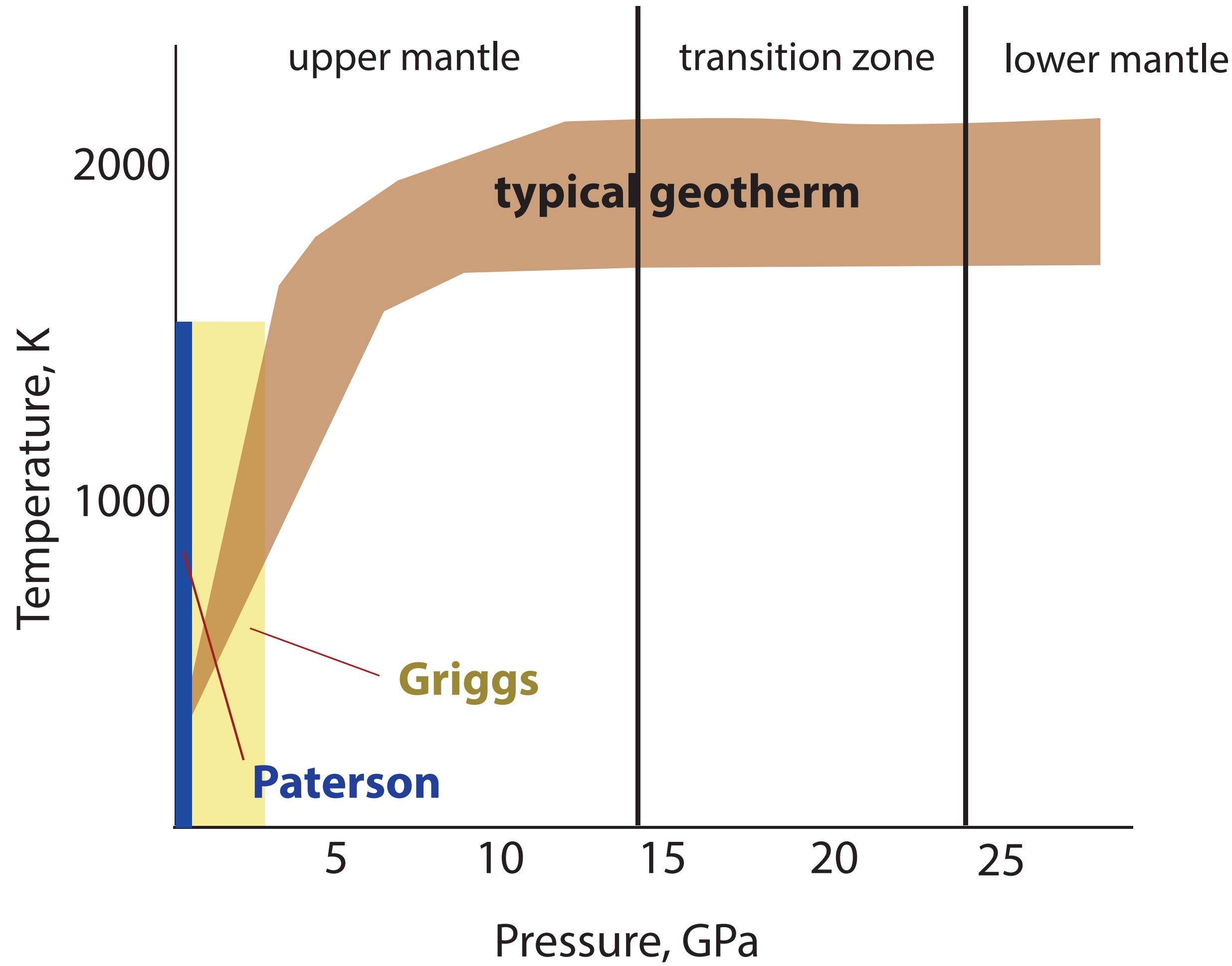

deformation mechanism map
(MgO)
dislocation creep
lower mantle
diffusion creep
(superplasticity)
stress, MPa
grain-size, mm

X-ray strain measurement



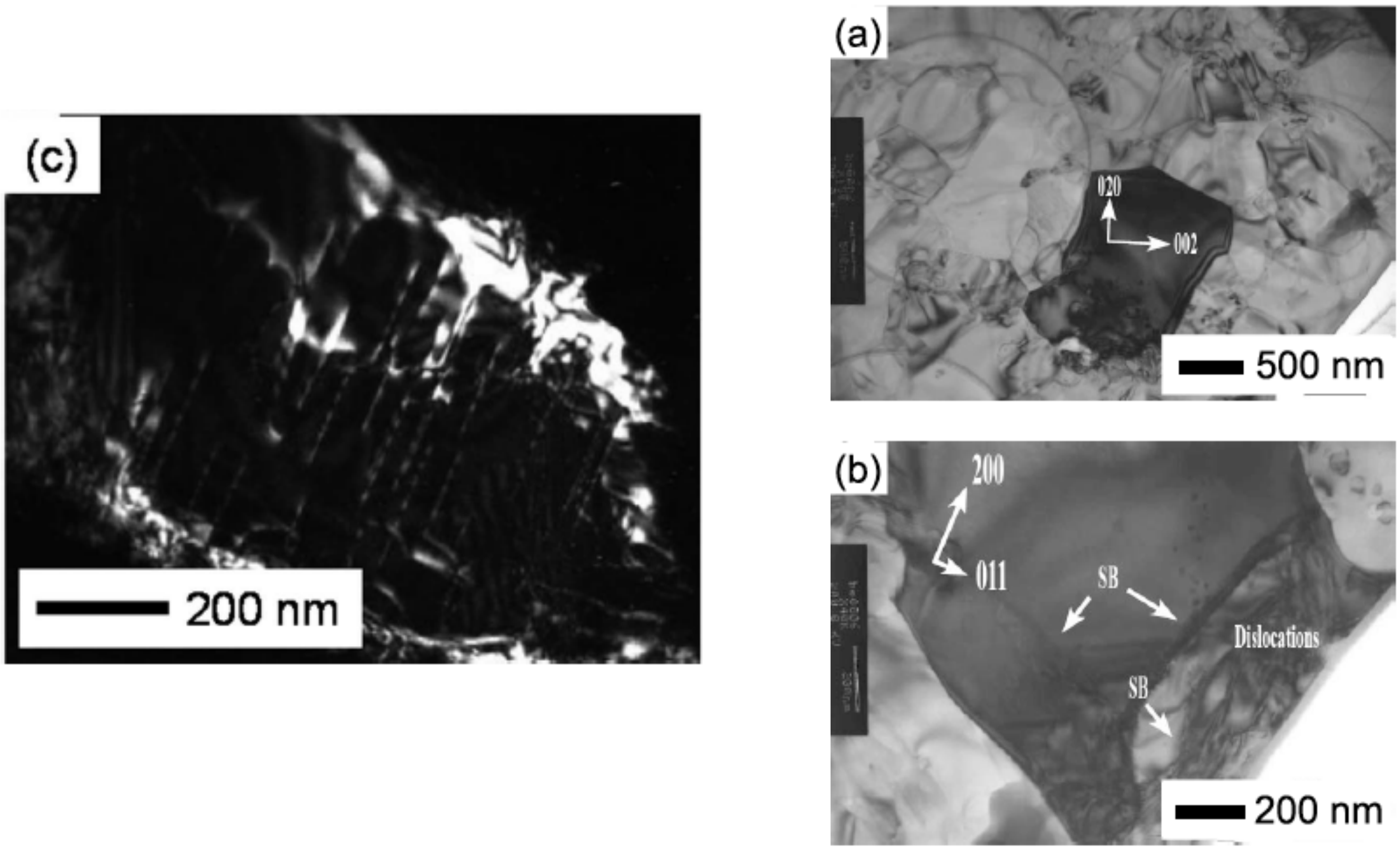
Girard et al. (2016)

Conditions for quantitative deformation experiments

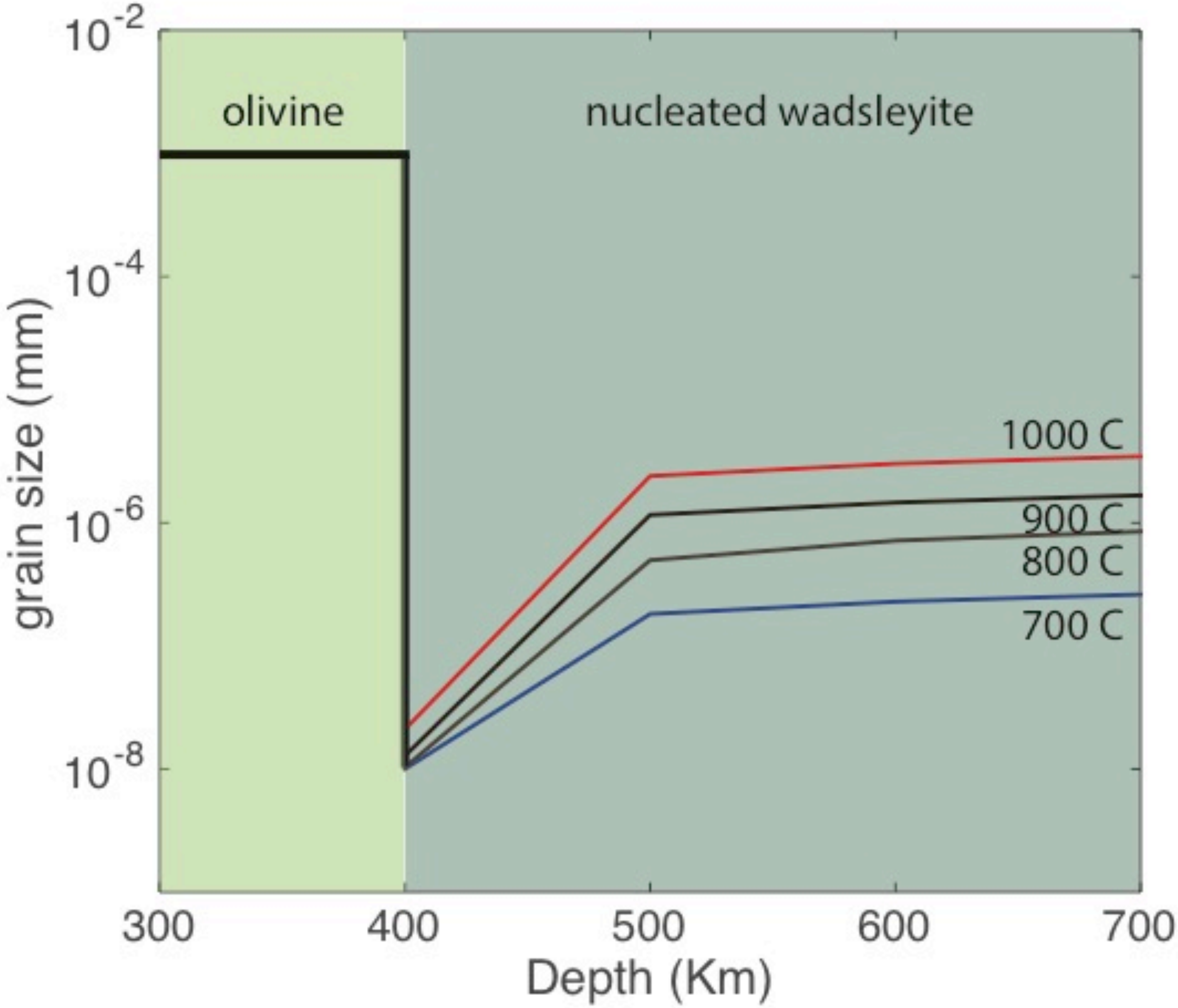


→ develop a new apparatus (techniques)

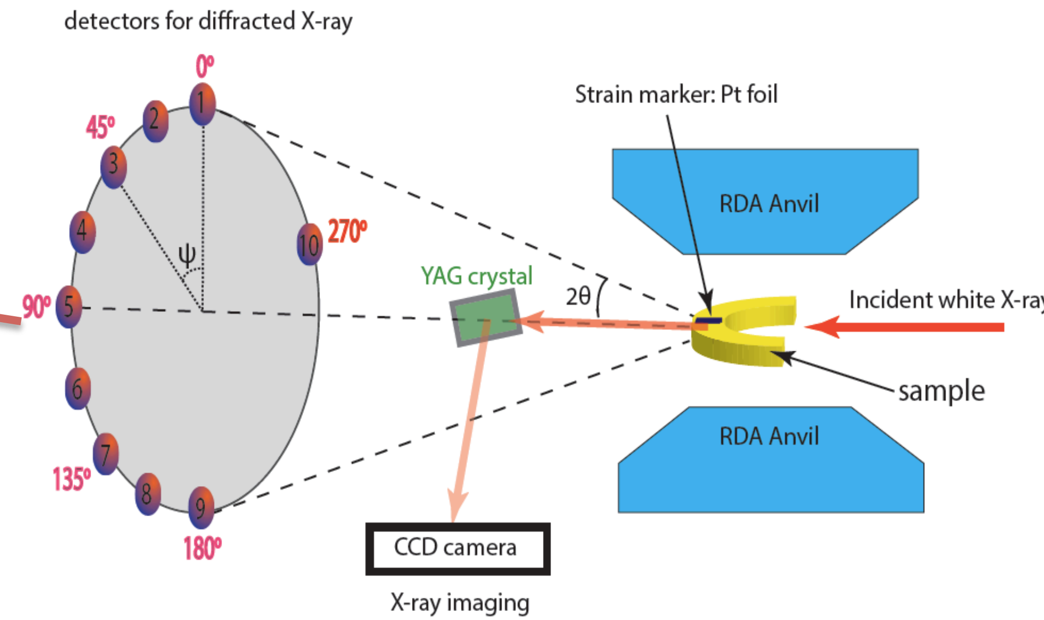
Microstructures → deformation mechanisms
Transmission electron microscopy
→ dislocation creep + diffusion creep



Kawazoe et al. (2010)


olivine
nucleated wadsleyite
1000 C
900 C
800 C
700 C
grain size (mm)
10-2
10-4
10-6
10-8
300
400
500
600
700
Depth (Km)

X-ray stress, strain measurements

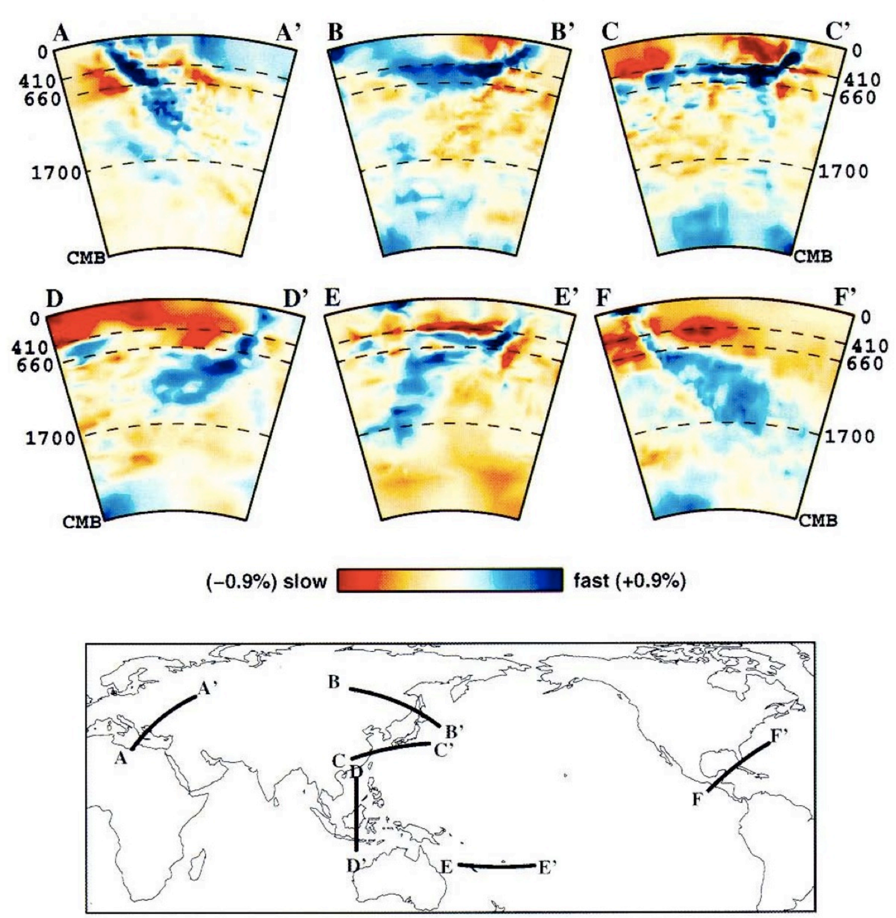


Strain ← X-ray absorption (imaging)
Stress ← X-ray diffraction

Motivation 1

Some (cold) slabs are deformed in the transition zone.

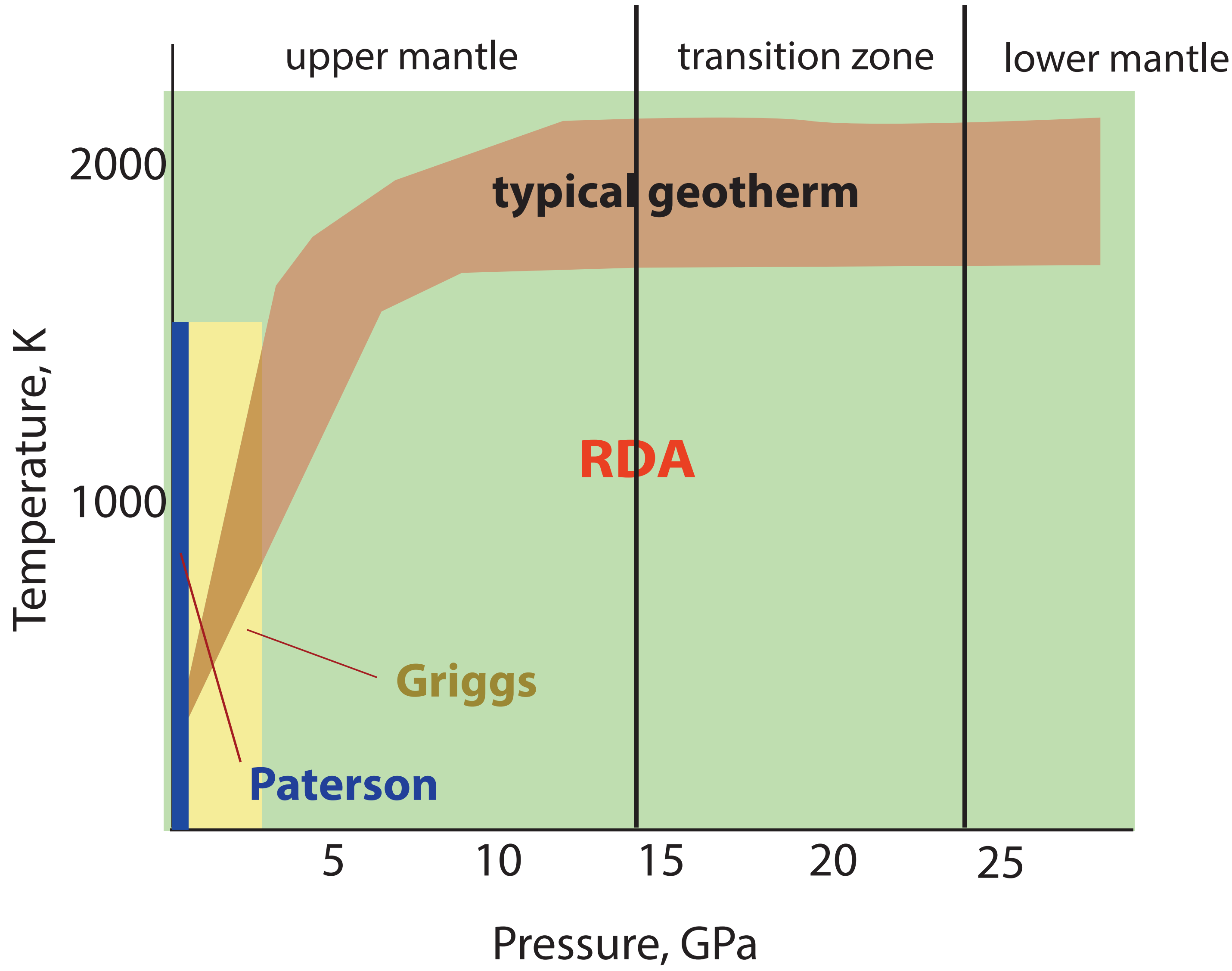
→ Why (how) does a cold slab deform?



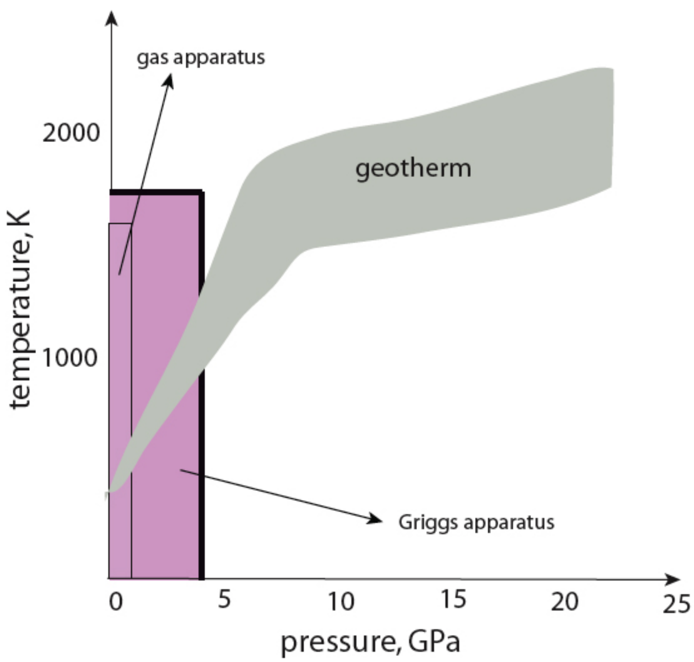
Karason-van der Hilst (2000)

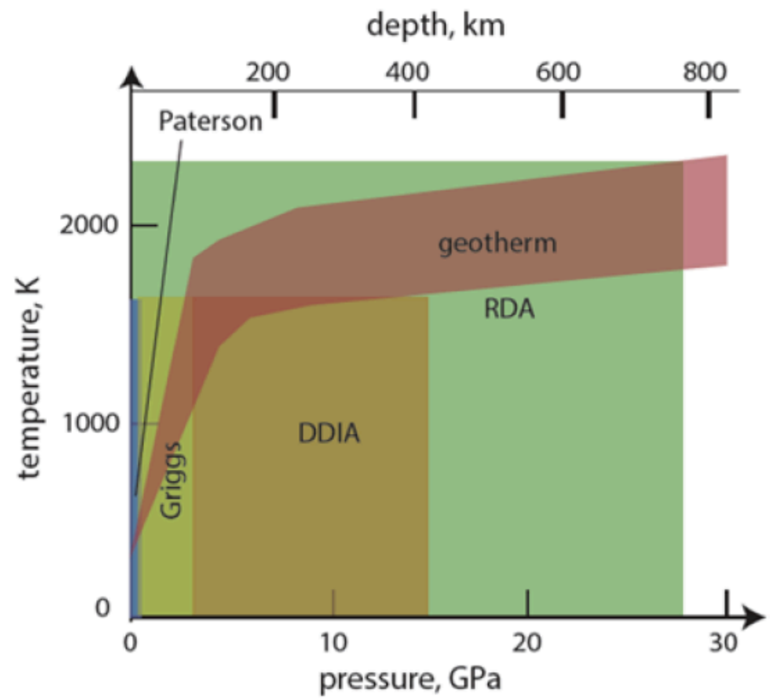
Conditions for quantitative deformation experiments

before **after**

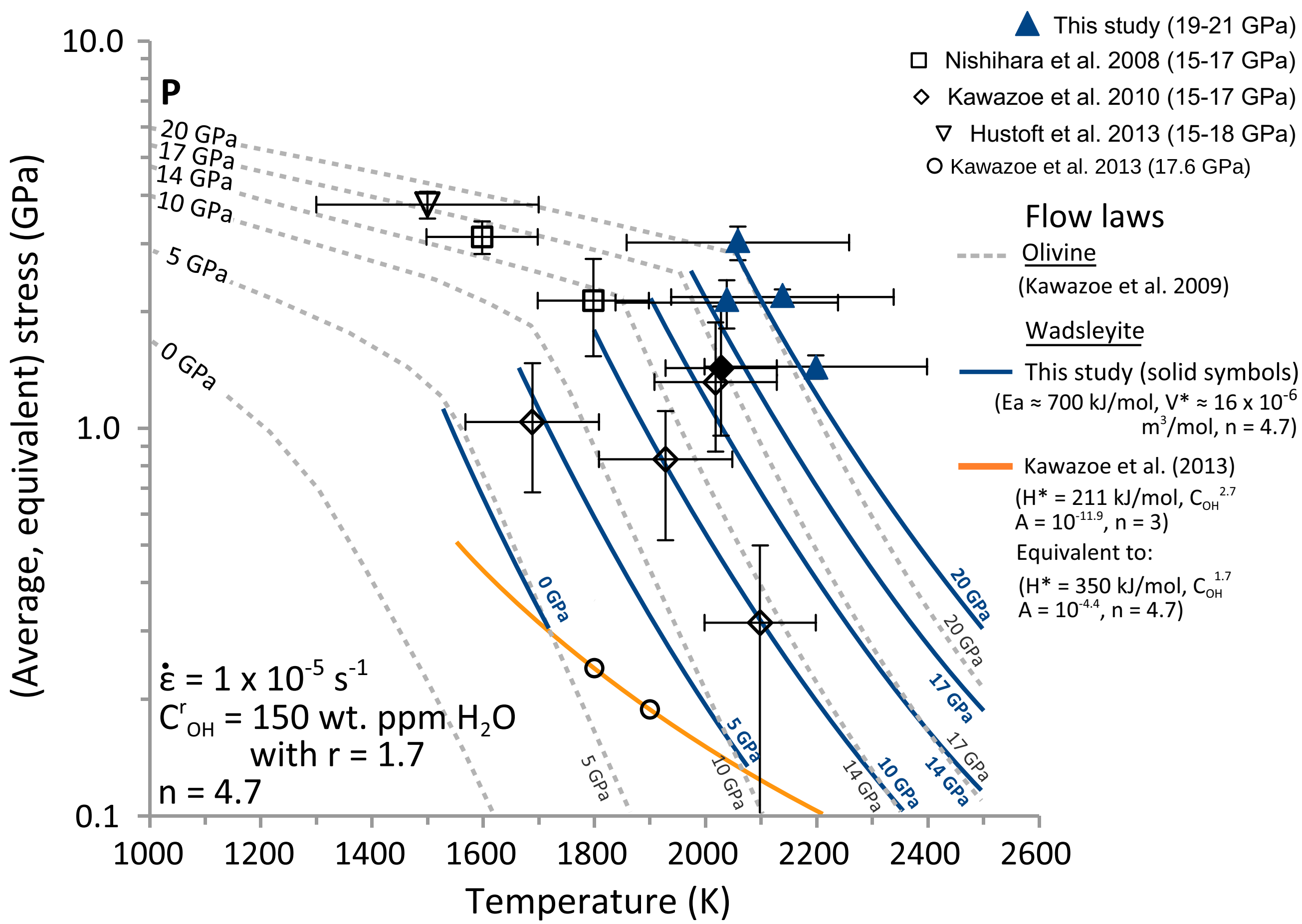


Conditions for experimental studies on deformation



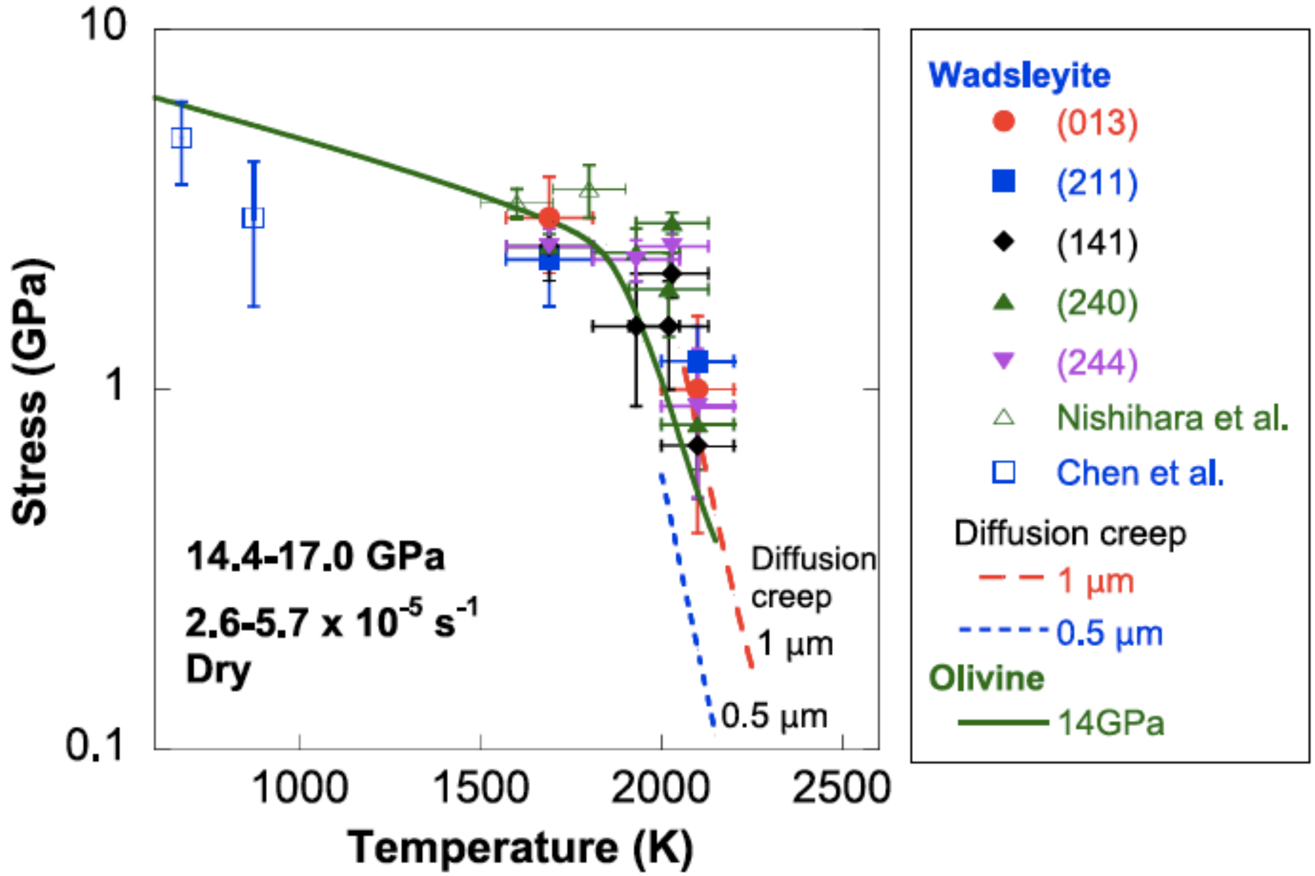


- ✓ needs for deformation experiments at higher P
- ✓ deformation experiments need to be conducted in the right regime (in order for geological applications)



Farla et al. (2015)

wadsleyite



Kawazoe et al. (2010)