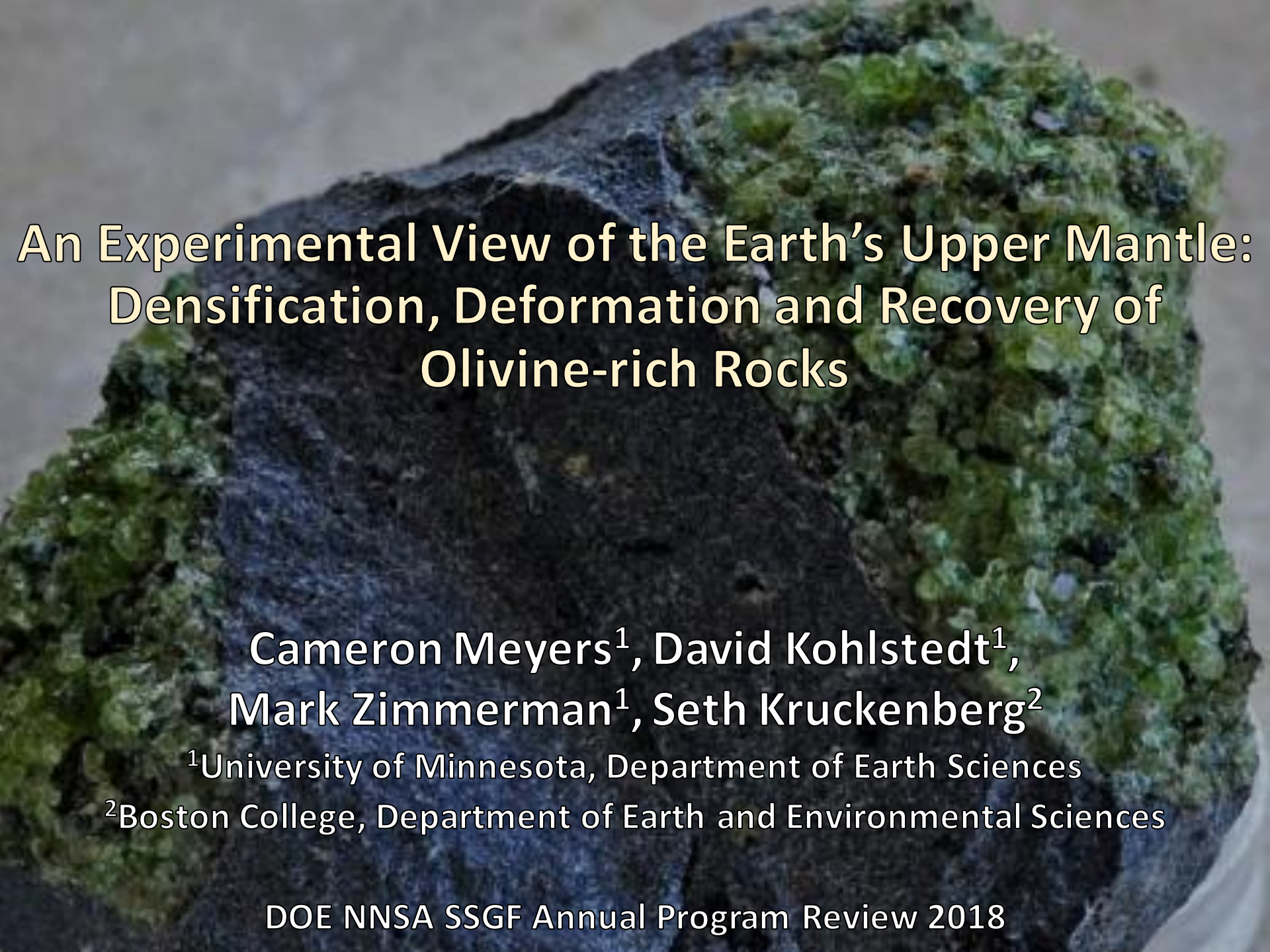


An Experimental View of the Earth's Upper Mantle: Densification, Deformation and Recovery of Olivine-rich Rocks

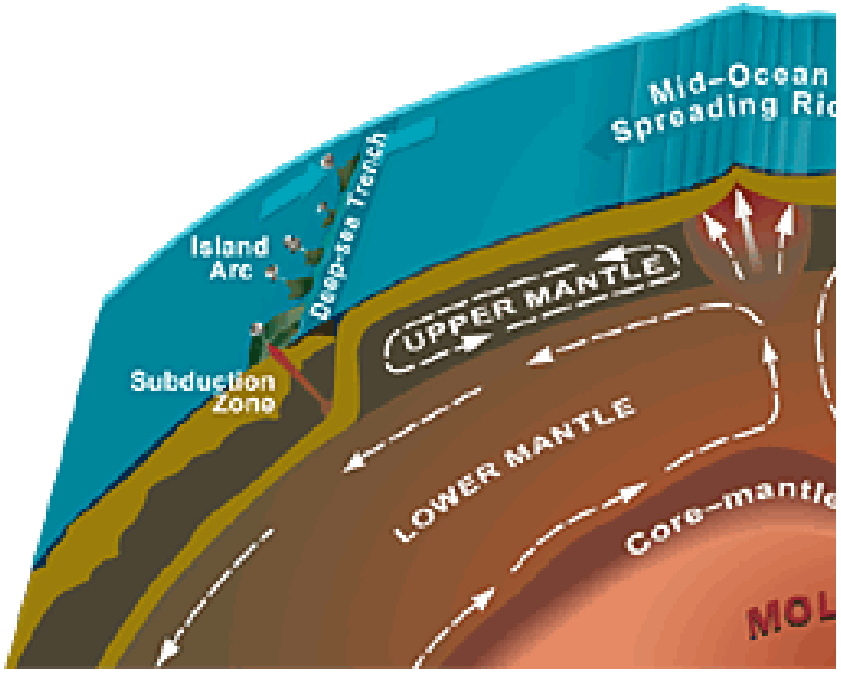
Cameron Meyers[1], David Kohlstedt[1],
Mark Zimmerman[1], Seth Kruckenberg[2]

[1]University of Minnesota, Department of Earth Sciences

[2]Boston College, Department of Earth and Environmental Sciences

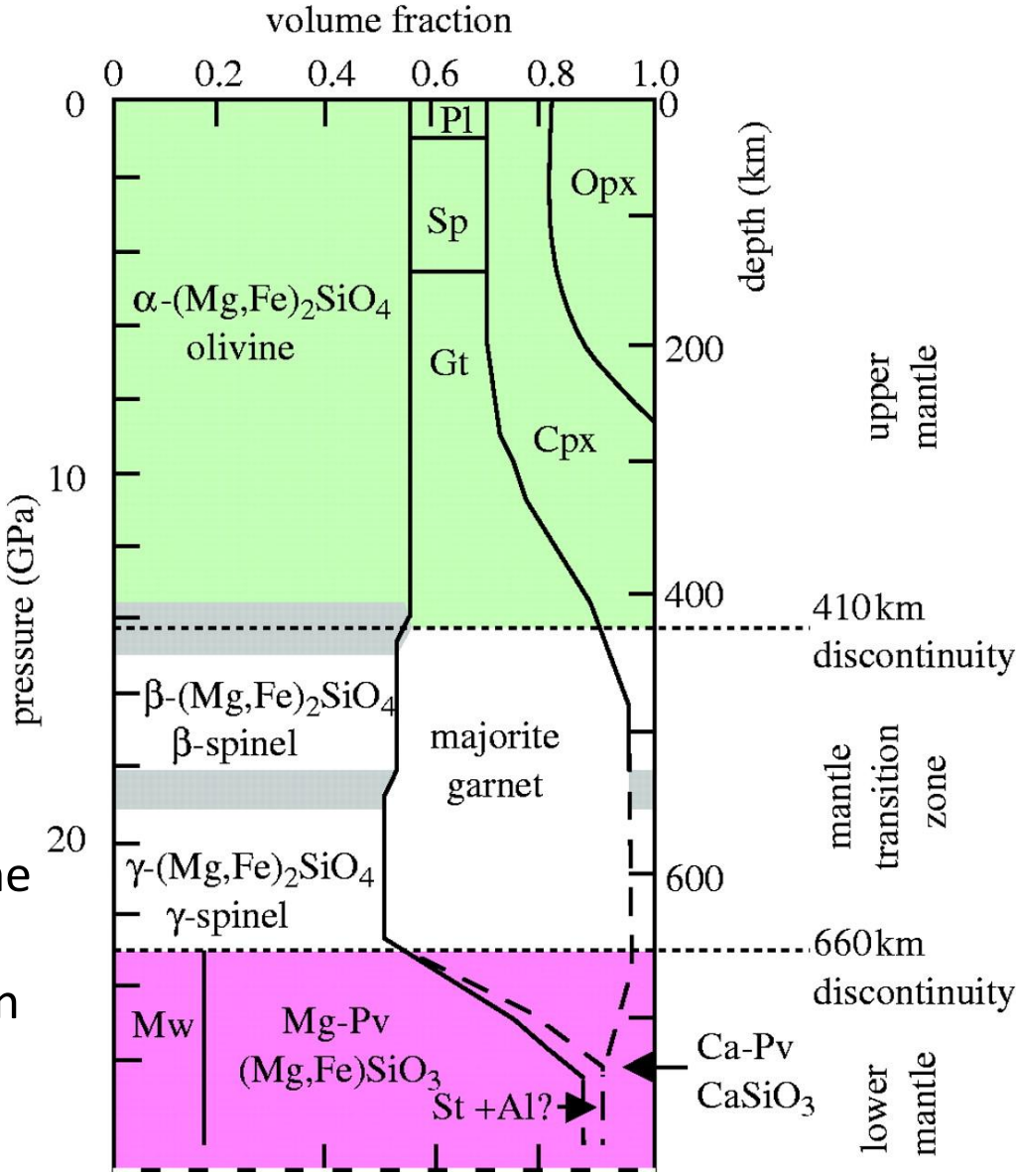
DOE NNSA SSGF Annual Program Review 2018

Introduction to the Earth's mantle



Detrick (2004)

Olivine makes up nearly 60% of the Earth's upper mantle and is considered to control deformation in this region of the Earth



Bovolo (2005)

Deformation Mechanisms and Power-law Creep

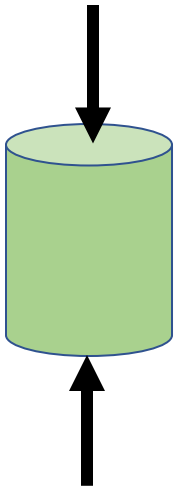
$$\dot{\varepsilon} = A(T, P, \mu_i)\, \sigma^n d^{-m}$$

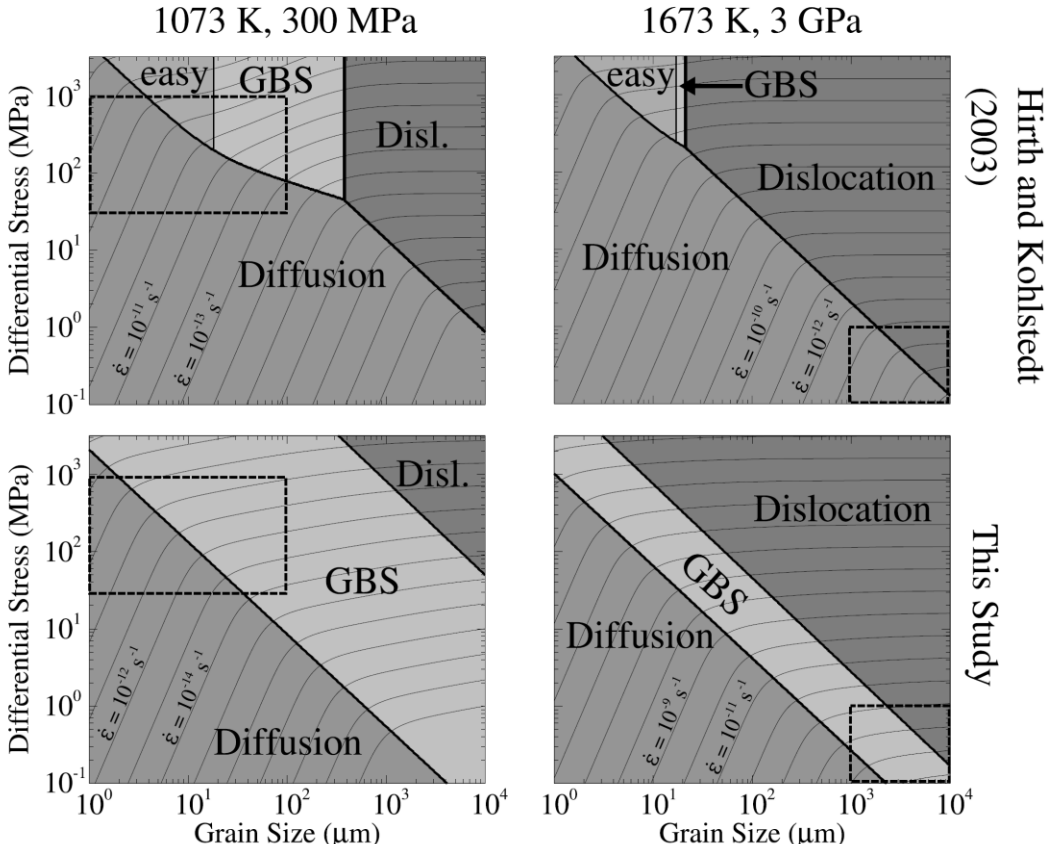
Strain rate is related to stress and grain-size by power-law; exponents n and m indicate deformation mechanism

Diffusion Creep: $n = 1; m = 3$

Dislocation Creep: $n = 3 - 5; m = 0$

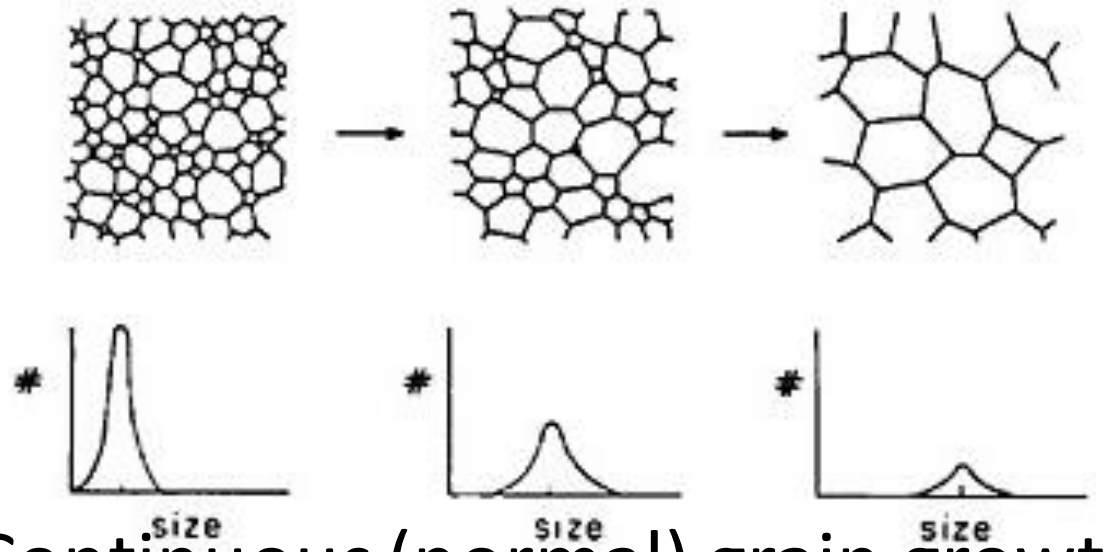
Dislocation Accommodated GBS: $n = 2 - 5; m = 1$



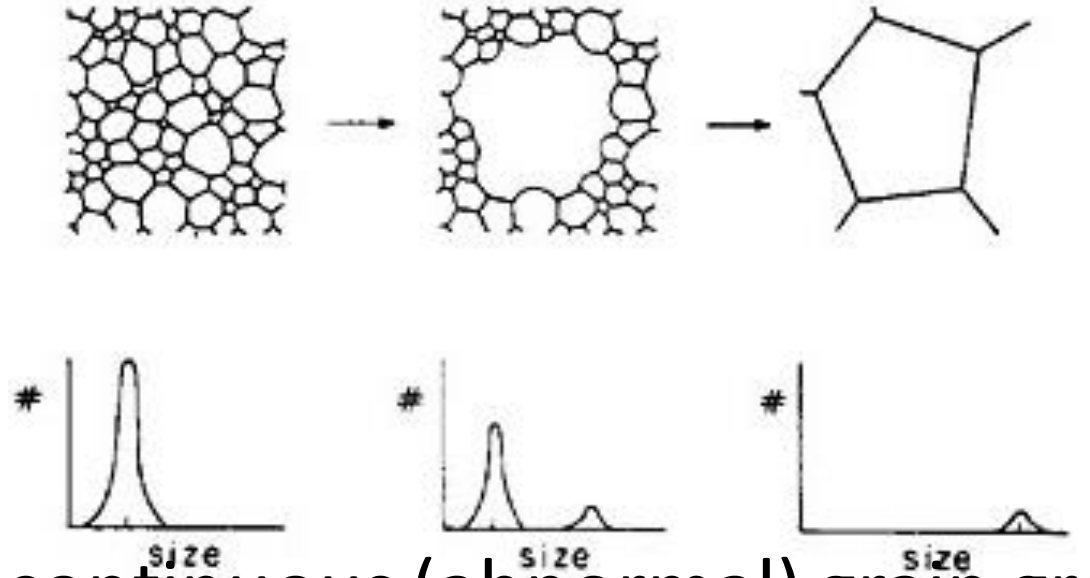


Hansen et al. (2011)

Mechanisms of grain growth



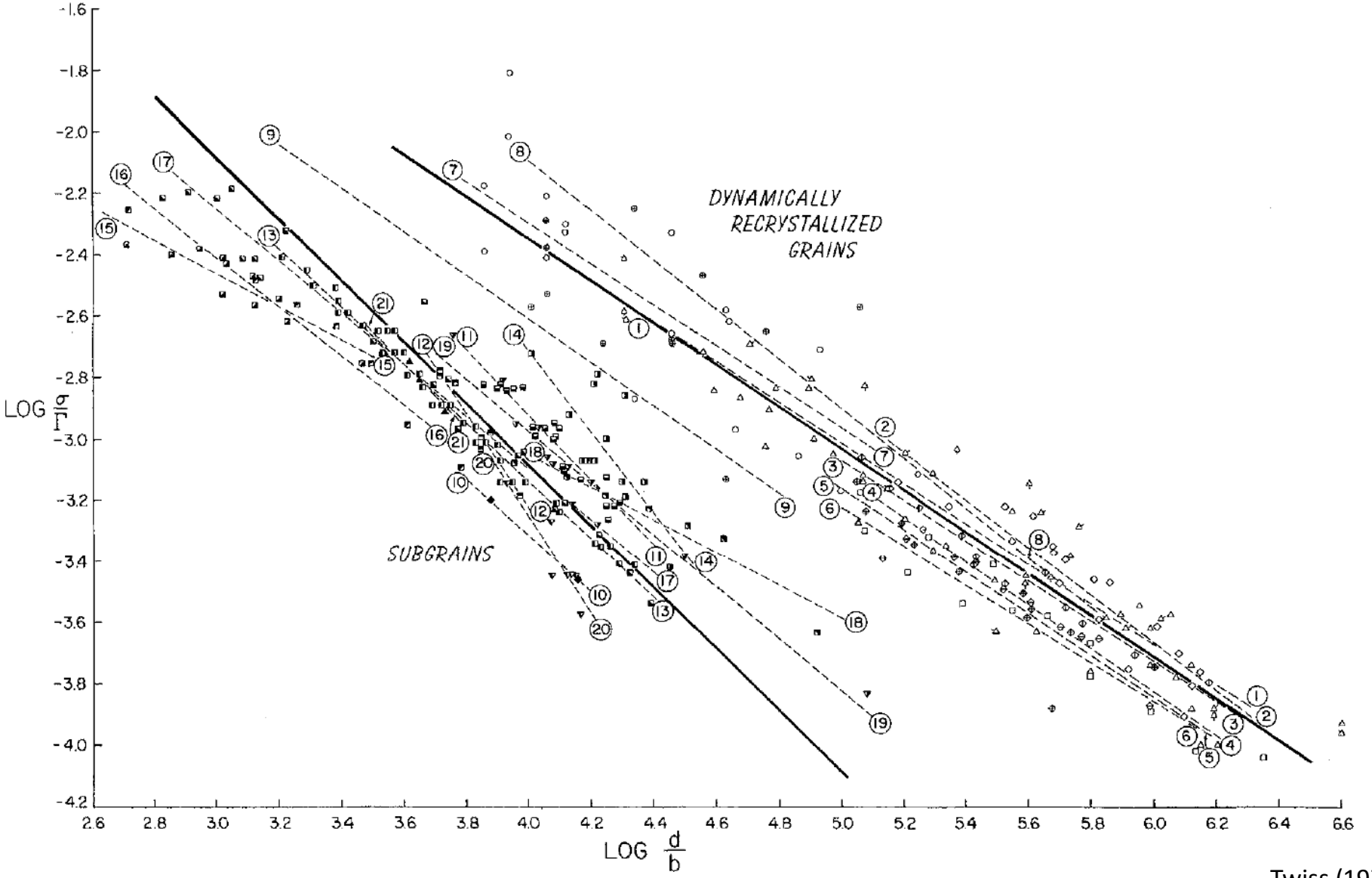
Continuous (normal) grain growth



Discontinuous (abnormal) grain growth

Cohen (1987)

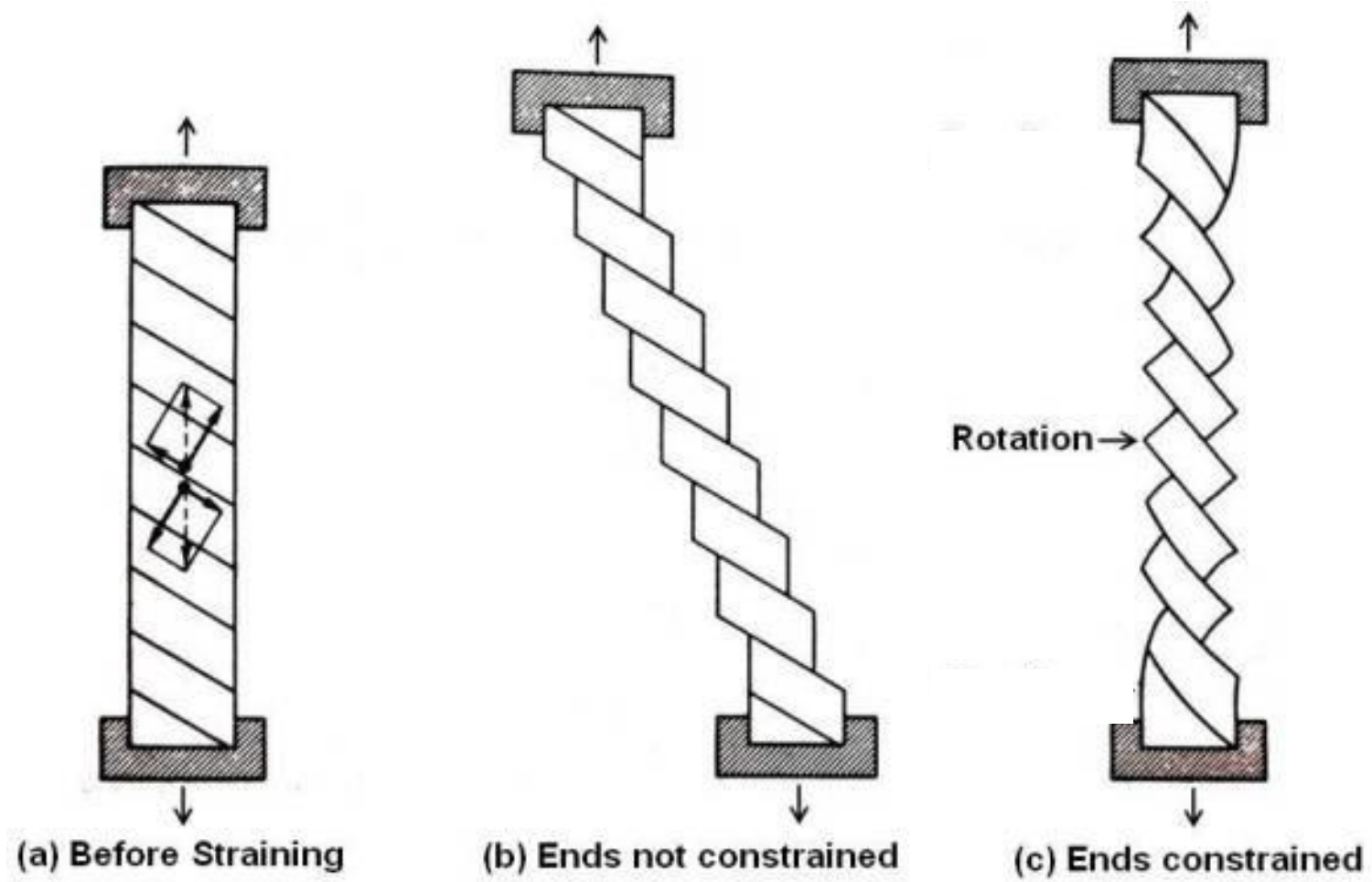
Dynamic Recrystallization: Grain-size reduction induced by deformation



Twiss (1977)

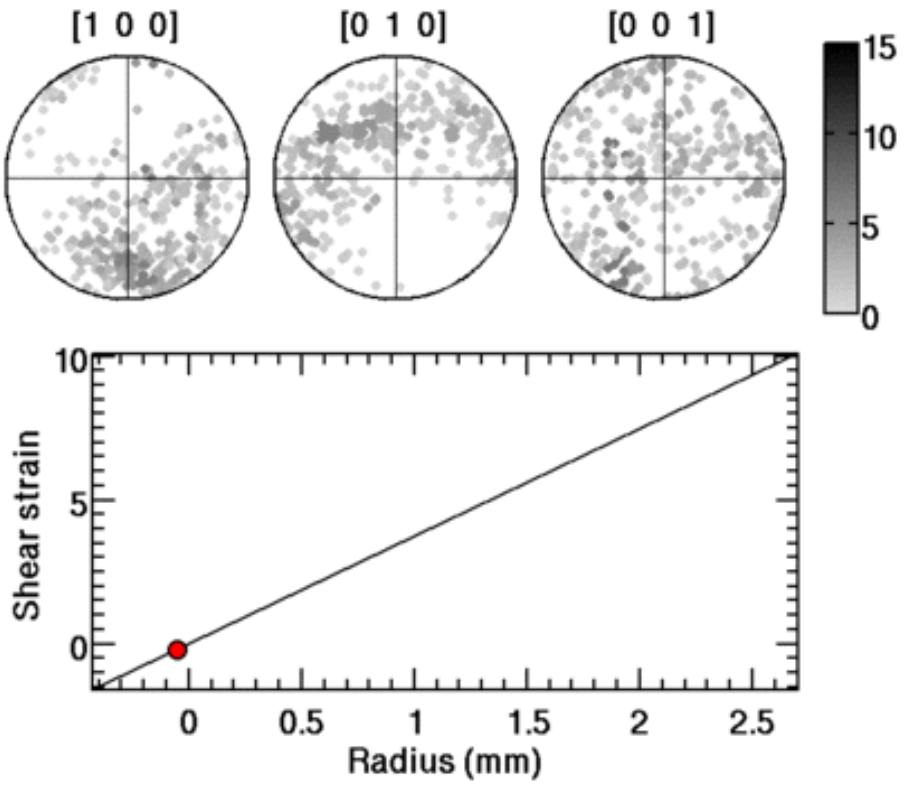
Crystallographic Preferred Orientation (CPO):

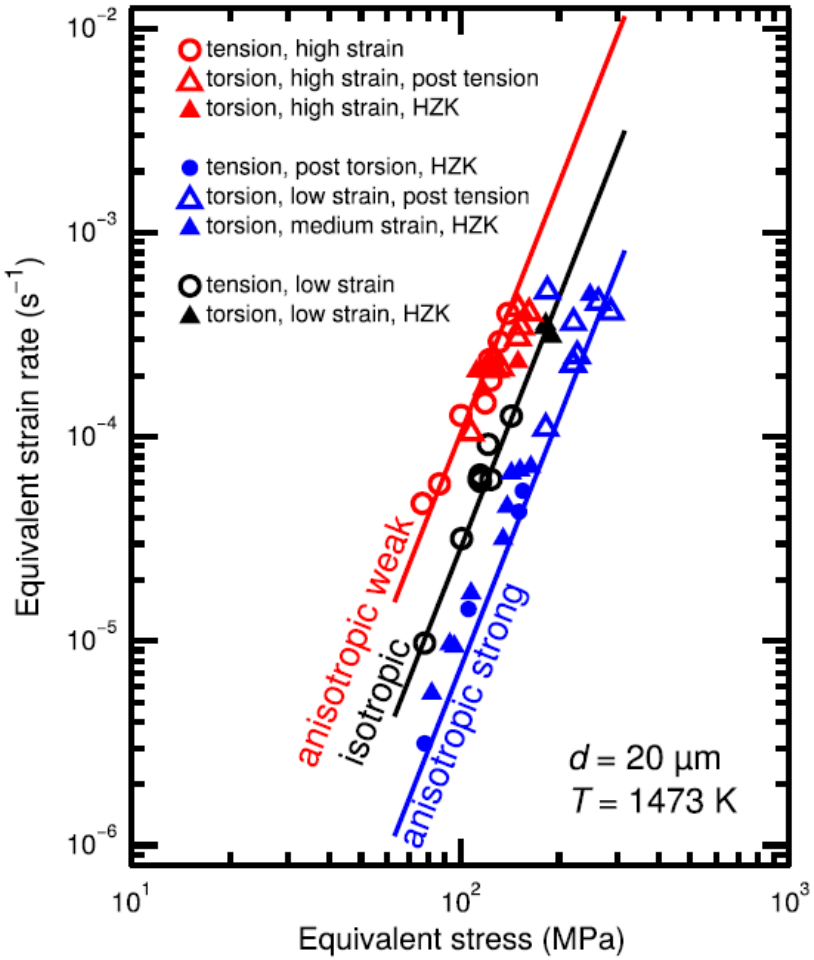
rotation and crystallographic alignment of grains due to slip of dislocations



Schematic Representation of Slip in Tension

Crystallographic Preferred Orientation (CPO) and Anisotropic Viscostiy

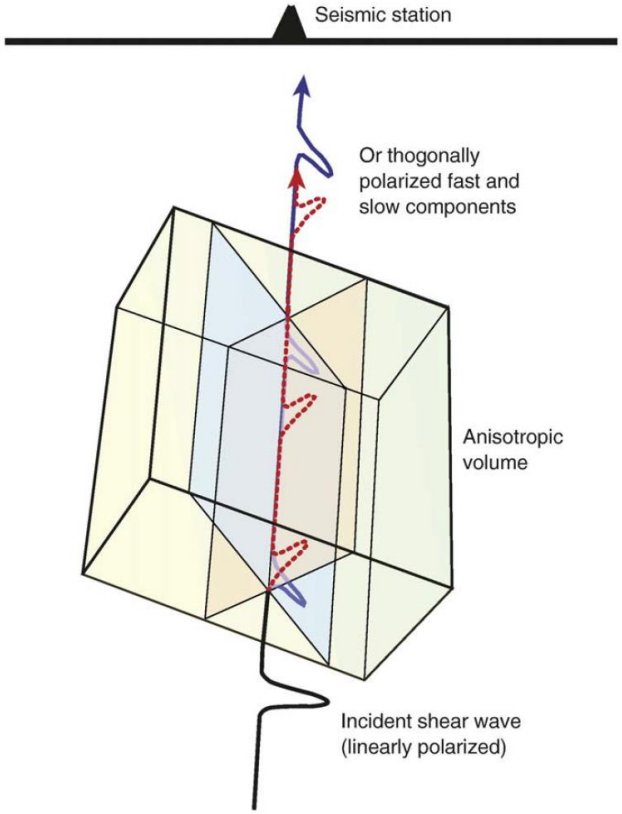


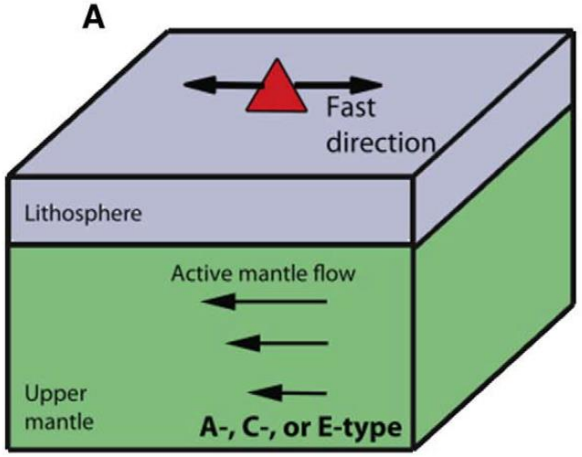


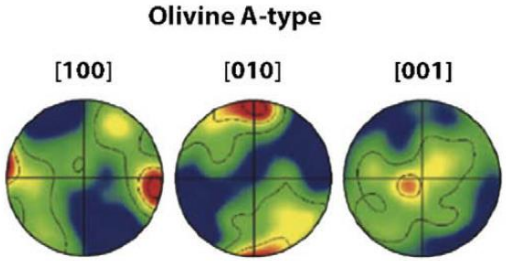
https://lnhansen.wordpress.com/research/

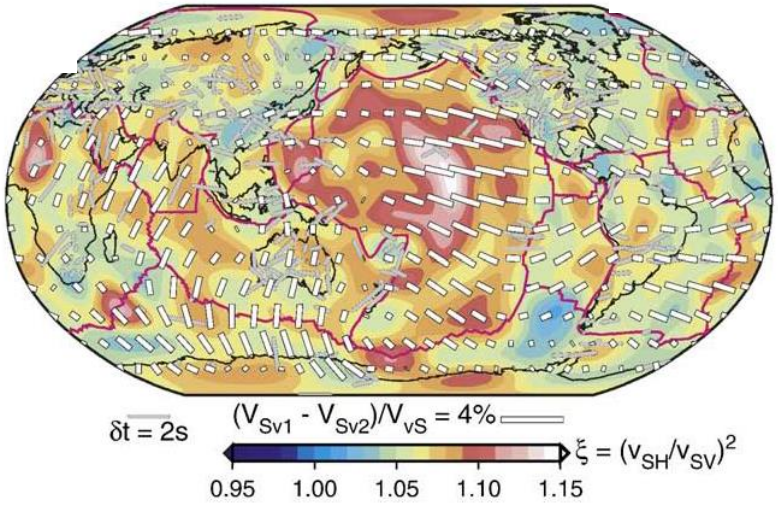
Hansen et al.(2016)

Seismic Anisotropy



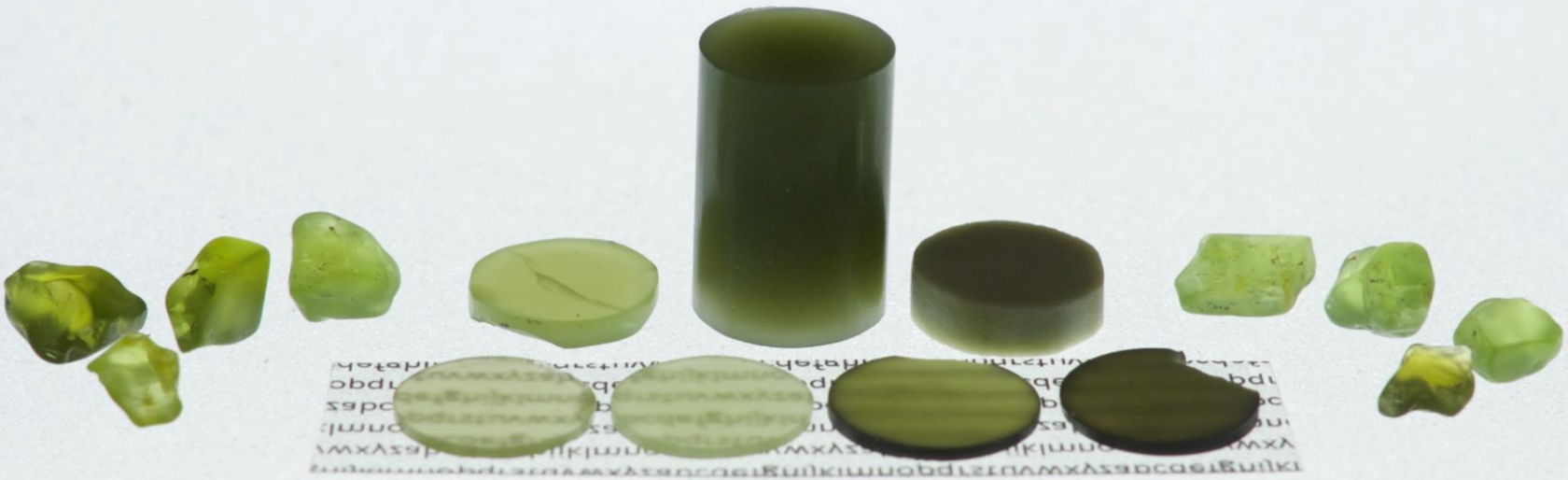




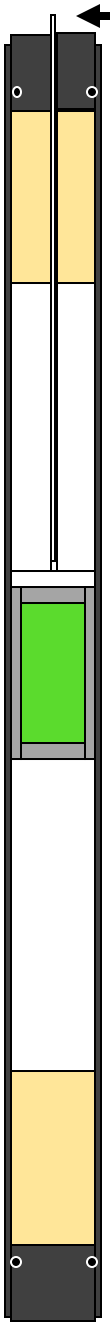


Long and Becker 2010

Development of improved starting material for experimental studies on olivine-rich rocks: Evacuated Hot-Pressing



Conventional hot-pressing



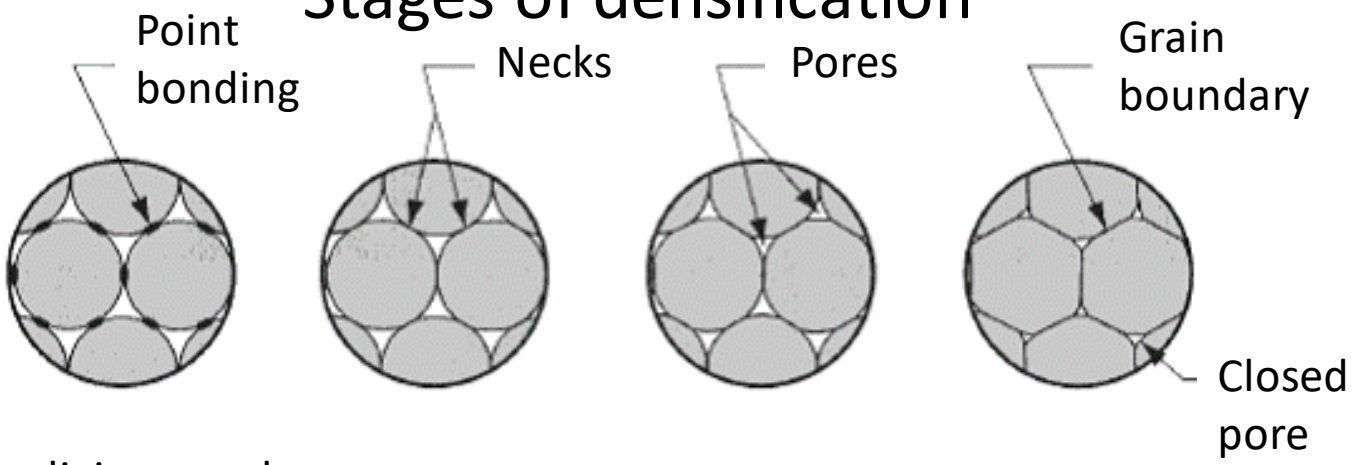
300 MPa
1250°C
fO_2=Ni/NiO

Gem-quality crystals of San Carlos olivine (hand picked)

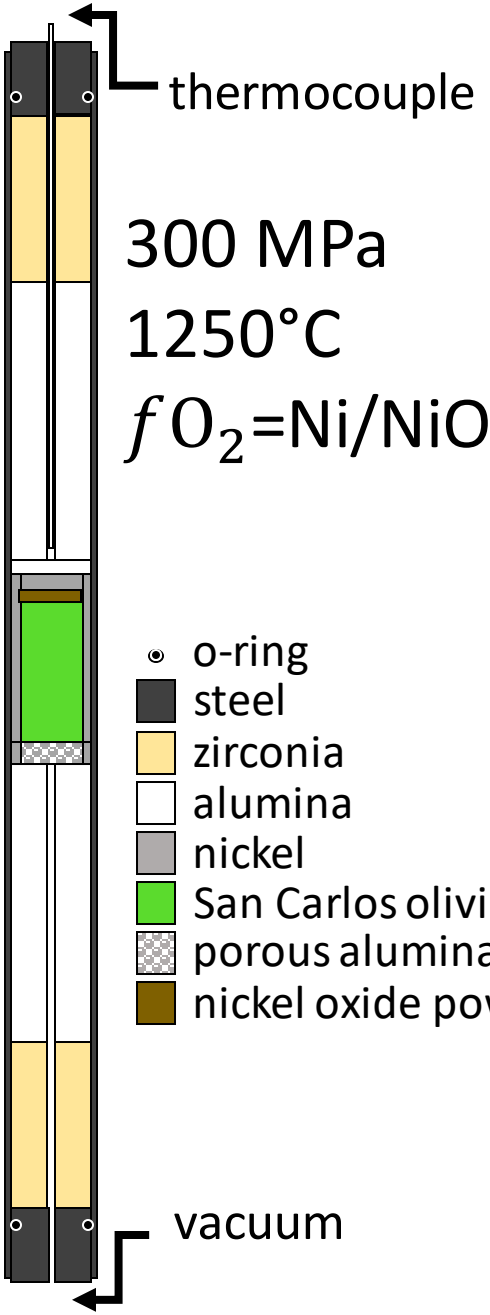
Pulverized by fluid-energy mill (6 ± 2 µm) Heated in mixed gas to *T* ≈ 1000°C

Hot pressed at 300 MPa, 1250°C, roughly 4 h in a sealed Ni capsule (~98% dense)

Stages of densification

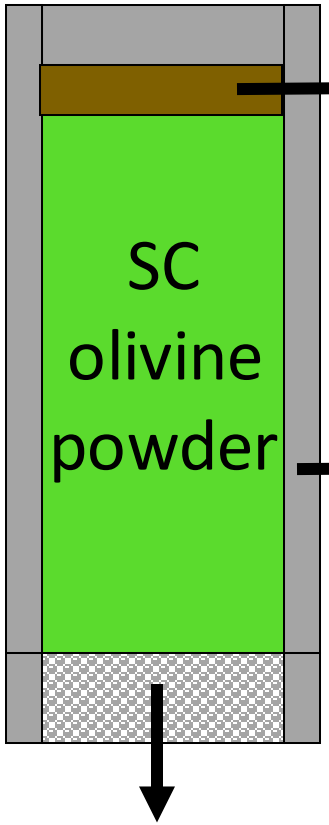


Evacuated hot-pressing



300 MPa
1250°C
fO_2=Ni/NiO

- o-ring
- steel
- zirconia
- alumina
- nickel
- San Carlos olivine powder
- porous alumina
- nickel oxide powder



nickel oxide powder (solid state fO_2 buffer)

nickel capsule

vacuum (through porous ceramic)

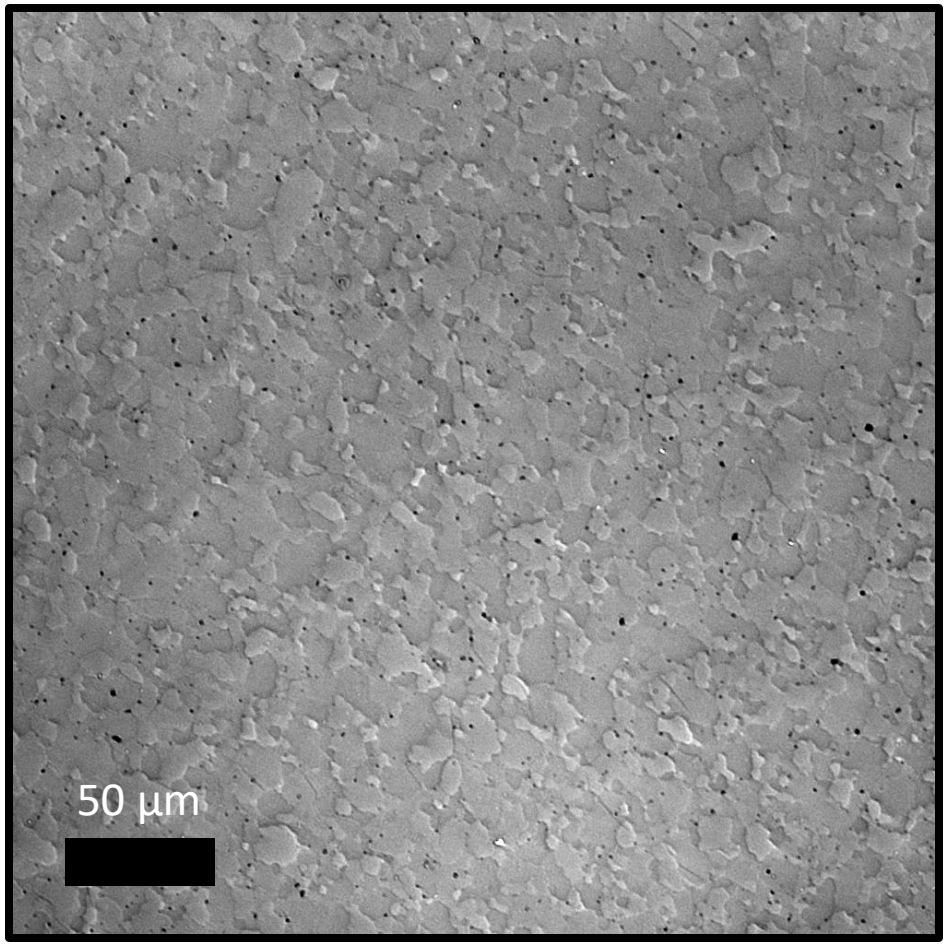
Conventional hot-pressed San Carlos olivine

Evacuated hot-pressed San Carlos olivine

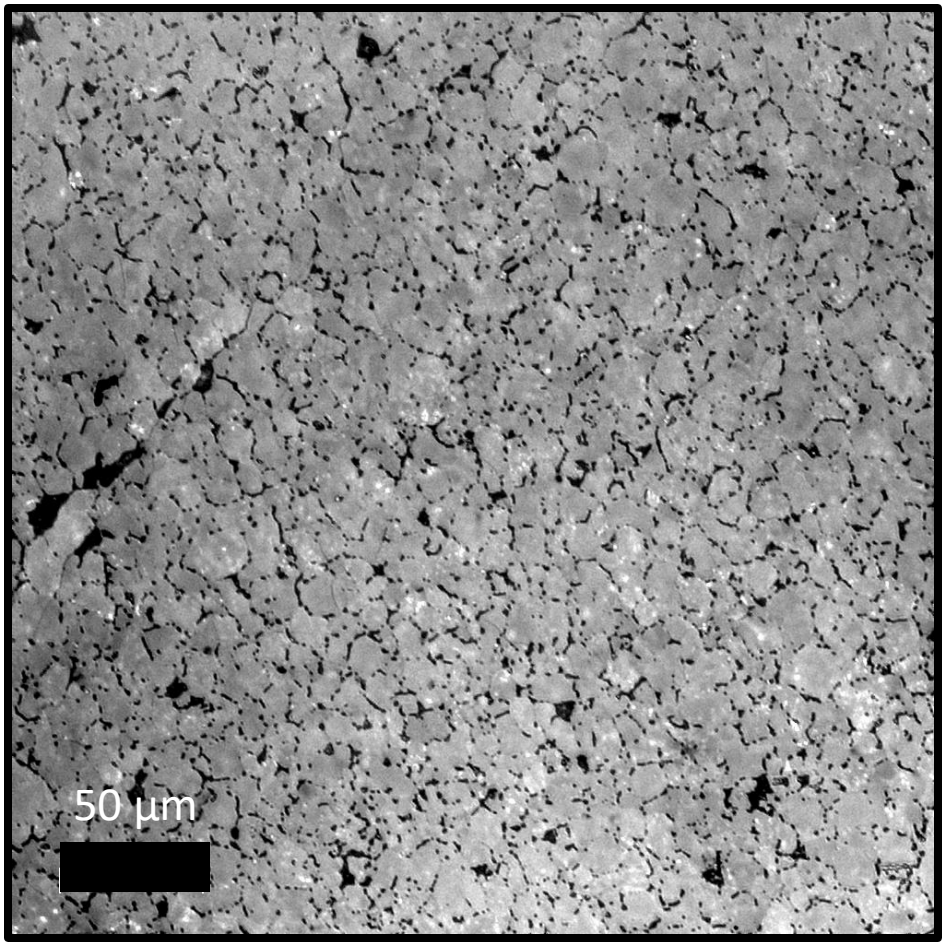
transmitted light through 1 mm thickness; 12 mm diameter

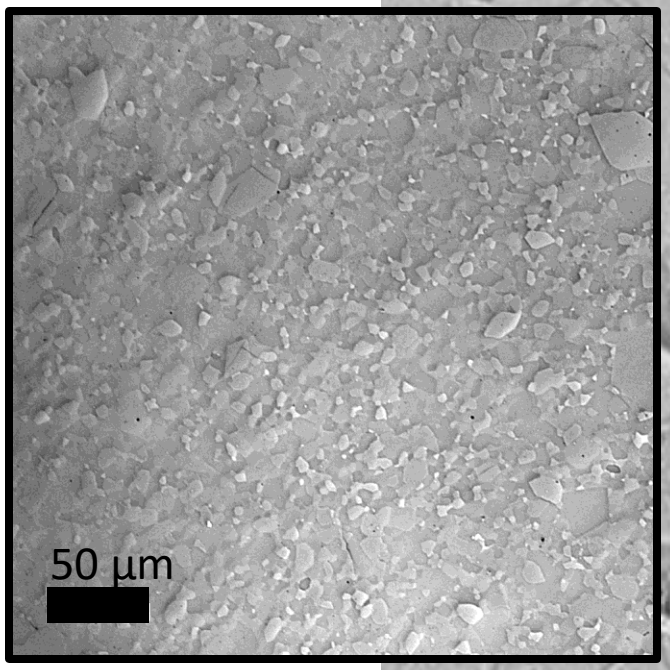
Static annealing of conventional hot-press at 1 atm

Conventional hot-press
1250°C; 300 MPa; 4 h



Annealed in mixed gas
1350°C; 0.1 MPa; 20 h



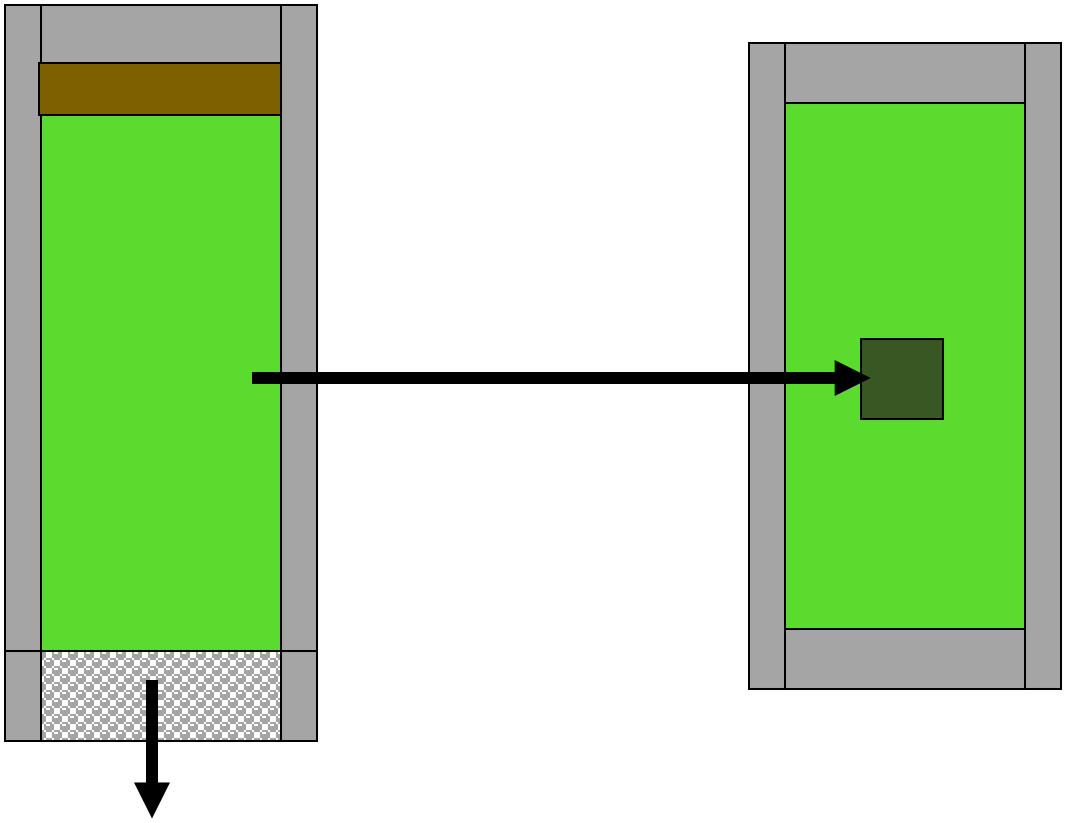


Evacuated hot-press
1250°C; 300 MPa; 4 h

50 µm

Annealed at 1 atm in mixed gas
1350°C; 0.1 MPa; 20 h

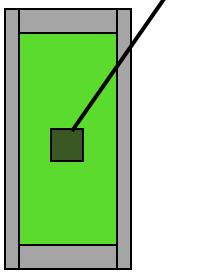
Static annealing of evacuated hot-press at 300 MPa



300 MPa
1250°C

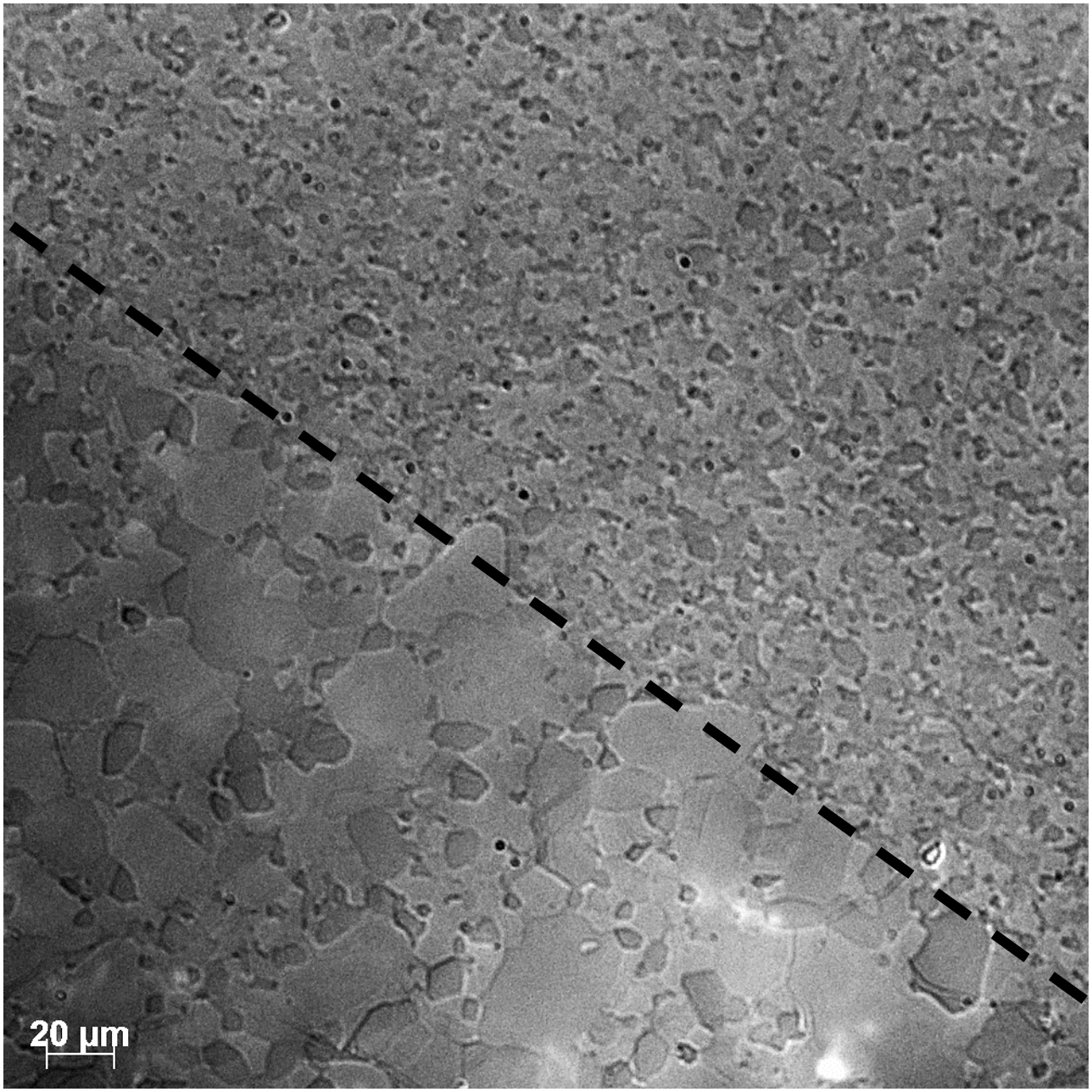
vacuum
(through porous ceramic)

nickel
San Carlos olivine powder
porous alumina
nickel oxide powder
evacuated HP San Carlos olivine



1250°C
300 MPa
4h

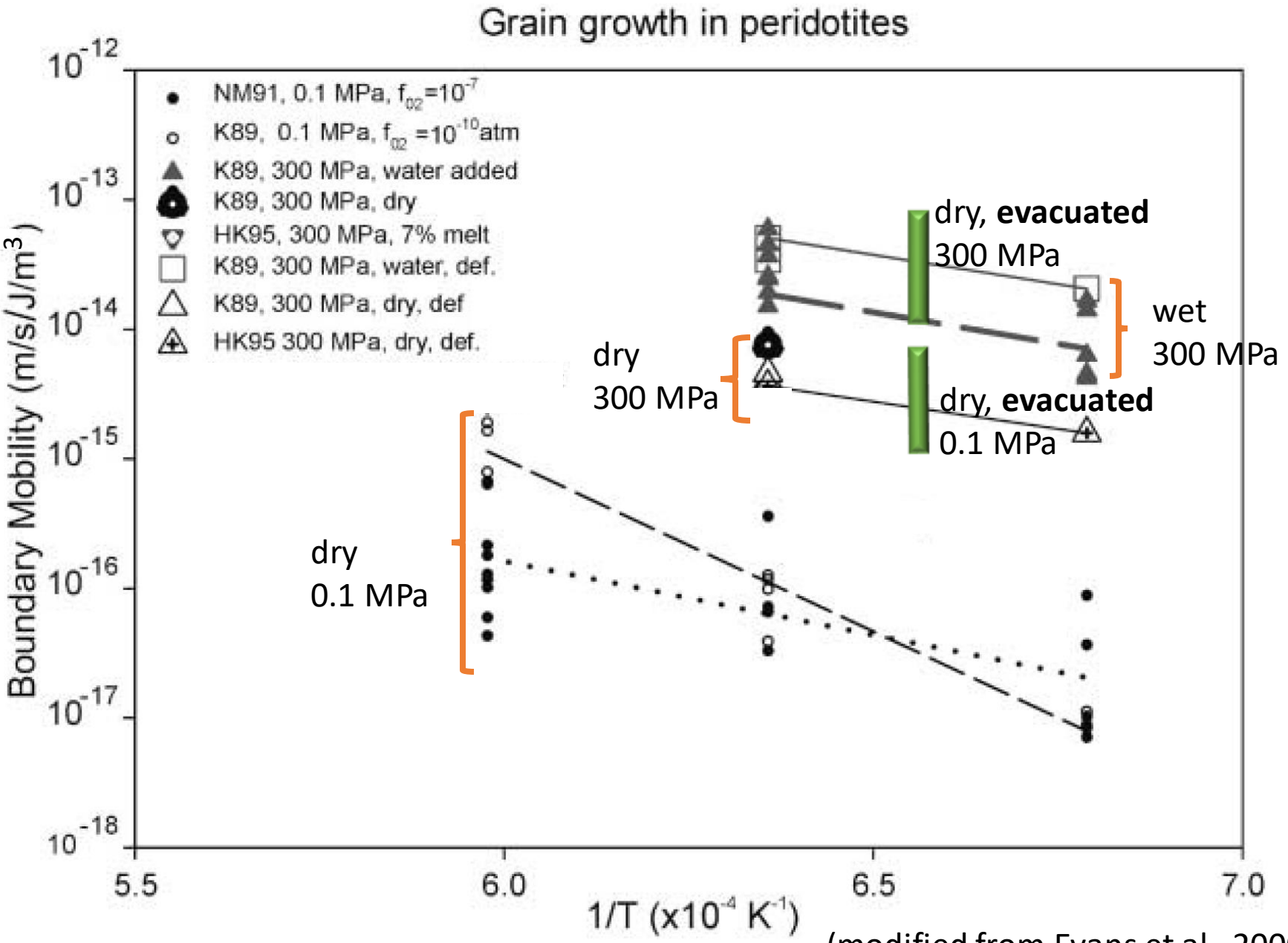
Static anneal of **evacuated hot-press**



Conventional hot-press of surrounding evacuated hot-press

(same starting powder)

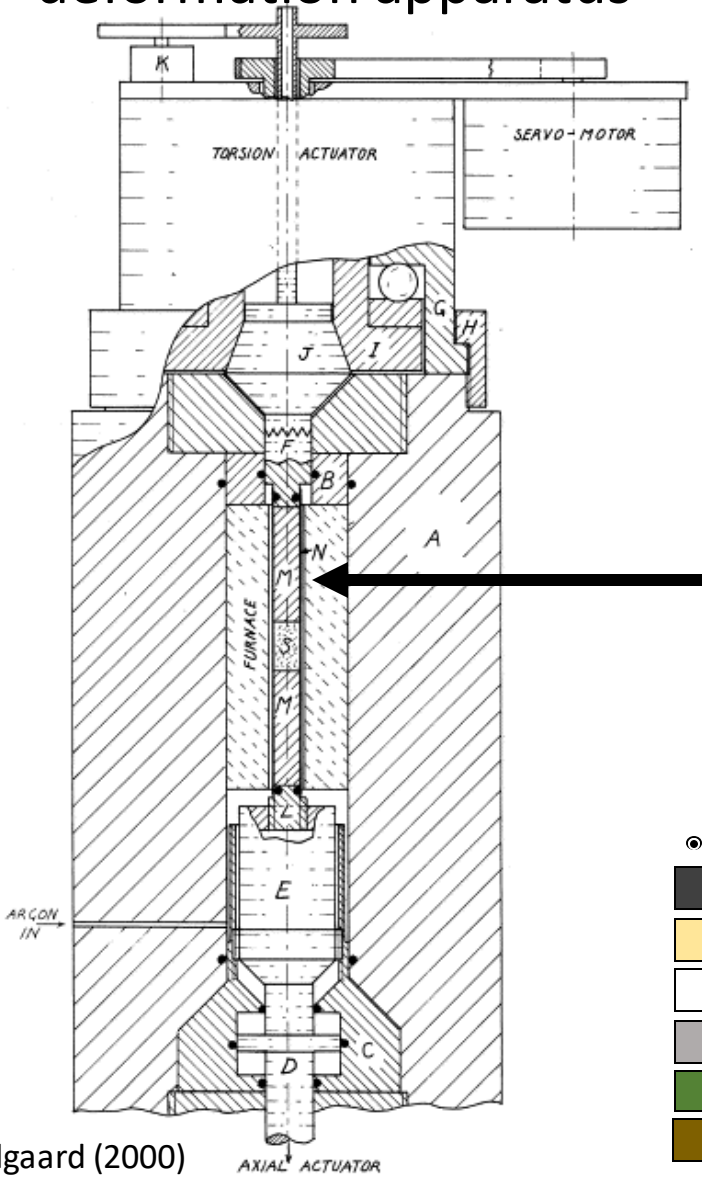
Comparison with previous work



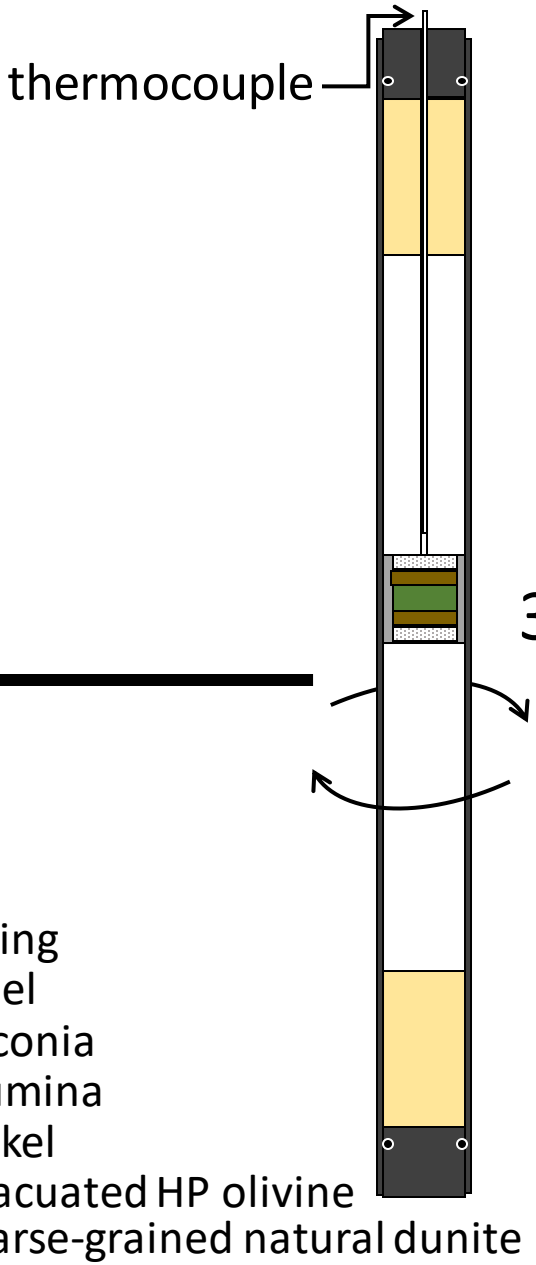
(modified from Evans et al., 2000)

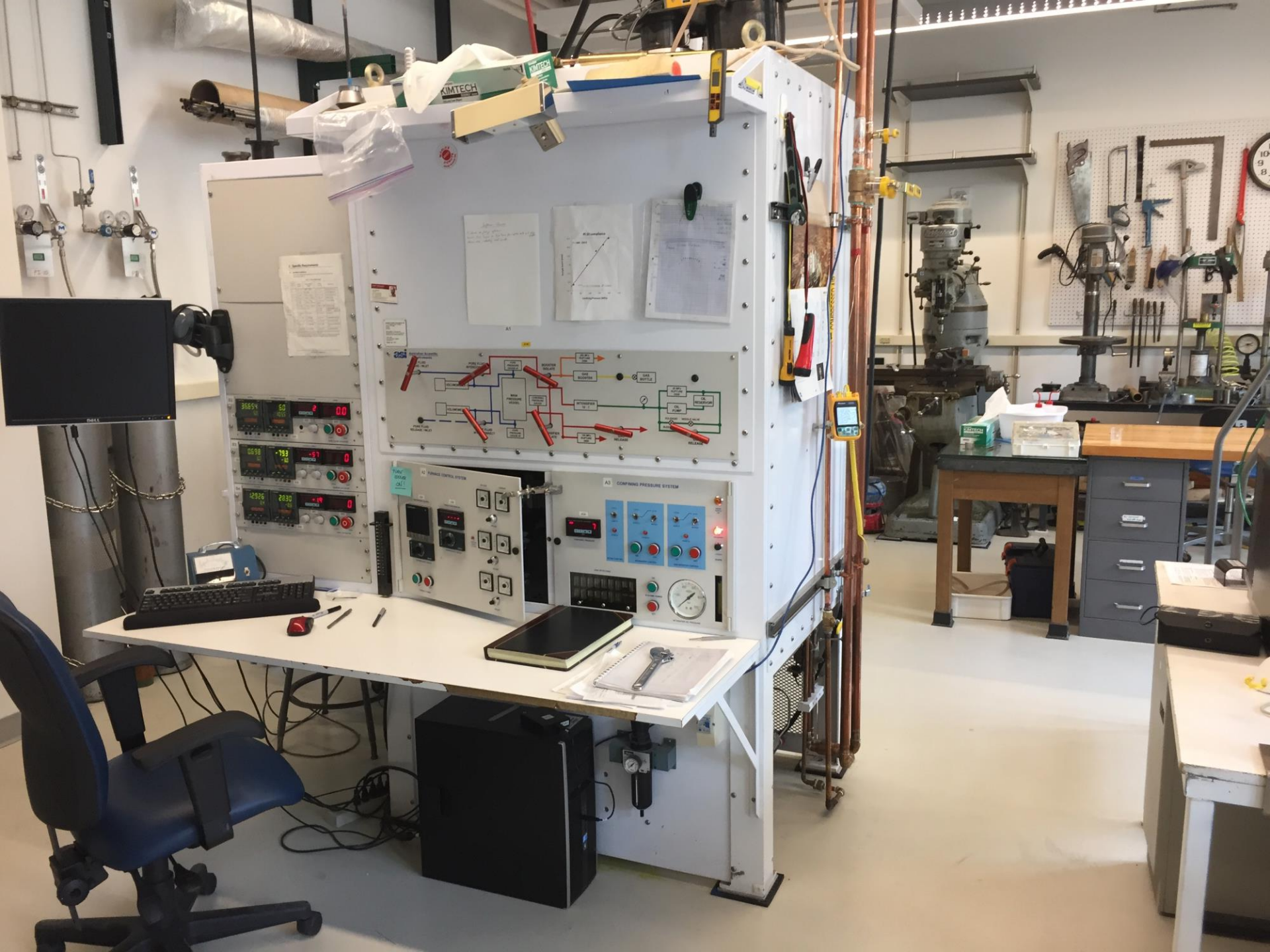
High-strain torsional deformation experiments

High-resolution gas-medium deformation apparatus

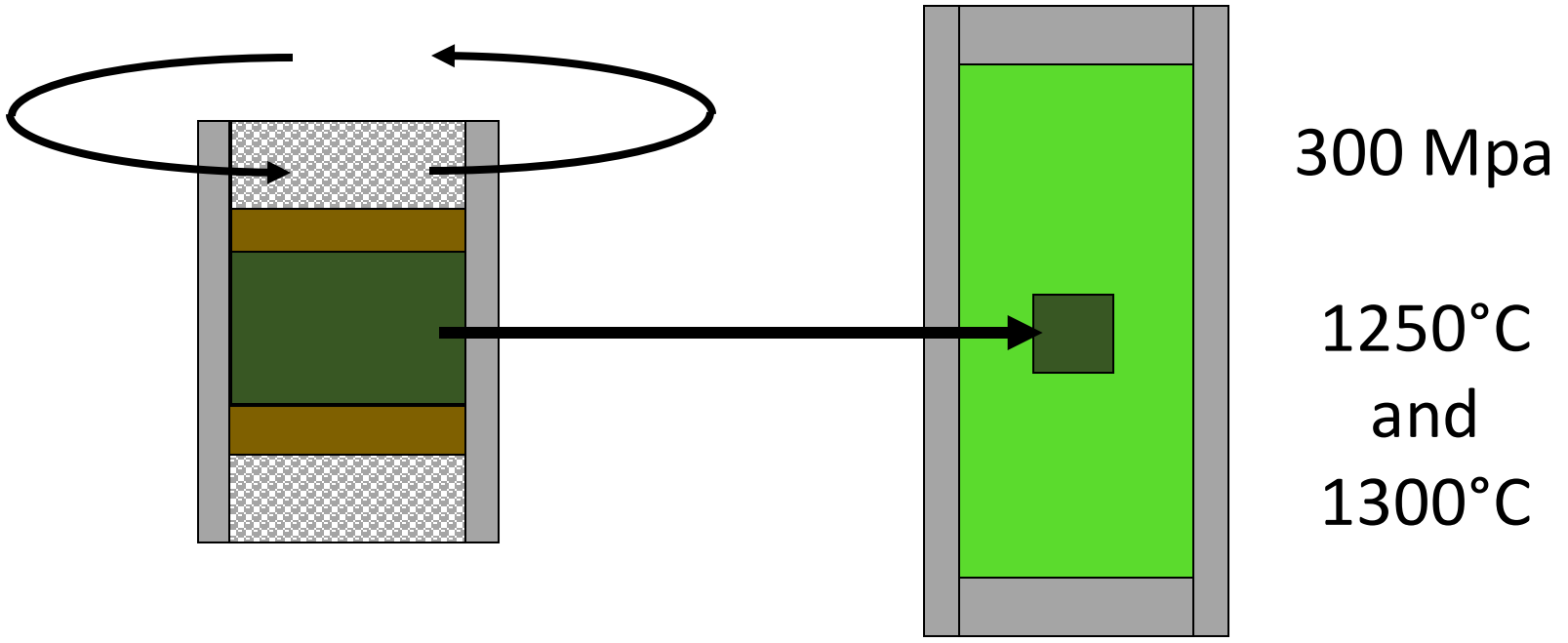


Paterson and Olgaard (2000)




KIMTECH
A2 FURNACE CONTROL SYSTEM
A3 CONFINING PRESSURE SYSTEM

Static annealing of deformed specimens at 300 MPa



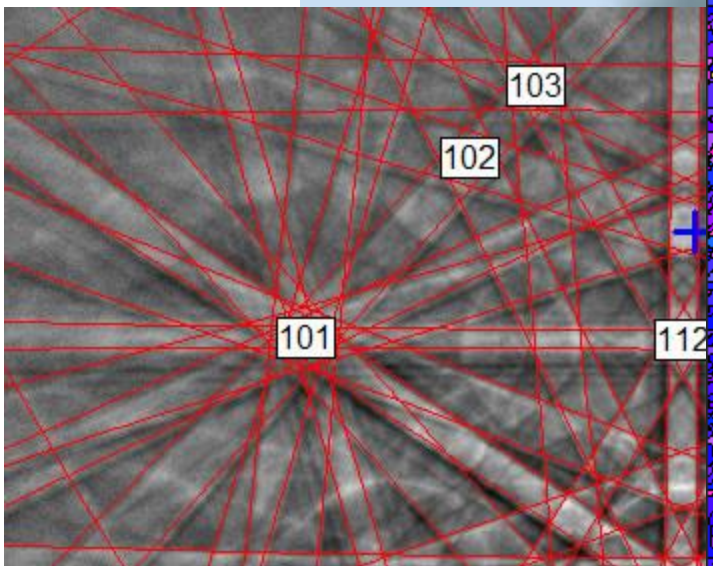
300 Mpa

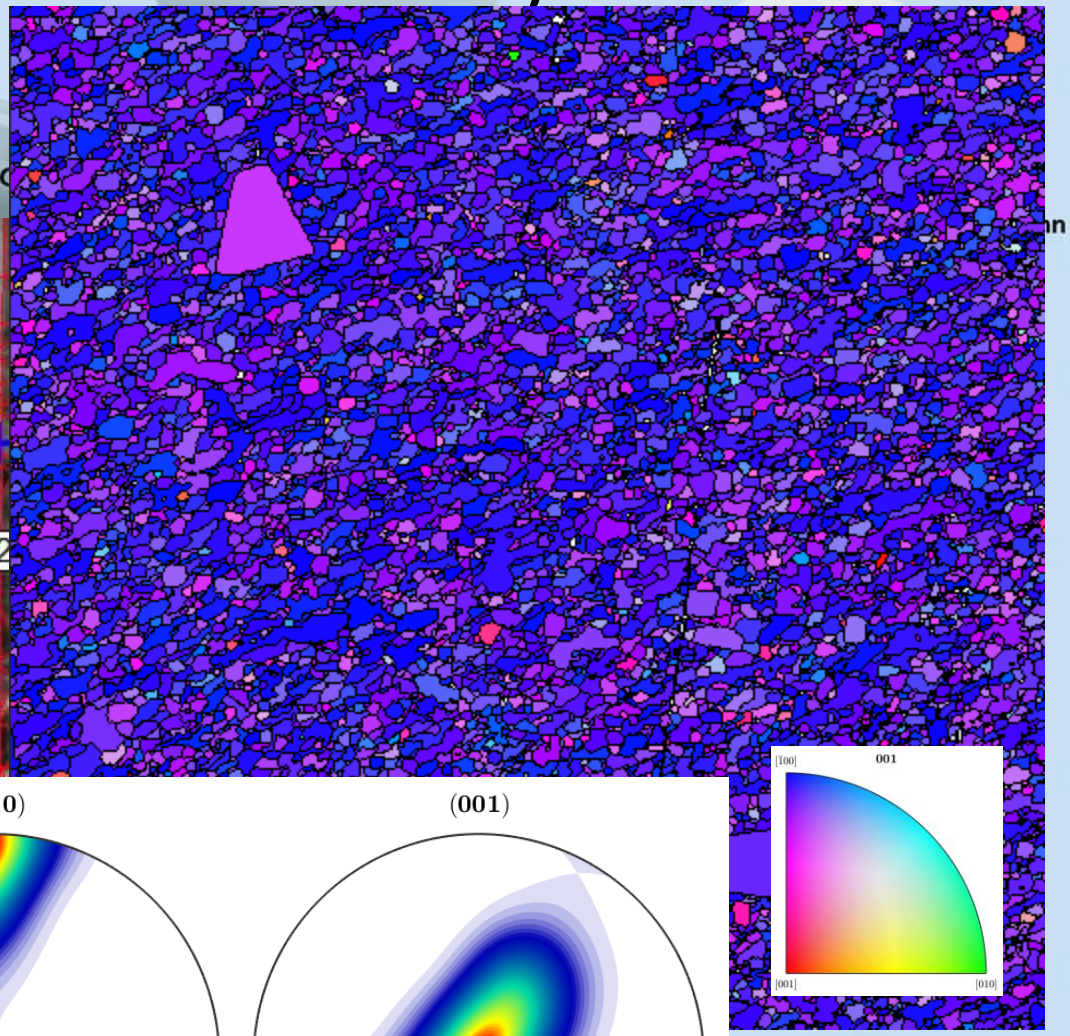
1250°C
and
1300°C

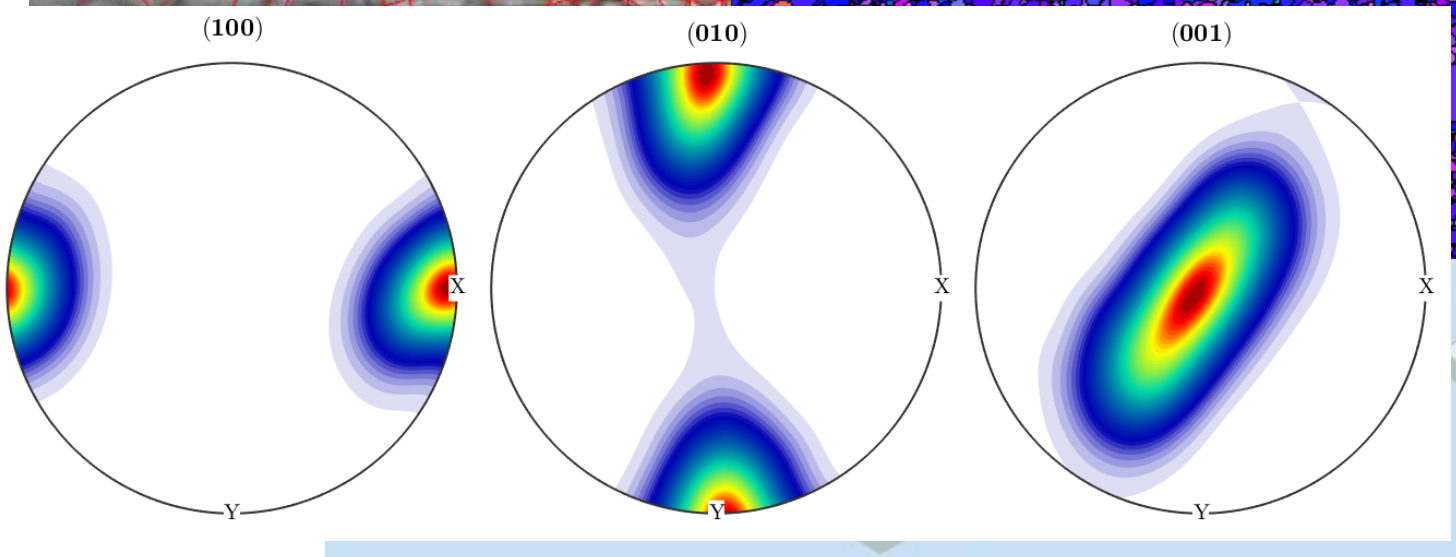
Torsional high-strain deformation experiment

- nickel
- San Carlos olivine powder
- porous alumina
- coarse-grained natural dunite
- evacuated HP San Carlos olivine

Overview of EBSD analysis

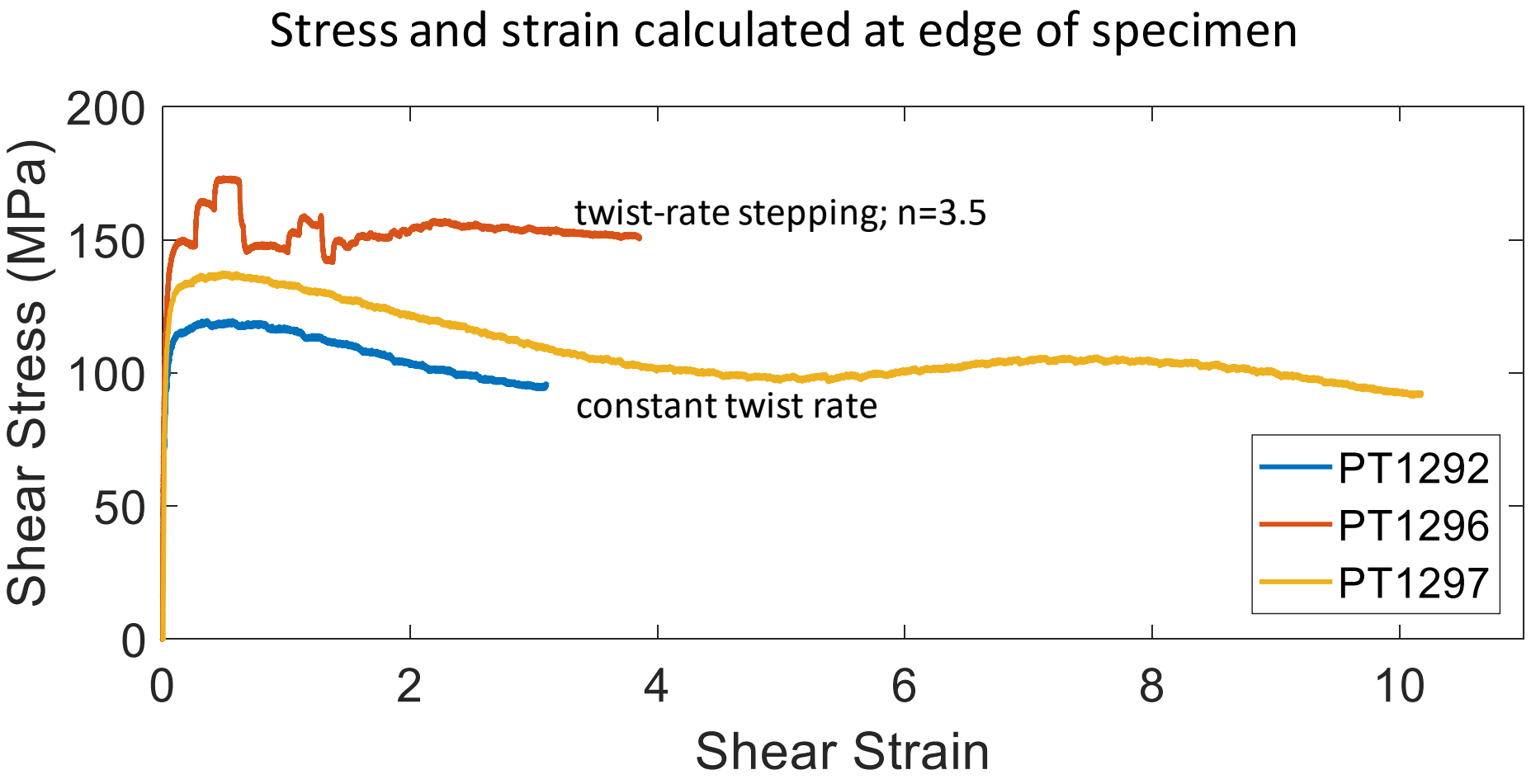






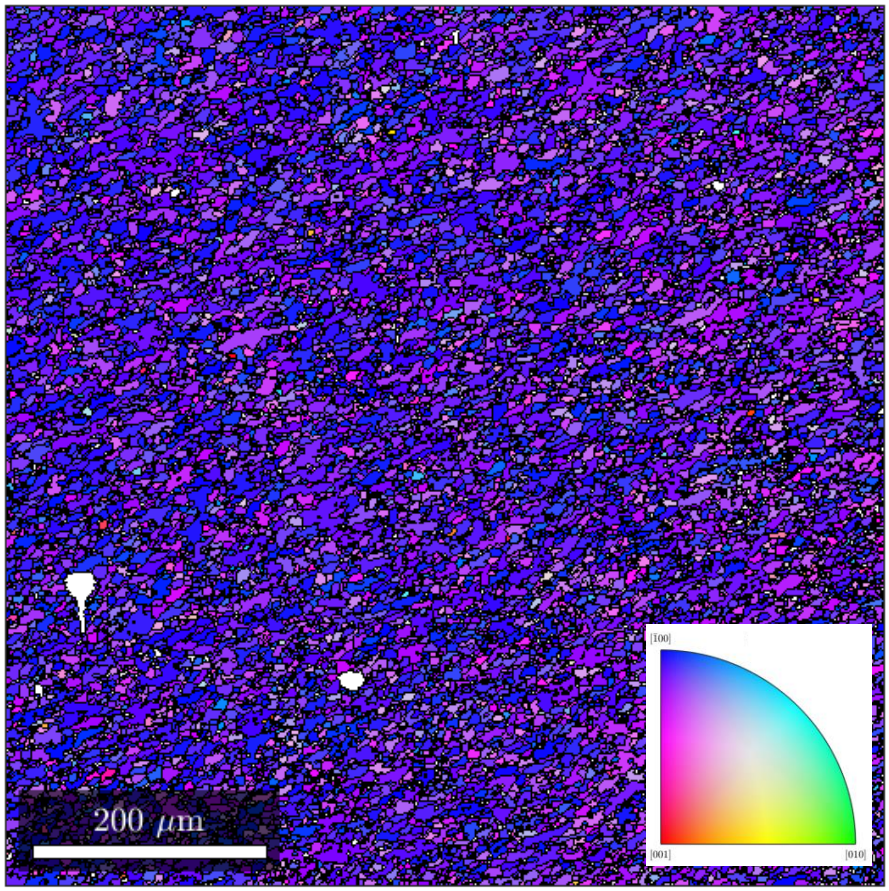
Controller

Mechanical data from high-strain torsion experiments

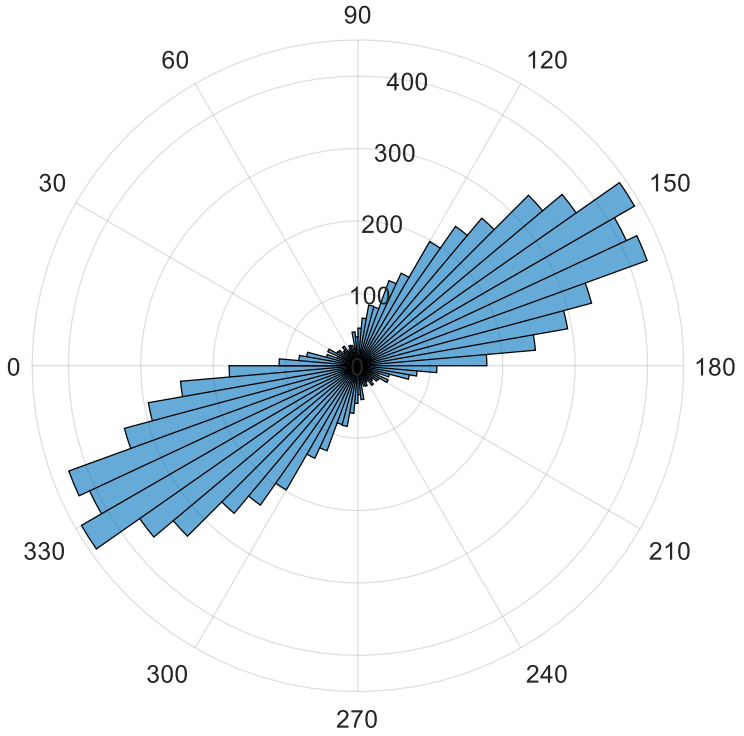


Tangential section of high-strain torsion samples

Inverse Pole Figure False Color Map

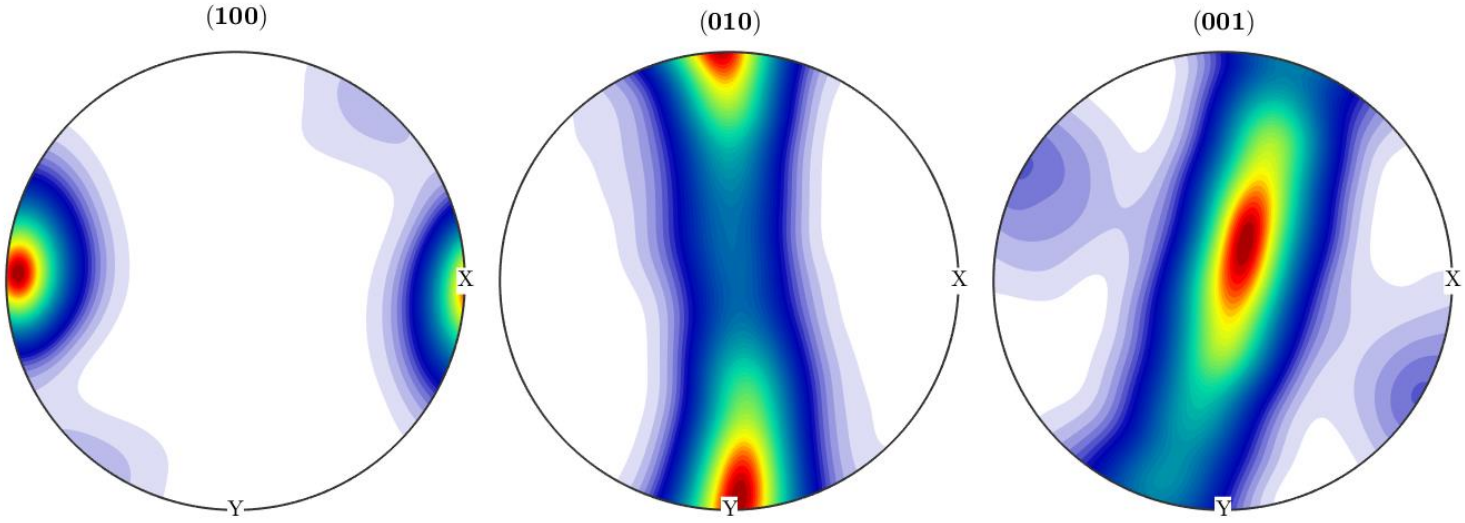


Grain Shape Orientation

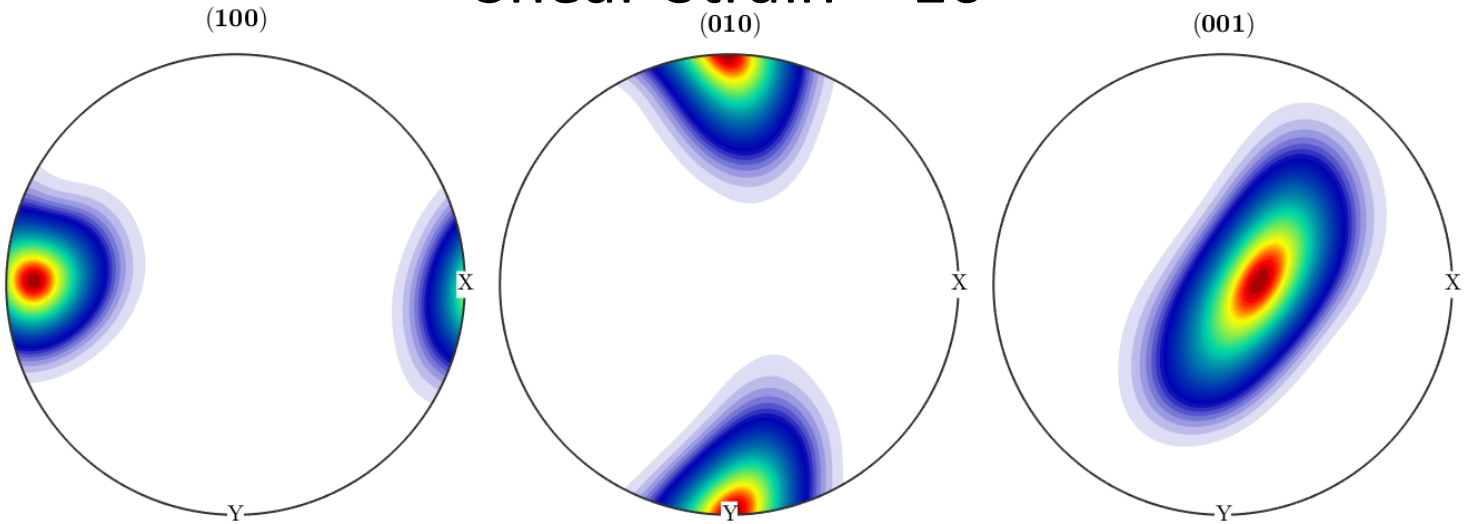


CPO of samples deformed in torsion to high-strain

Shear Strain = 3

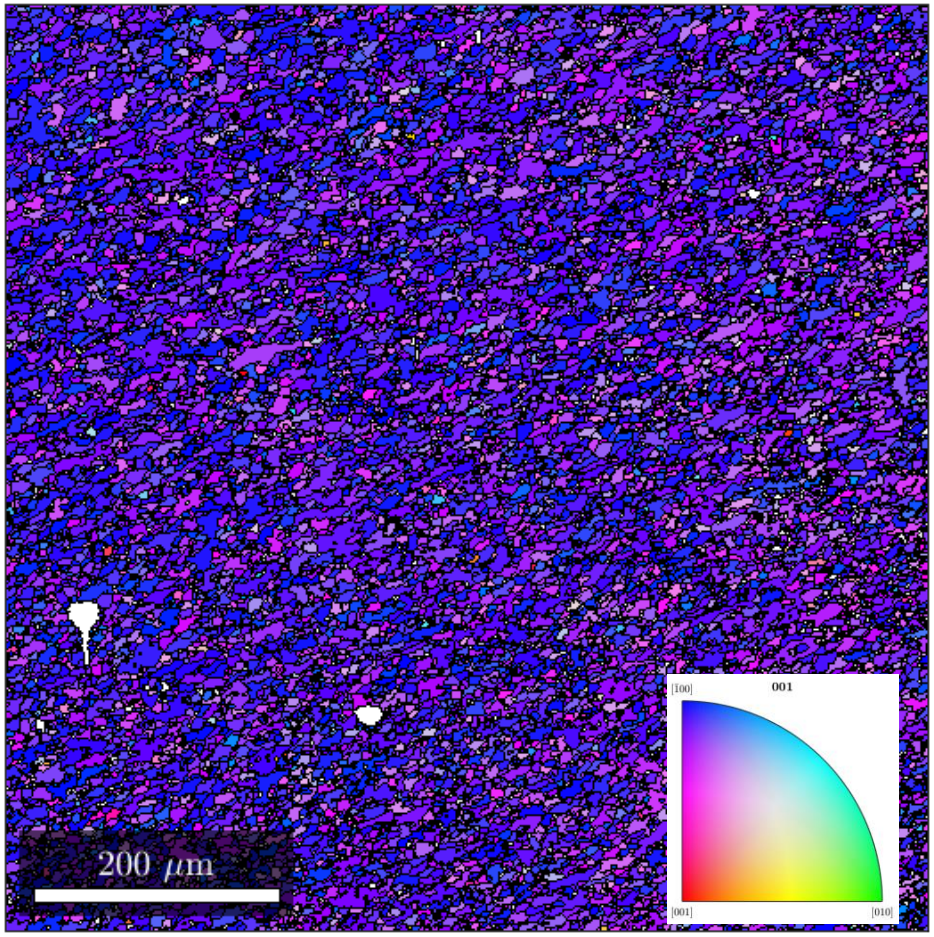


Shear Strain = 10

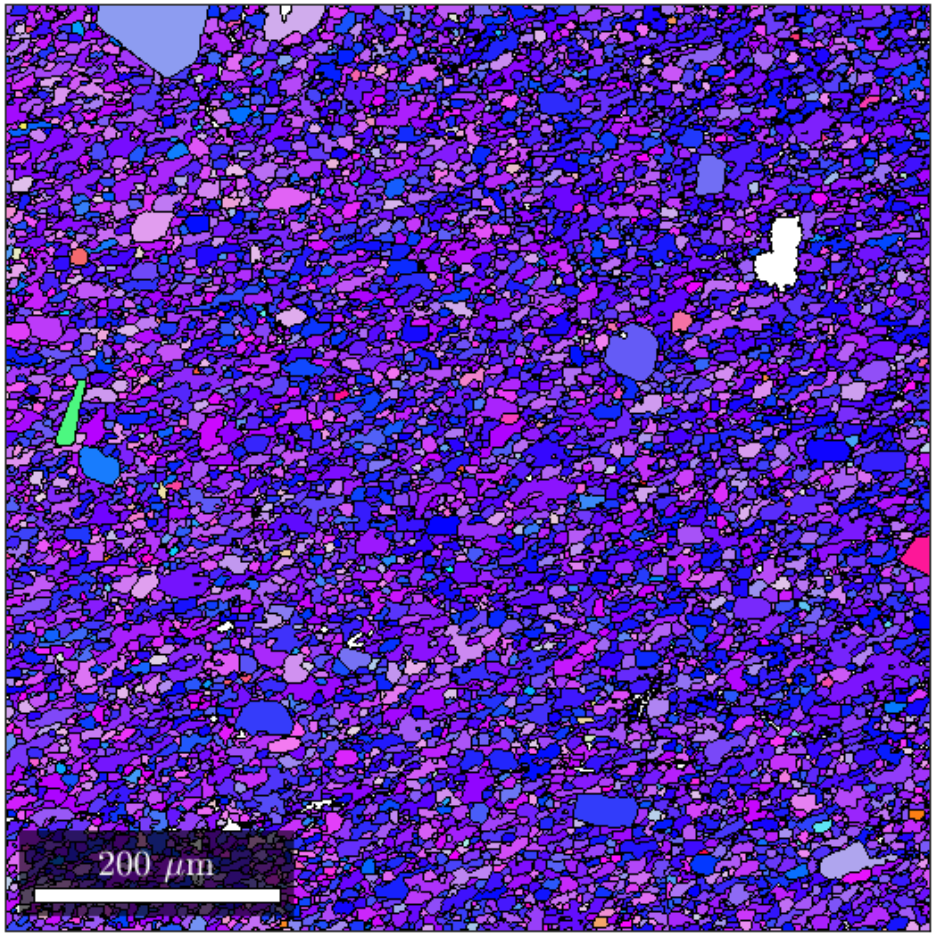


Microstructures of annealed tangential sections

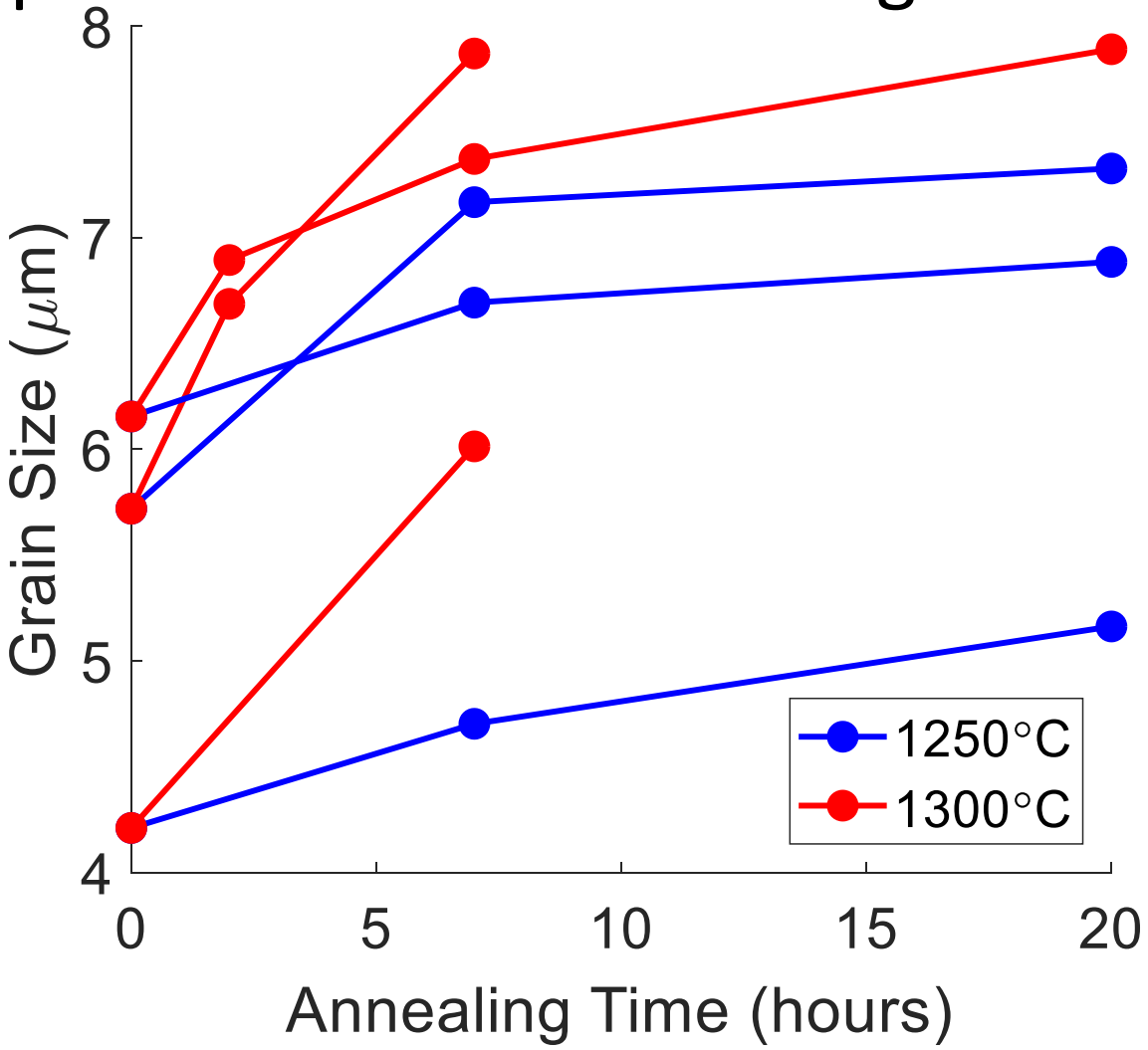
After Deformation



Annealed at 1300°C, 300 Mpa, 7hrs

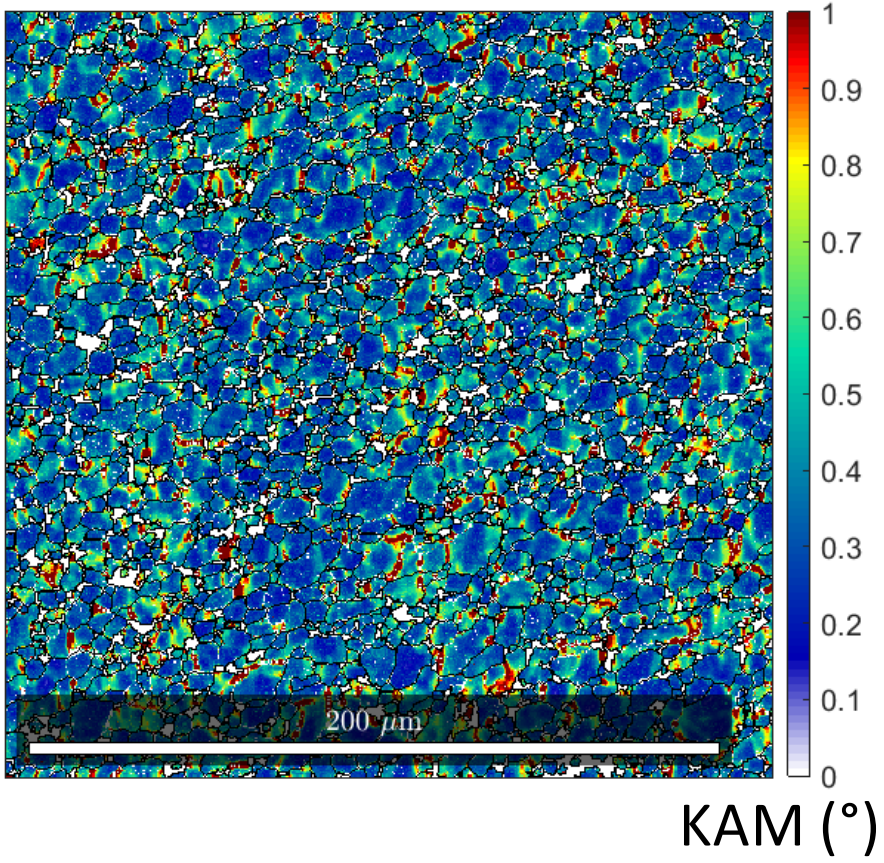


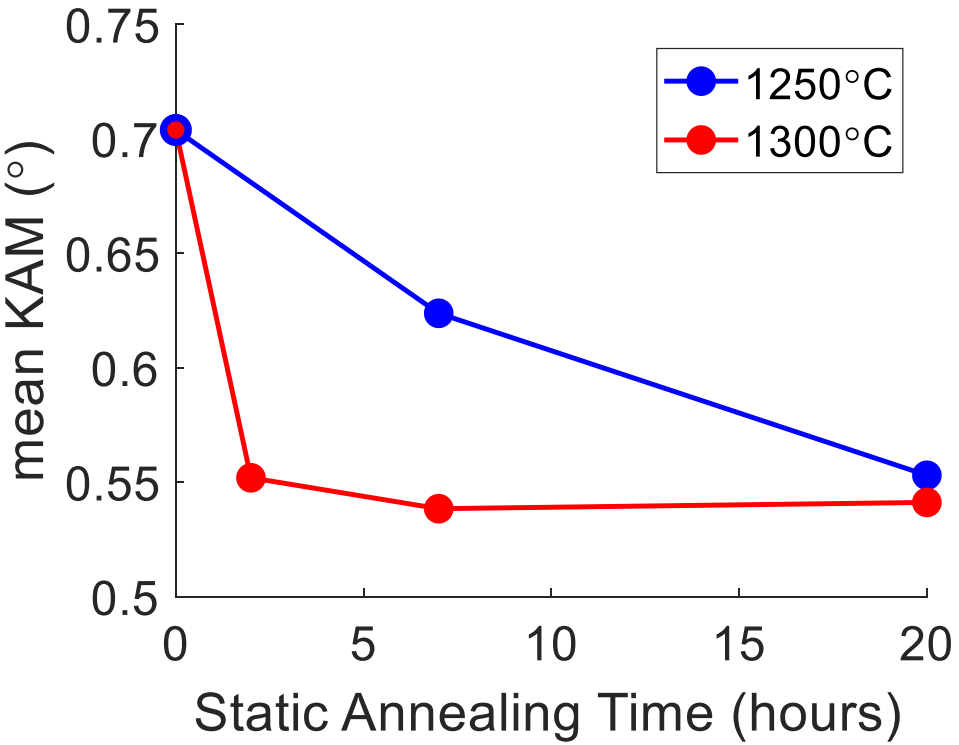
Grain growth in tangential sections of specimens deformed to high shear strain



Normal Grain Growth Law: $d_{final}^{m} - d_{initial}^{m} = kt;$ $\quad k = k_o \exp\left(\frac{-Q}{RT}\right)$

Intragranular Crystallographic Distortion: Kernel Angular Misorientation





Overview

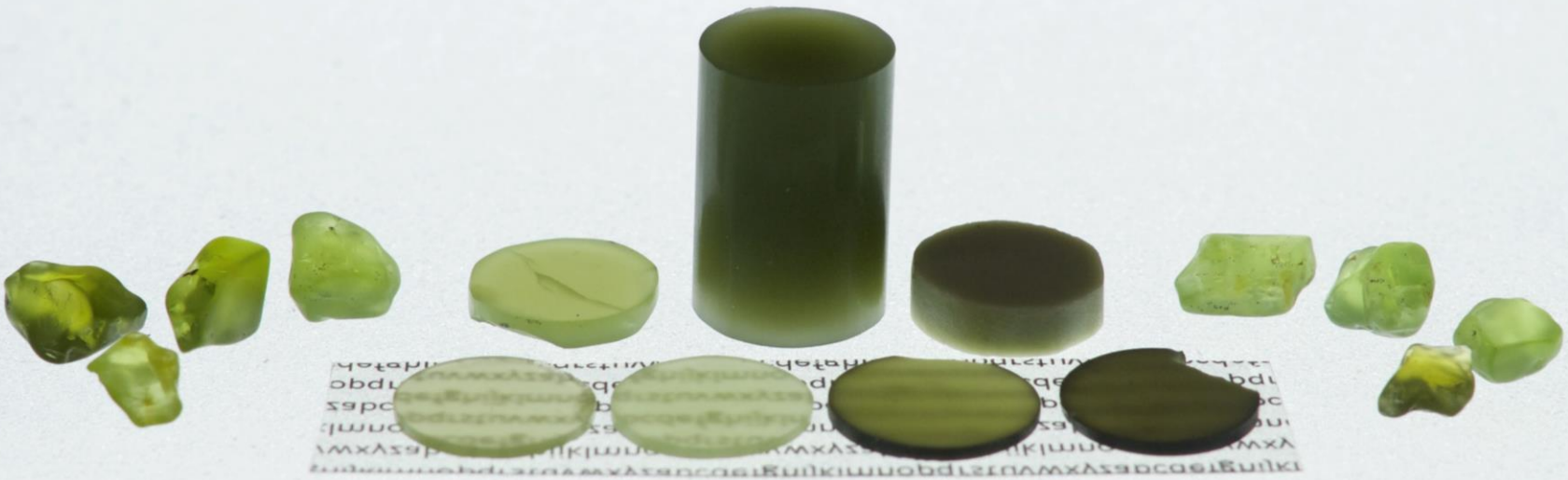
- Evacuated hot-pressing reduces contamination filled porosity to the point that one can easily read through a 1-mm thick slice.

- Grain boundary mobility is enhanced in evacuated hot-presses relative to conventional hot-presses of the same powder.

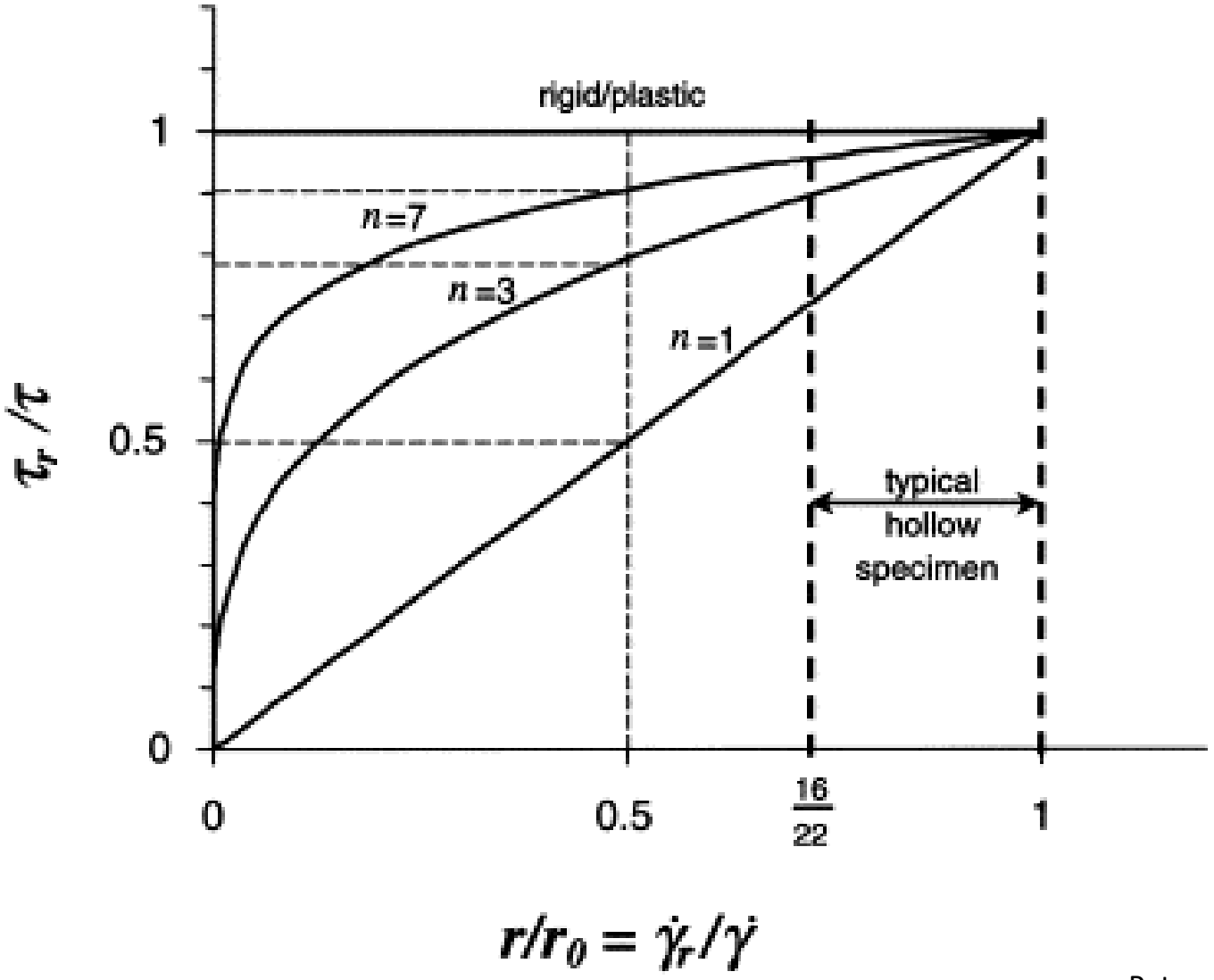
- High-strain torsion of evacuated hot-pressed olivine aggregates leads to grain-size refinement, intragranular crystallographic distortion, development of a strong shape preferred orientation (SPO), and development of a strong crystallographic preferred orientation (CPO)

- During static annealing of samples deformed to high strains, grains become progressively equiaxed and intragranular crystallographic distortion is reduced, while CPO geometry and strength remains relatively constant

Thanks to:
National Nuclear Security Administration Stewardship Science Graduate Fellowship
National Science Foundation
University of Minnesota Characterization Facility
Minnesota Nano Center
Members of the Kohlstedt Research Group
Kruckenberg Research Group



Radial stress and strain gradient in torsional deformation

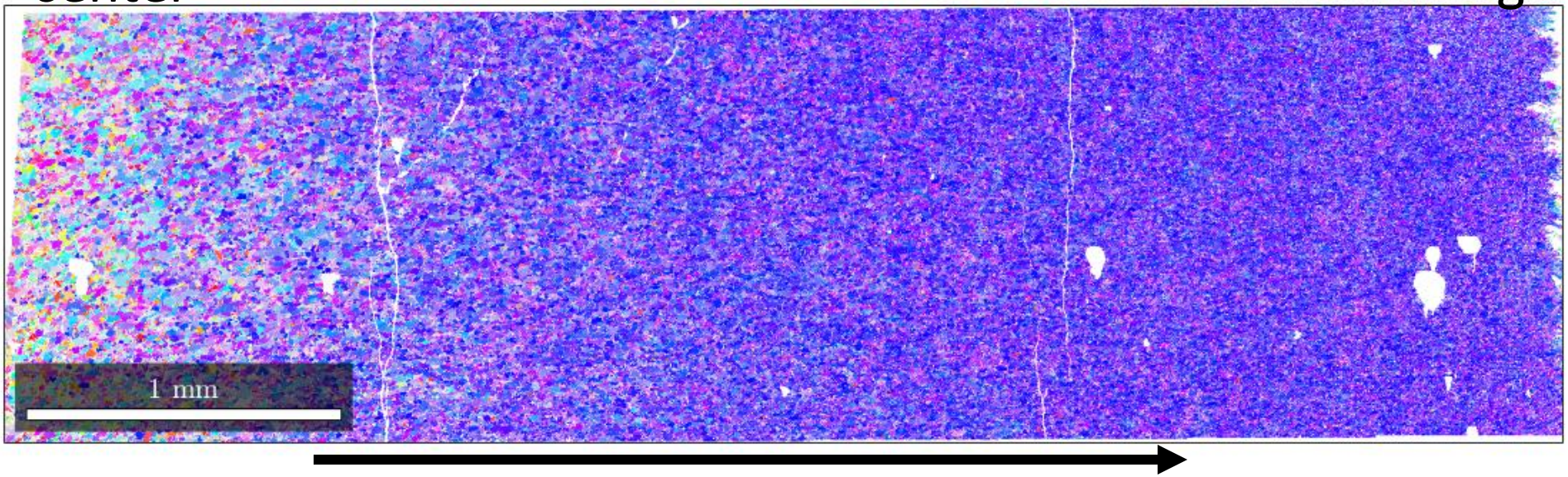


Paterson and Olgaard (2000)

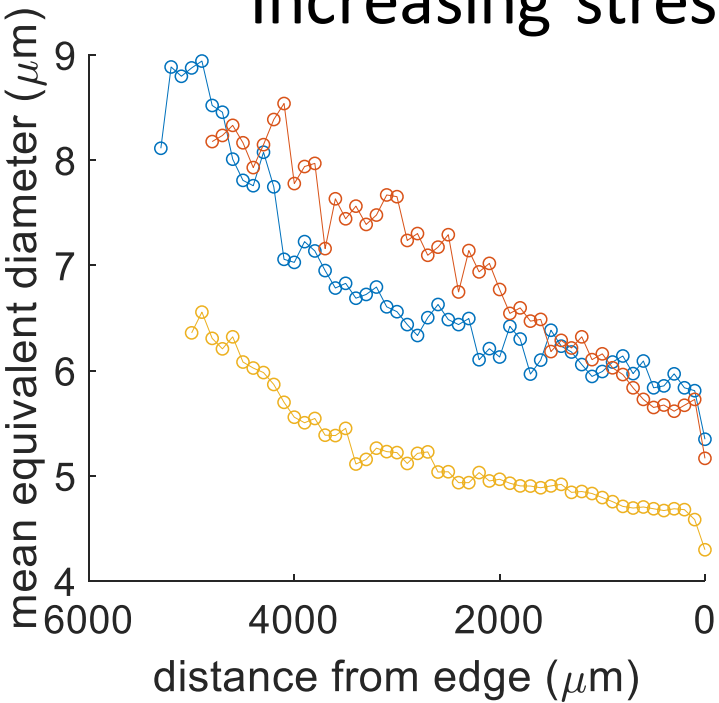
Microstructures of Radial Sections

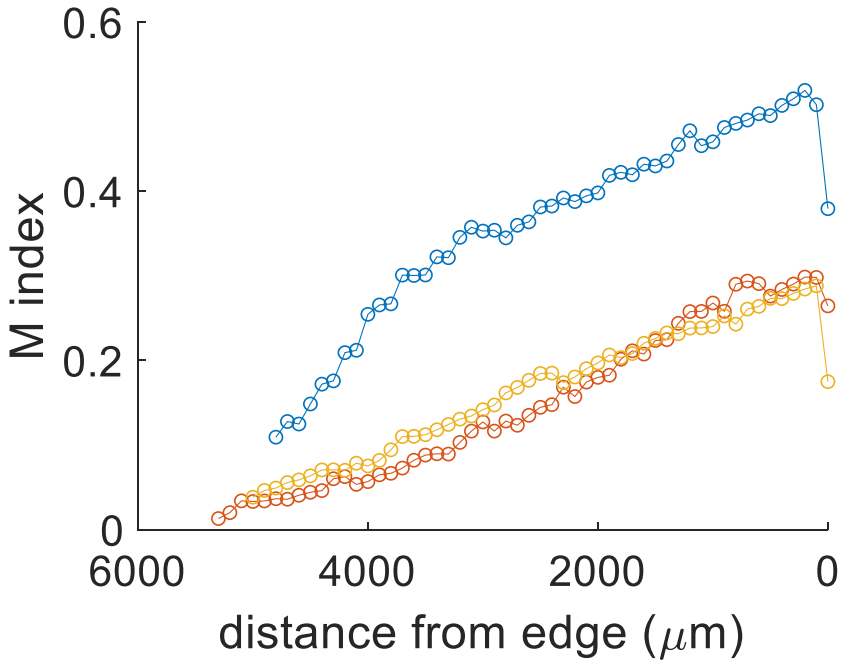
center

edge

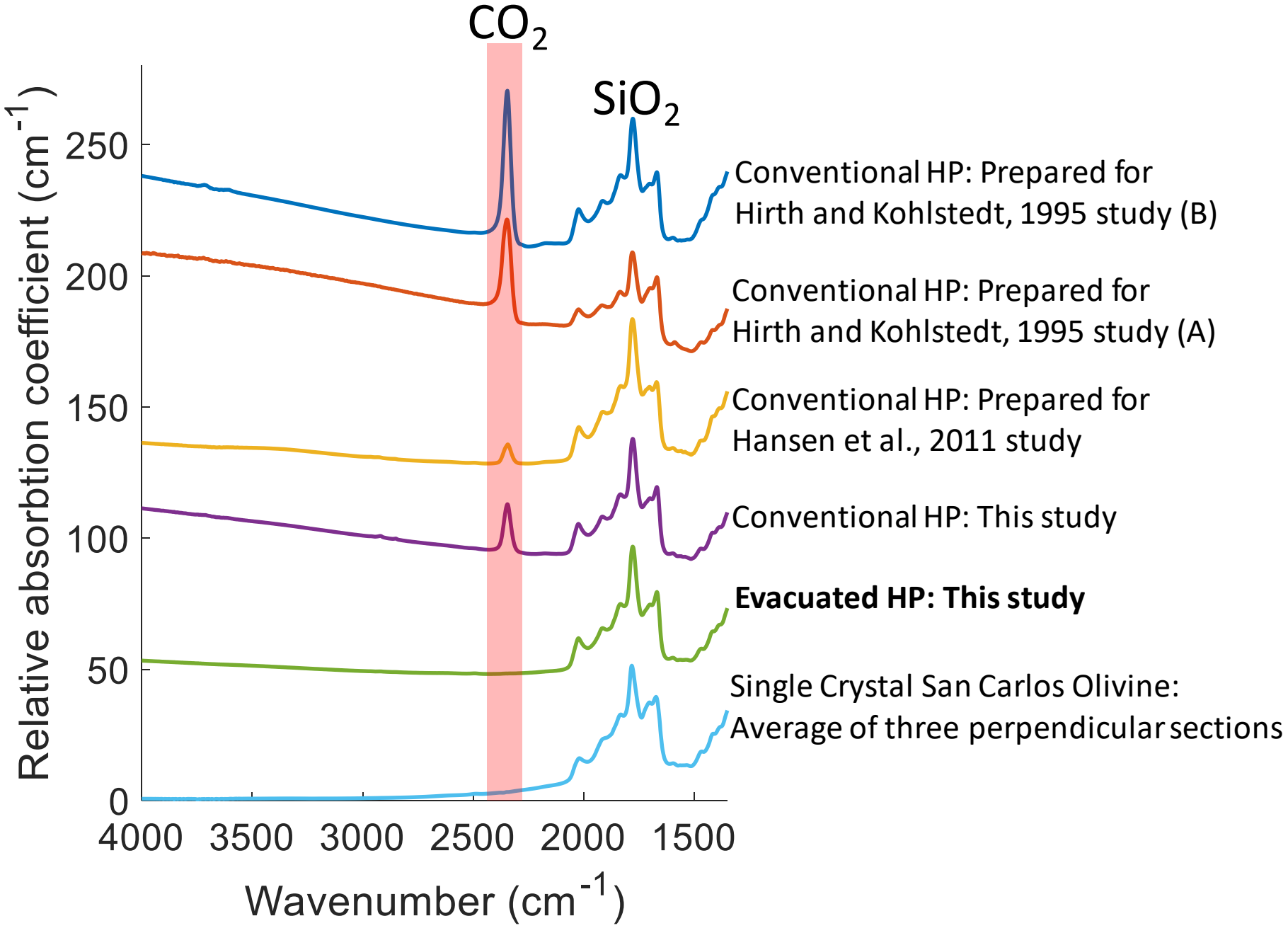


Increasing stress, strain, strain-rate

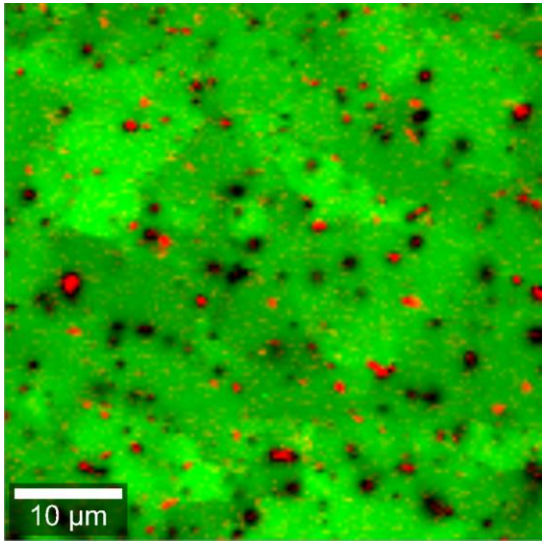


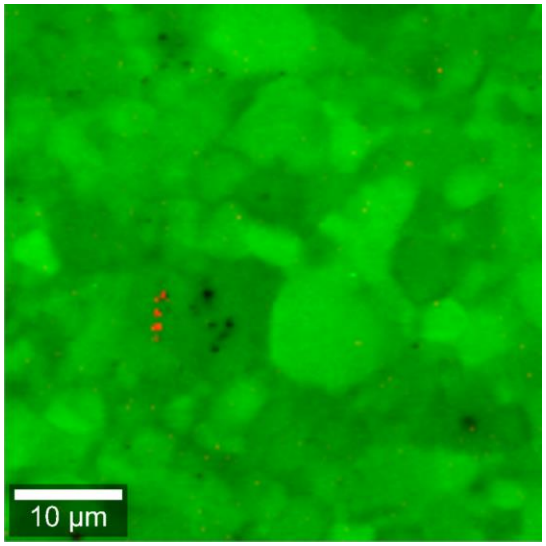


Fourier transform infrared spectroscopy (FTIR)



Confocal Raman spectroscopy





Conventional hot-press

Evacuated hot-press