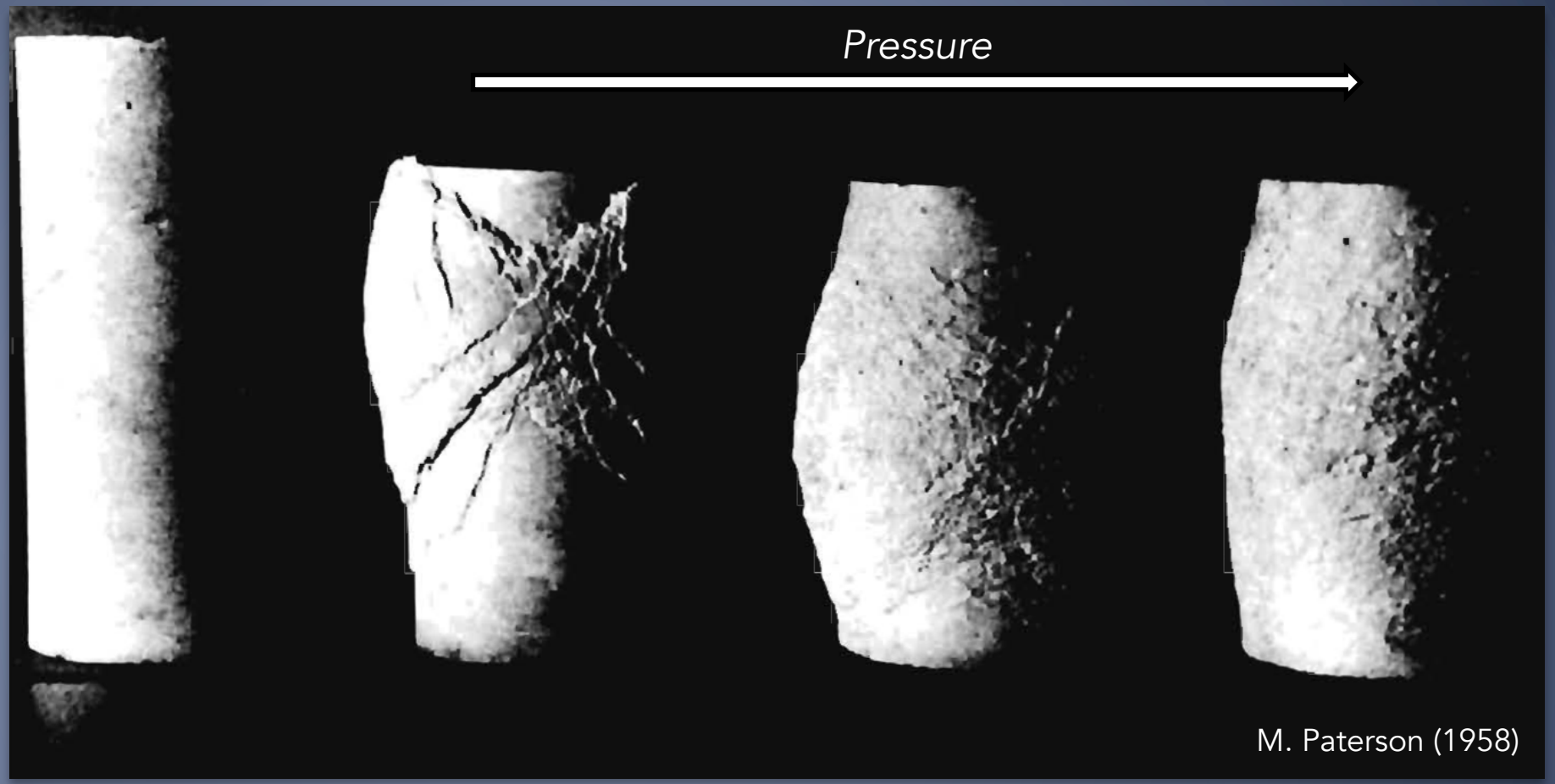
Rheology
or
How to Squish a Rock
or
What is η and how do we know?

Phil Skemer
Washington University in St Louis

CIDER
June 29th, 2017

Washington University in St. Louis
Earth and Planetary Sciences

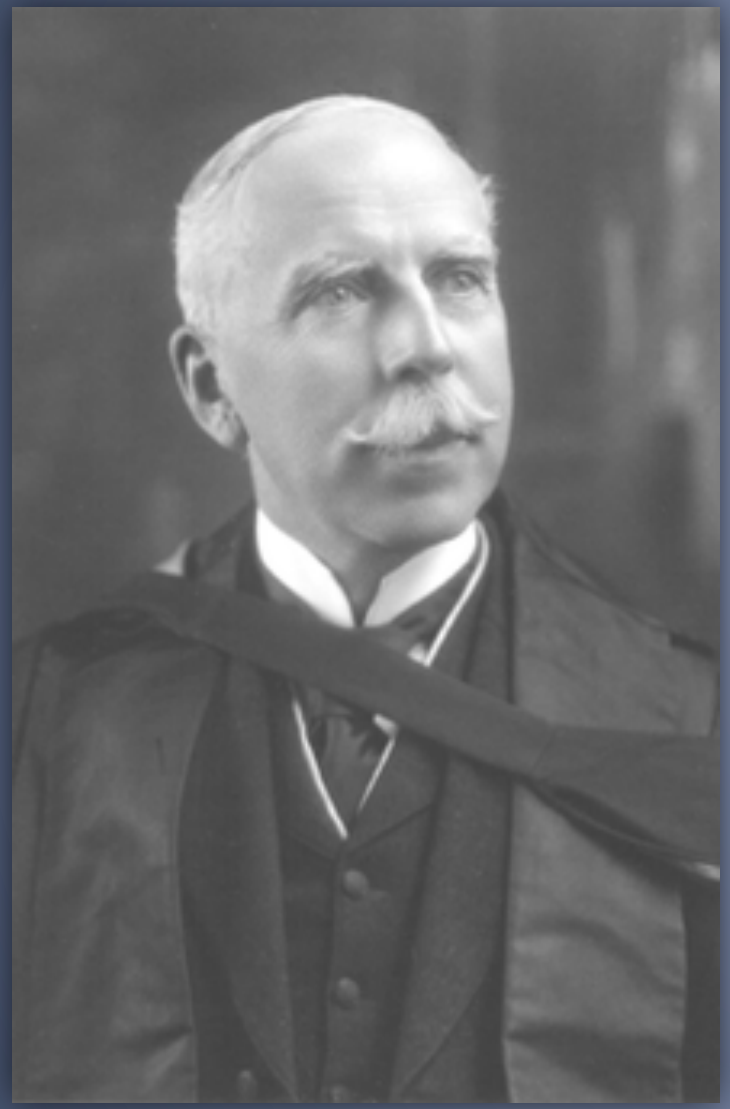
ESPM
Experimental Studies of Planetary Materials



BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 69, PP. 465-476, 8 FIGS., 2 PLS. APRIL 1958

EXPERIMENTAL DEFORMATION AND FAULTING IN WOMBEYAN MARBLE

BY M. S. PATERSON



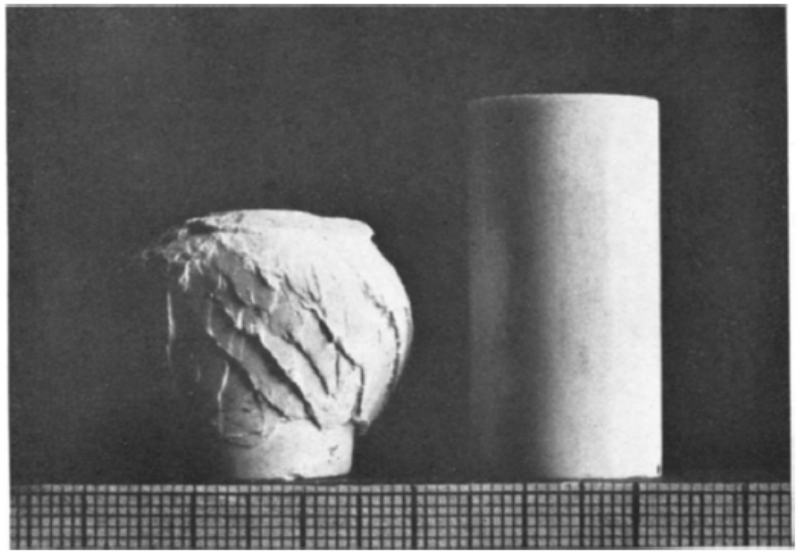
THE

JOURNAL OF GEOLOGY

SEPTEMBER–OCTOBER, 1910

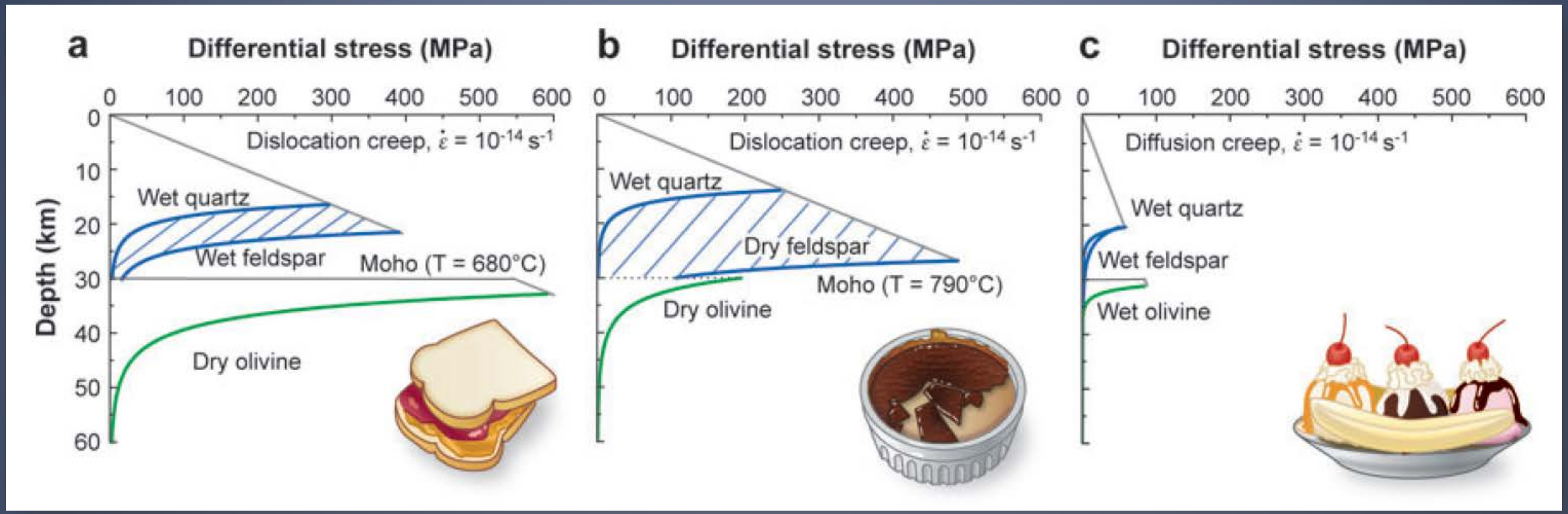
AN EXPERIMENTAL INVESTIGATION INTO THE ACTION OF DIFFERENTIAL PRESSURE ON CERTAIN MINERALS AND ROCKS, EMPLOYING THE PROCESS SUGGESTED BY PROFESSOR KICK

FRANK D. ADAMS
McGill University, Montreal



(*b*) Column of Carrara marble before and after deformation, using alum as an embedding material

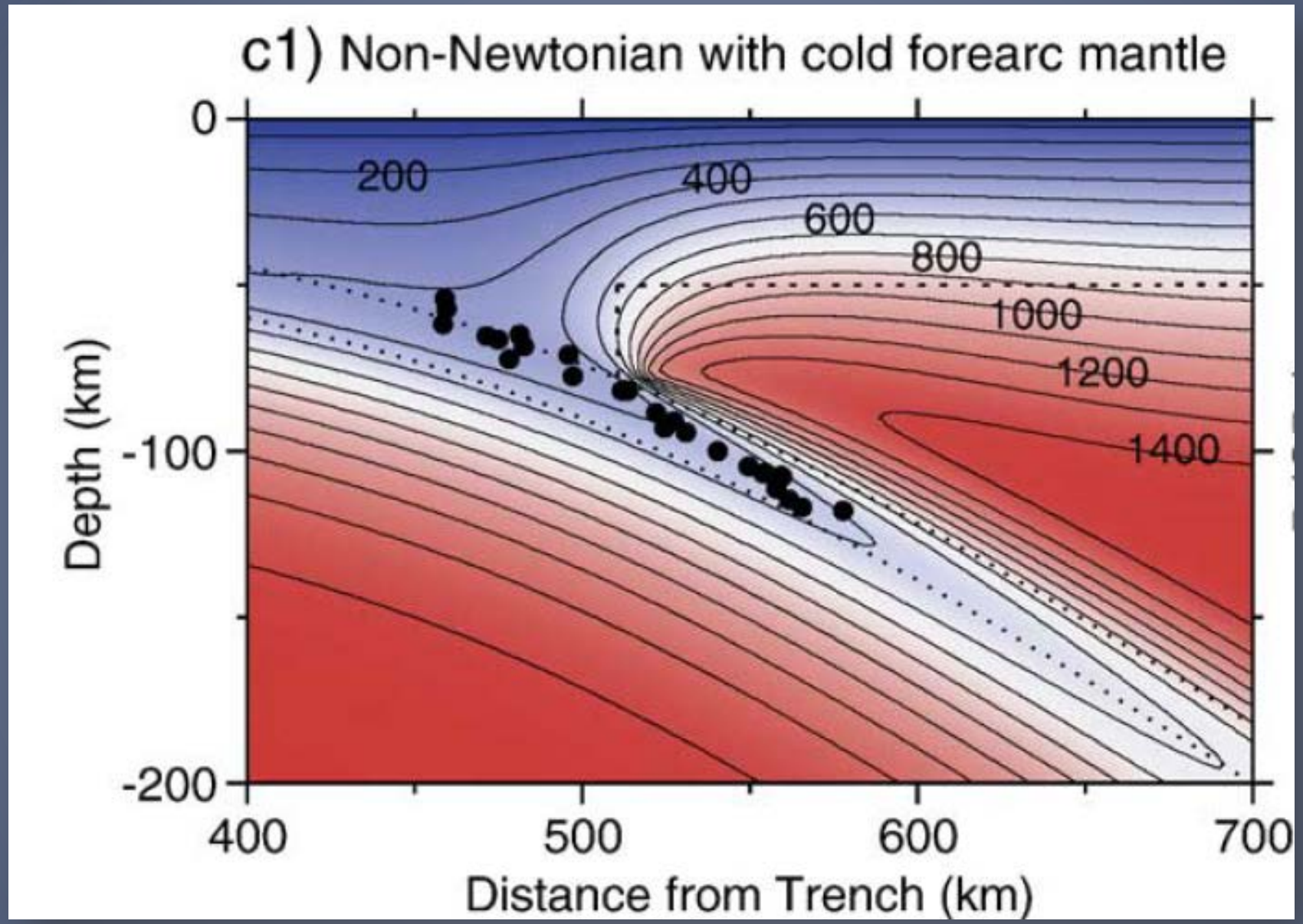
The Brittle → Ductile or Plastic Transition



Bürgmann and Dresen (2008)

The upper mantle:

- Bread in the jelly sandwich?
- Crème in the crème brulee?
- Banana in the banana split?



Abers et al 2006

Rheology

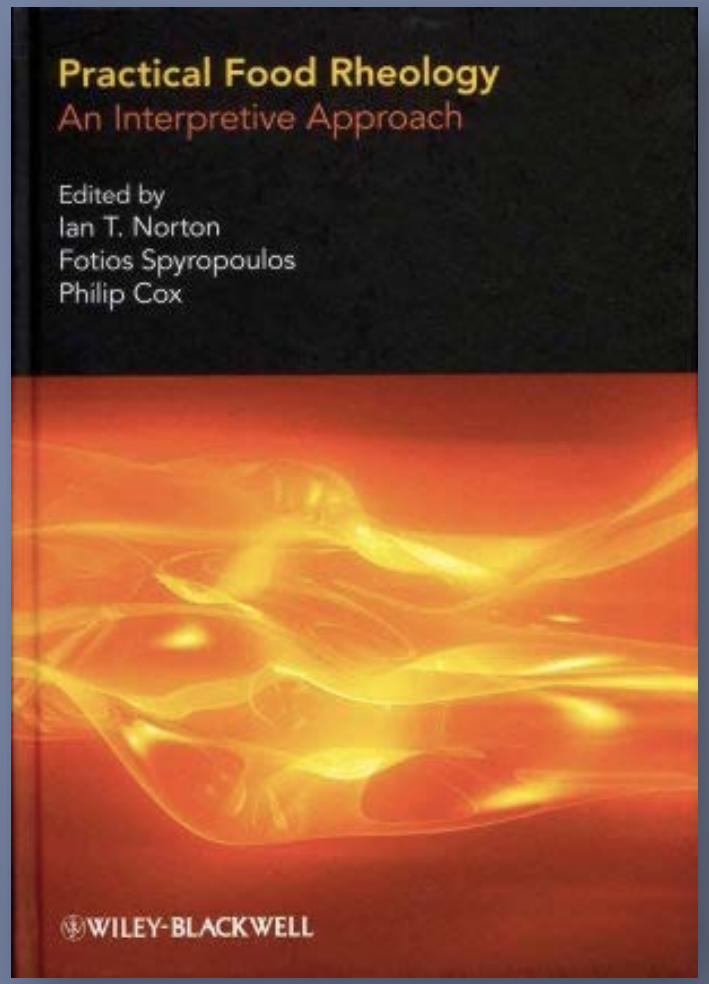
Rheology (n): describes the ability of stressed materials to deform, or flow, using fundamental parameters including as strain rate, elasticity and viscosity (from Greek, *rheos*, to stream or flow)

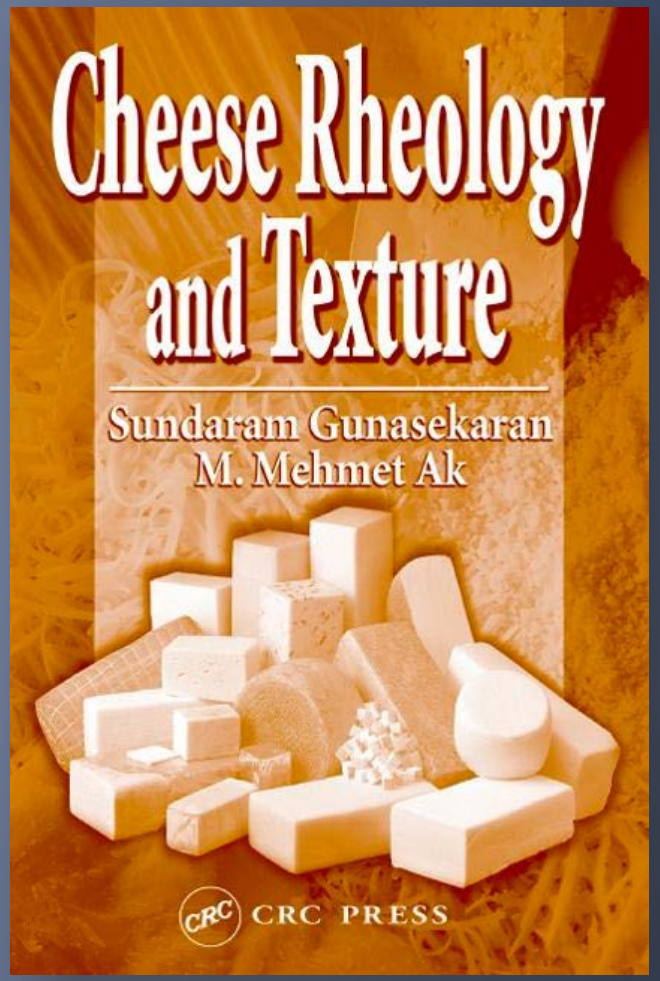
van der Pluijm and Marshak (2017)

Rheology

Metals and Engineered Ceramics

Lubricating Eye Drops



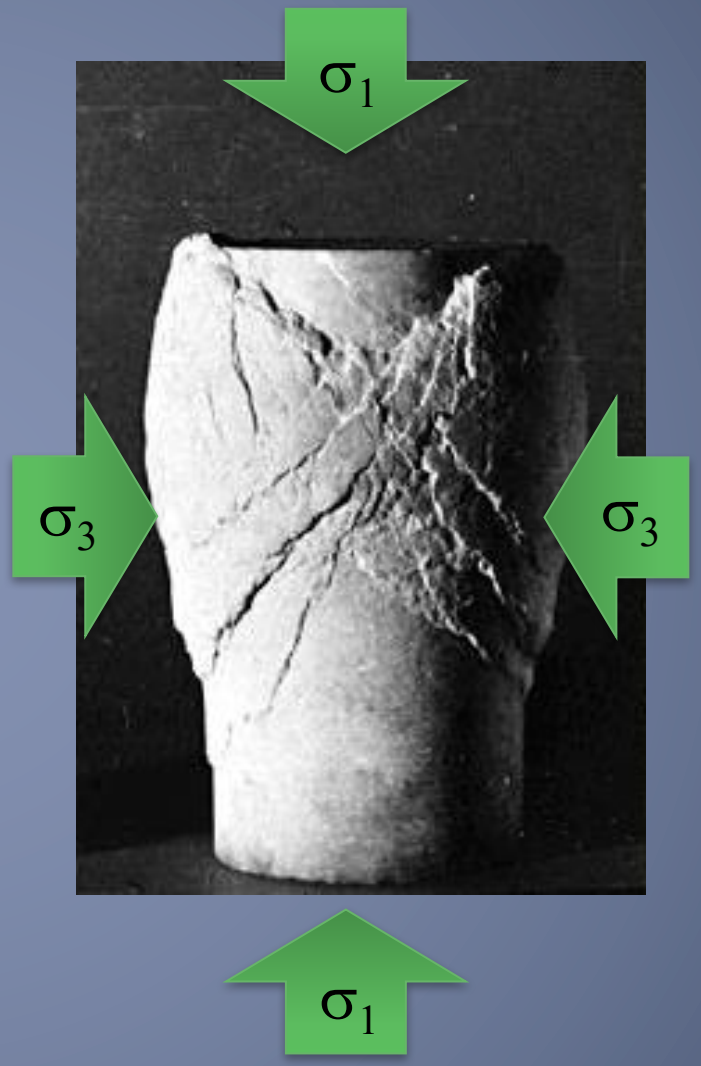


Stress

$$\sigma = F / A \text{ [Pa]}$$

$$\sigma_{ij} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix}$$

$$\sigma_1 > \sigma_2 > \sigma_3$$



Longitudinal Strain(-rate)

$$\varepsilon = -\frac{l_{final} - l_{initial}}{l_{initial}}$$

l_o

Before

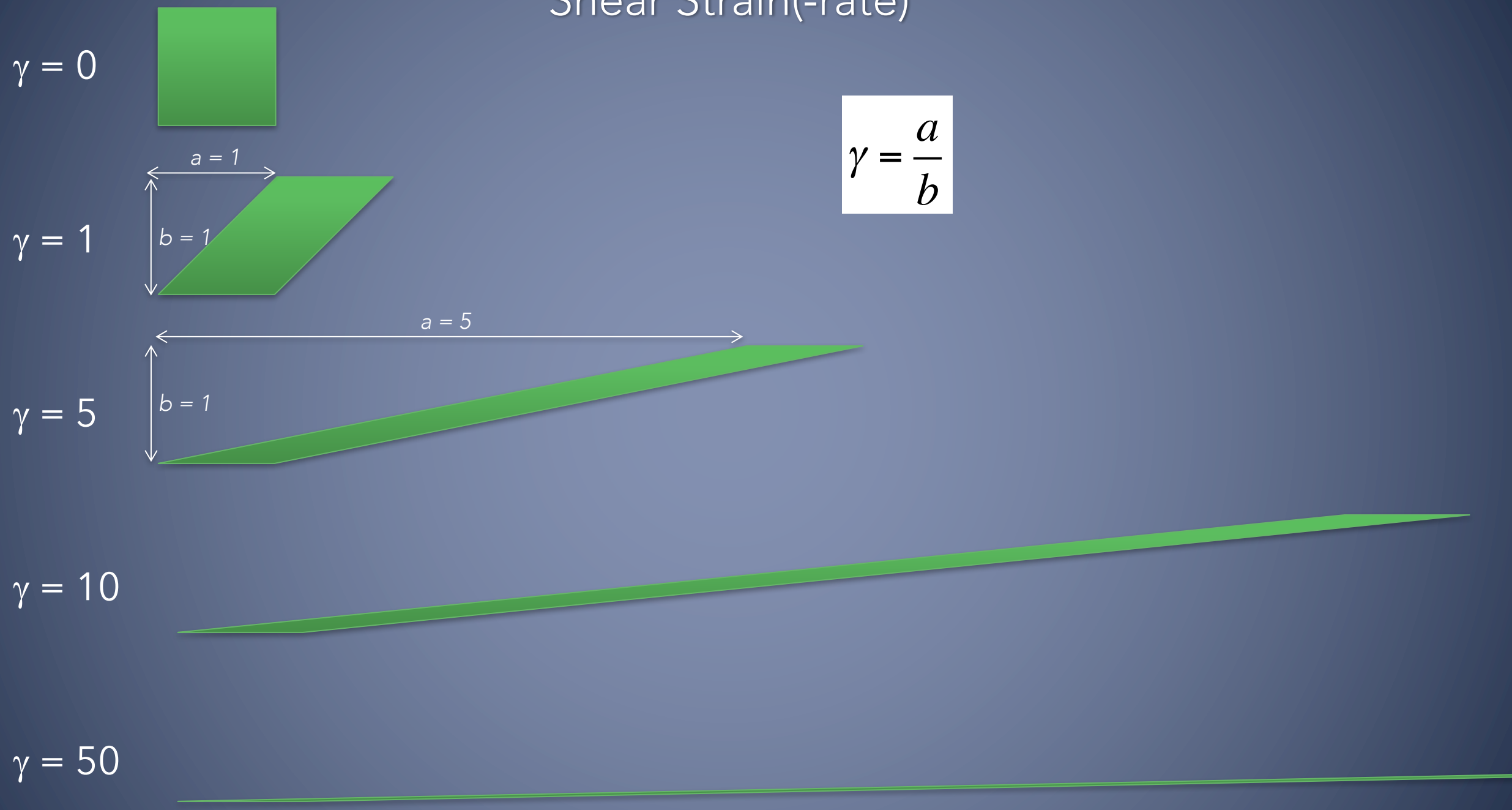
l_f

After

$\varepsilon = 0.23$

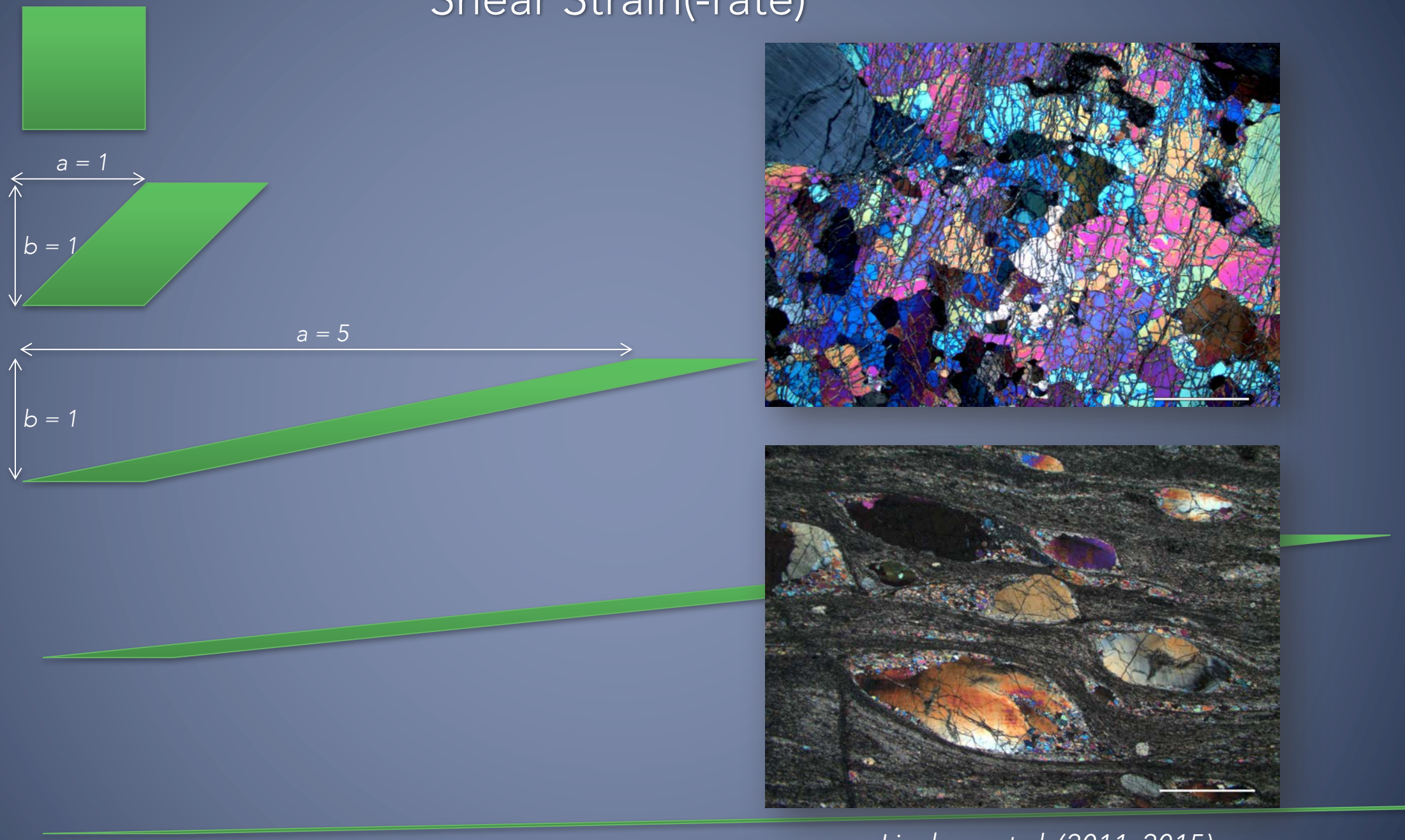
Shear Strain(-rate)

$$\gamma = \frac{a}{b}$$



Shear Strain(-rate)

$\gamma = 0$



$\gamma = 1$

$\gamma = 5$

$\gamma = 10$

$\gamma = 50$

Linckens et al. (2011, 2015)

Silly Putty

Propane	No
Prosthetics	Yes
Protein Powder	Yes
Putty Balls	Yes
Radio You may transport this item in carry-on or checked bags. For items you wish to carry on, you should check with the airline to ensure that the item will fit in the overhead bin or underneath the seat of the airplane.	Yes
Razor-Type Blades Box cutters, razor blades not in a cartridge are prohibited in carry-on. Any sharp objects in checked bags should be sheathed or securely wrapped to prevent injury to baggage handlers and inspectors.	No

Approved!

C4

What controls the style of deformation?

Forces applied (stress)

Magnitude of deformation (strain)

Rate at which it is deformed (strain-rate)

Temperature
Pressure
Composition

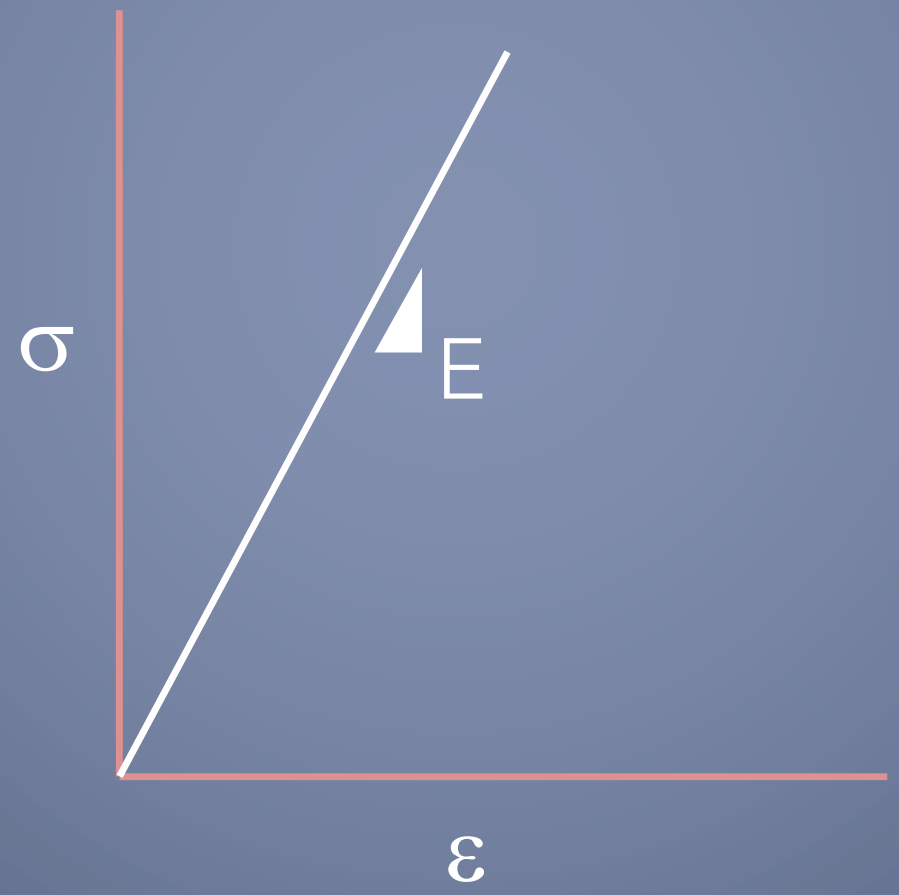
Ideal Models of Rheology

Spring, representing elastic behavior

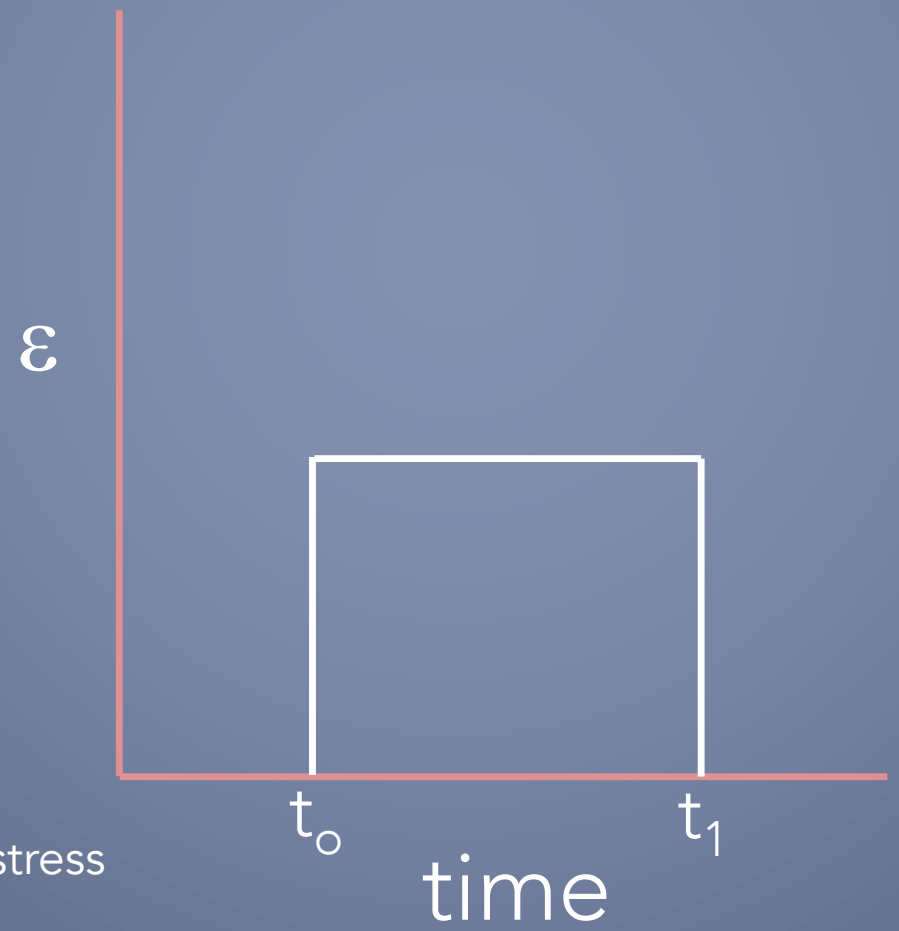
Dashpot, representing viscous behavior

Sliding block, representing plastic behavior

Elastic

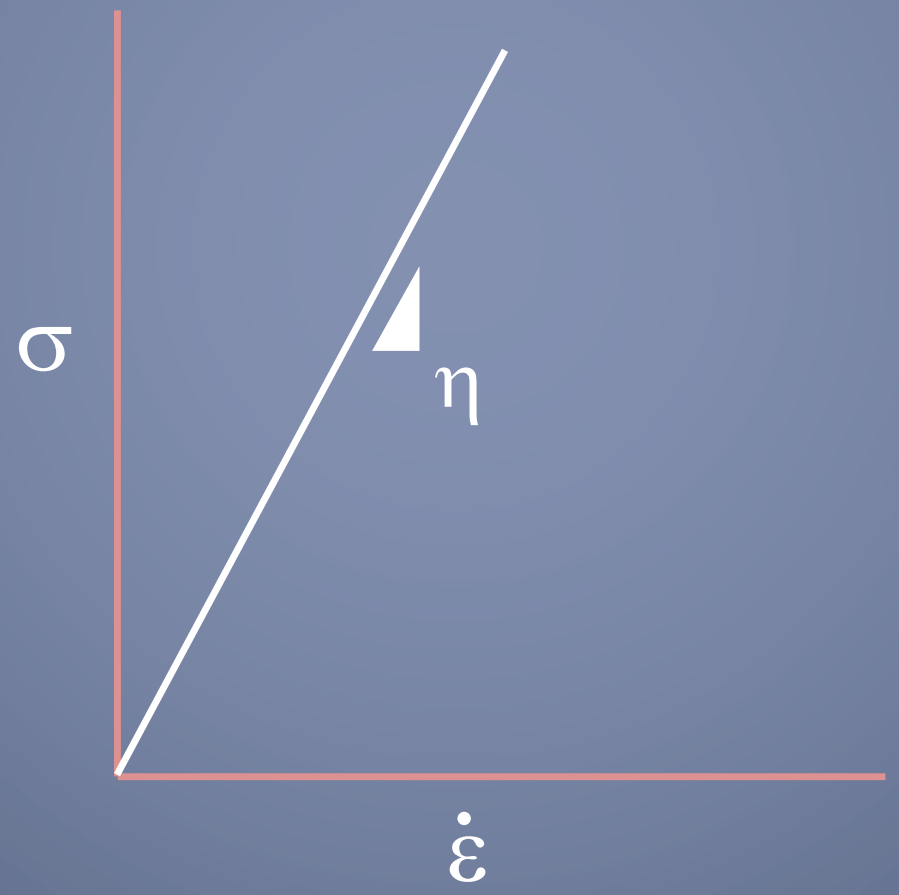


Elastic

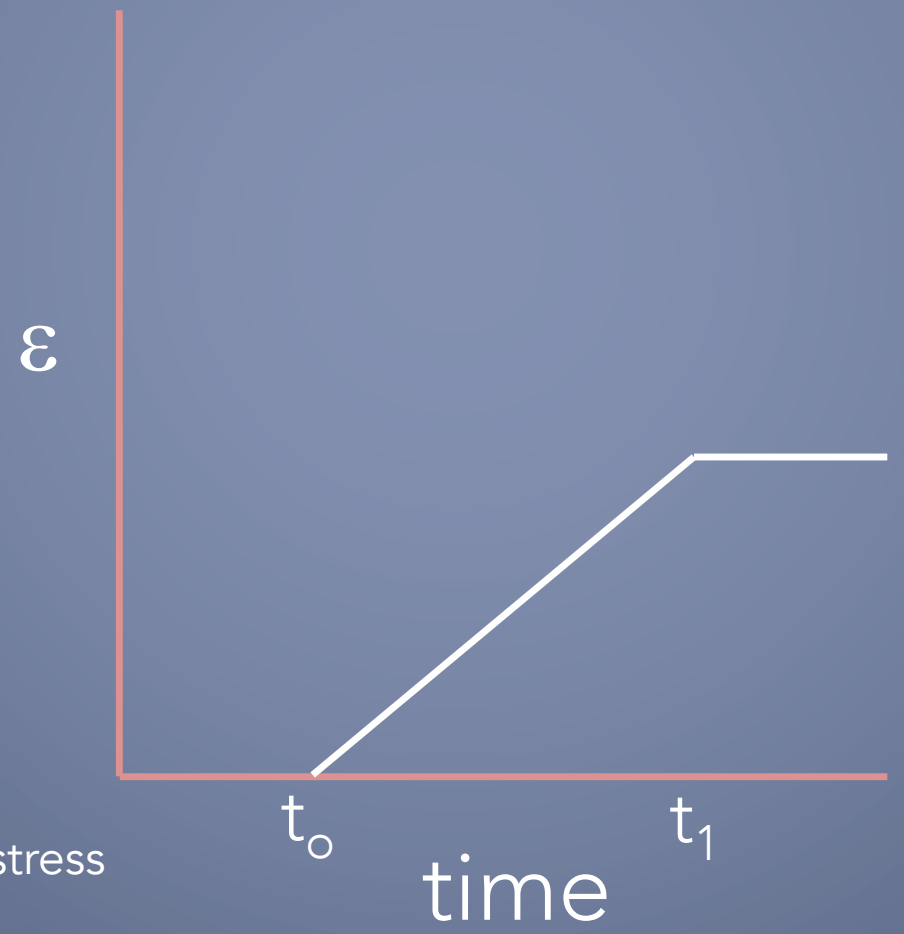


t_o = apply a constant stress
t_1 = remove stress

Viscous

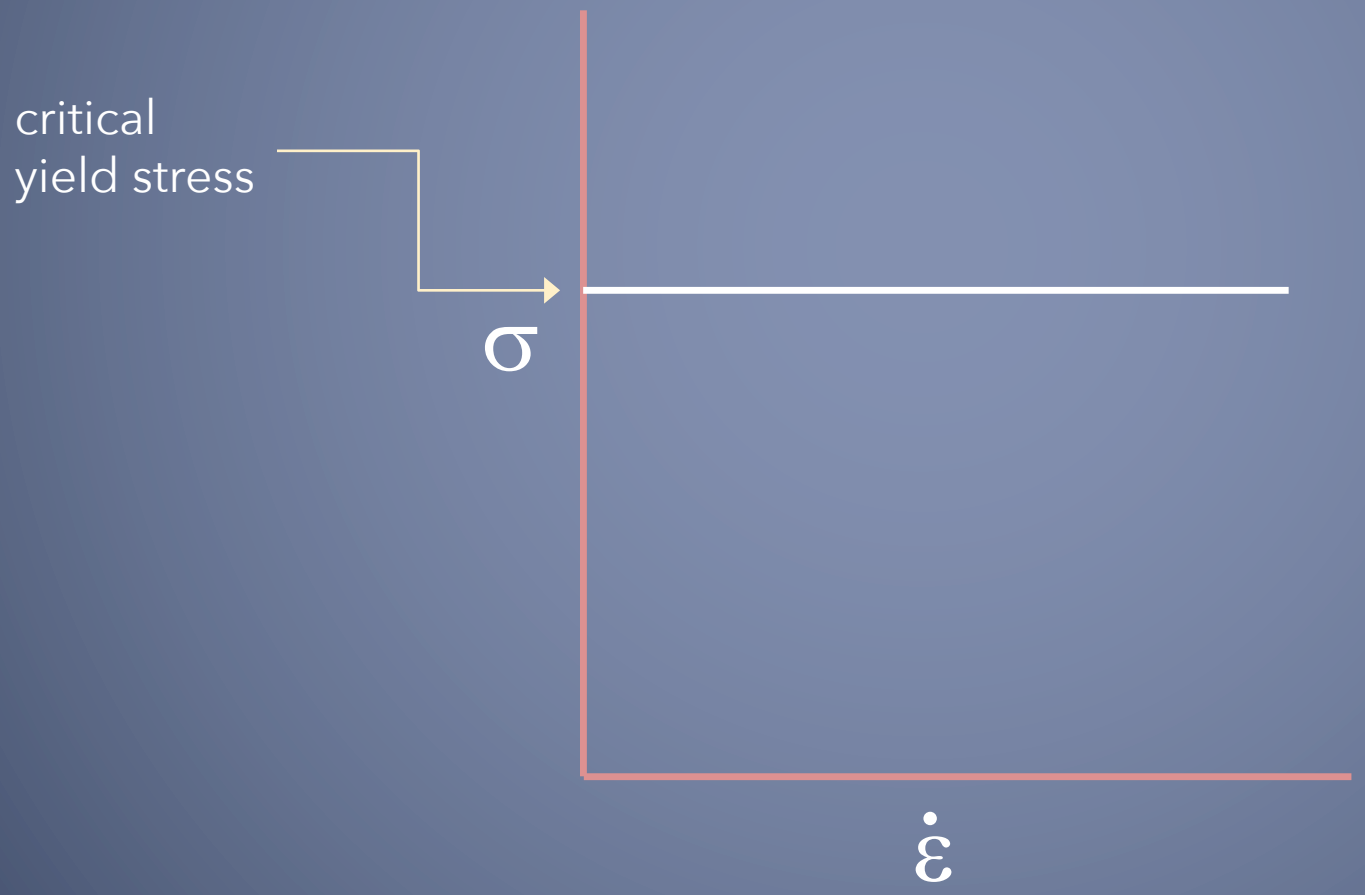


Viscous

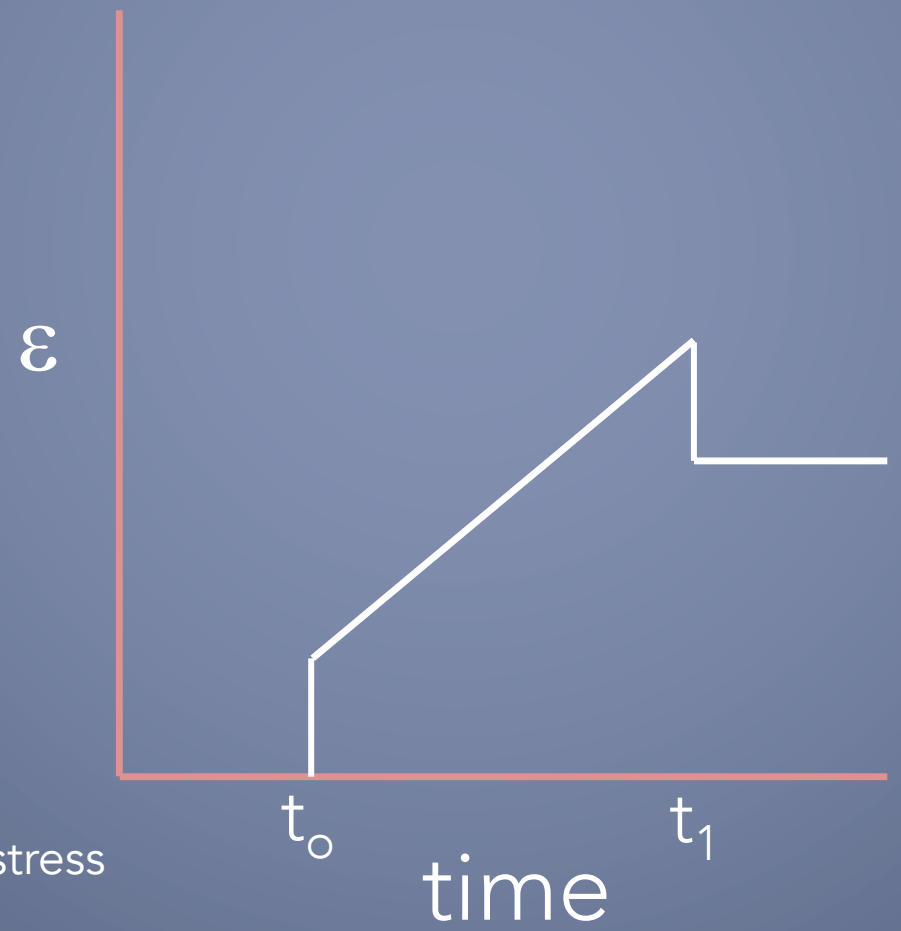


t_o = apply a constant stress
t_1 = remove stress

Plastic

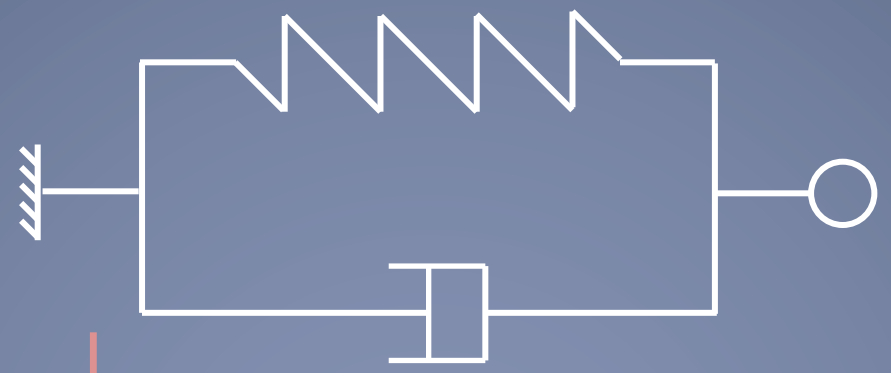


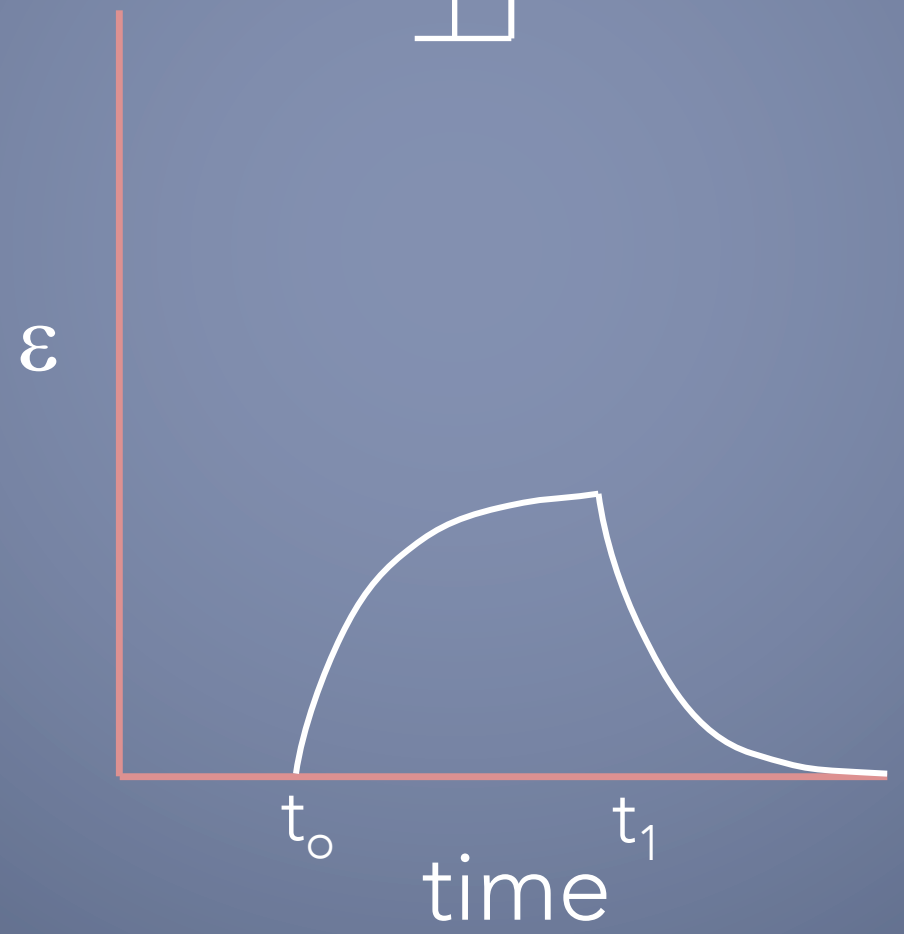
Maxwell (Elastico-viscous) Solid



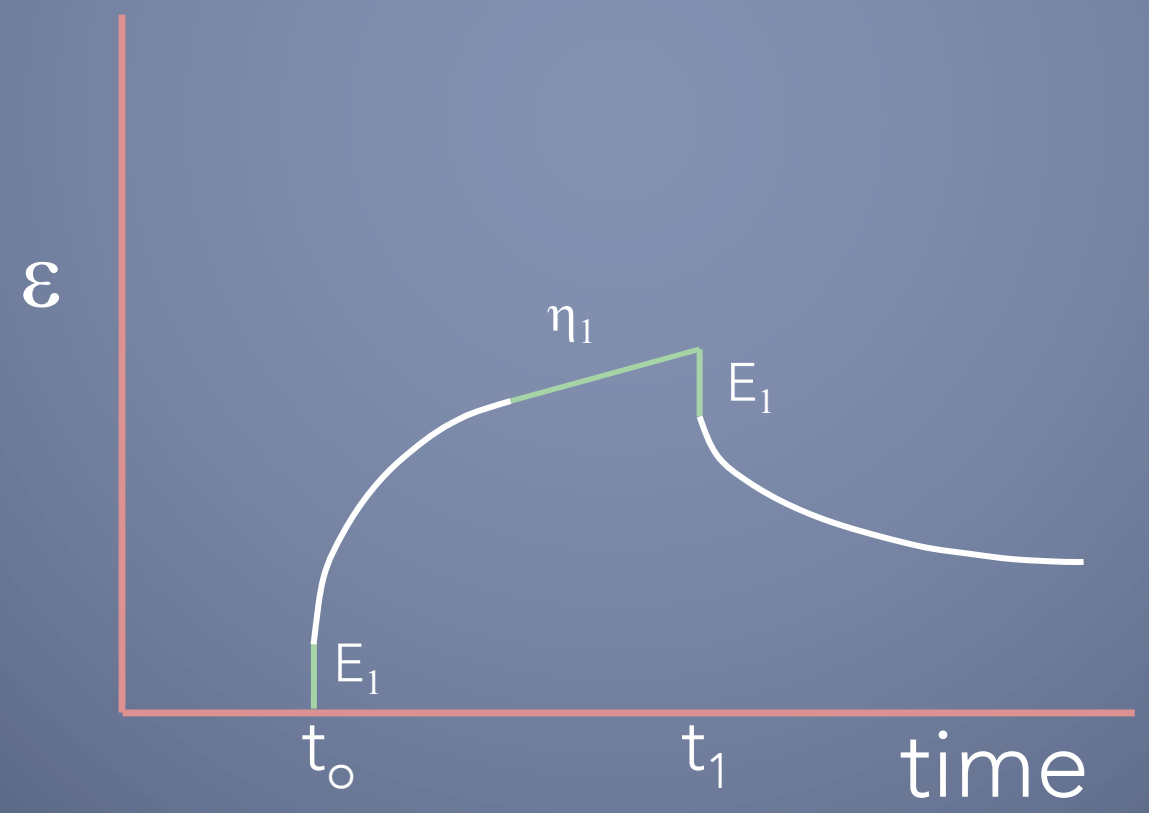
t_o = apply a constant stress
t_1 = remove stress

Kelvin (Visco-elastic) Solid

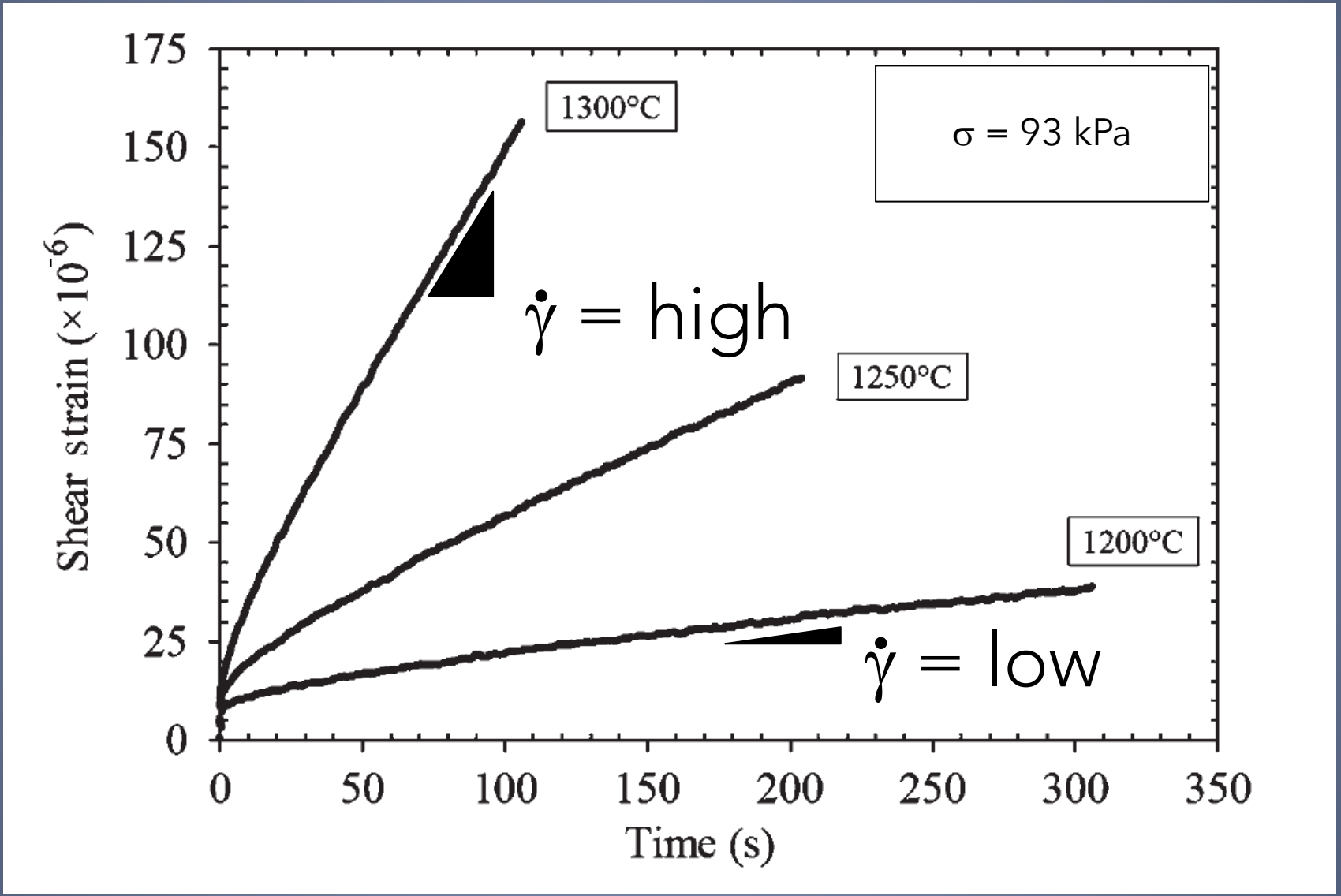




Burgers (General Linear) Solid

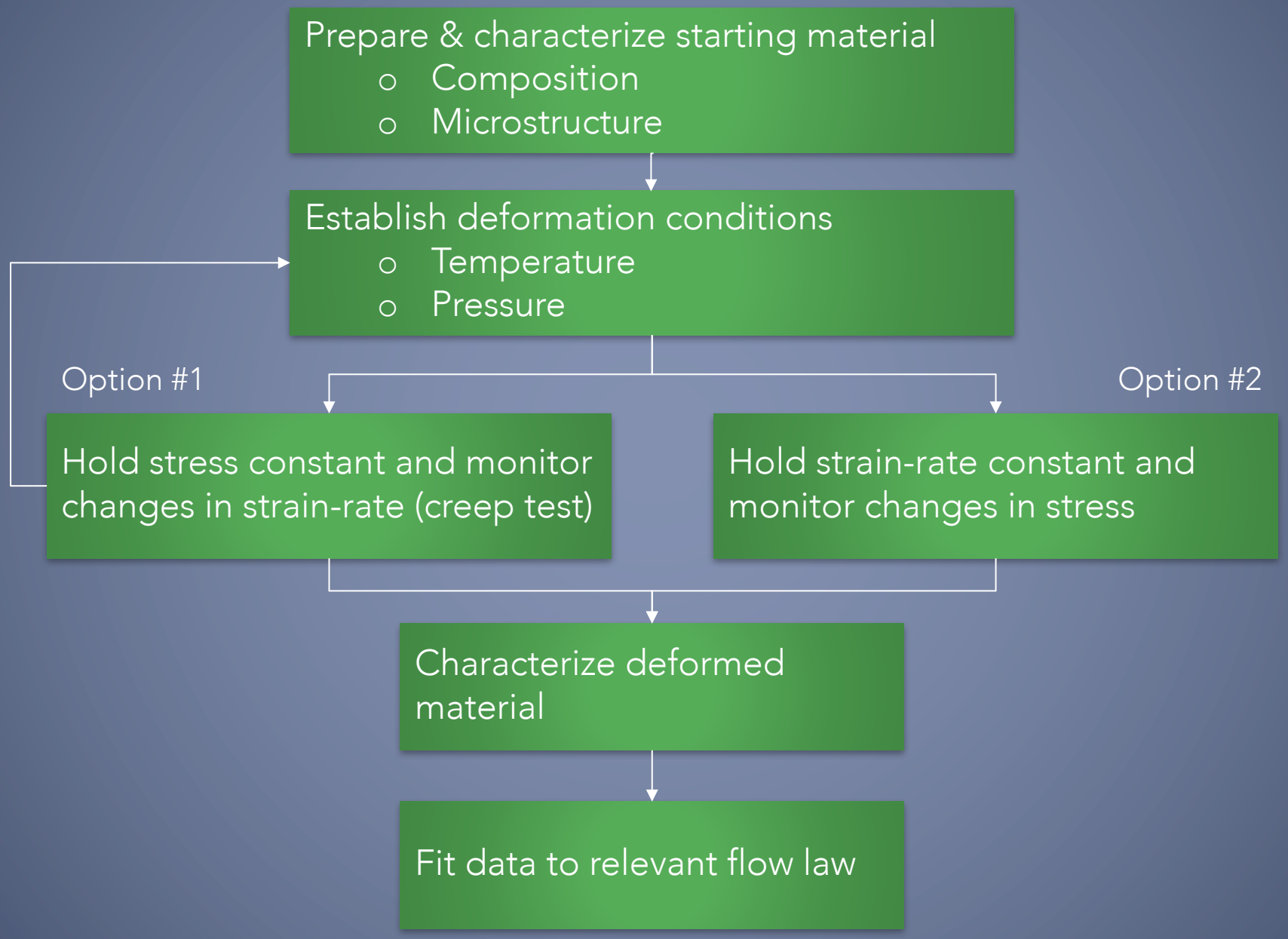


Micro-Creep Curves in Geologic Materials



Sundberg and Cooper (2010)

Experimental Rock Deformation



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. B9, PAGES 21,471–21,481, SEPTEMBER 10, 2000

Influence of water on plastic deformation of olivine aggregates
2. Dislocation creep regime

S. Mei

Department of Chemical Engineering and Materials Science, University of Minnesota-Twin Cities
Minneapolis

D. L. Kohlstedt

Department of Geology and Geophysics, University of Minnesota-Twin Cities
Minneapolis

Rheology of the Upper Mantle and the Mantle Wedge: A View from the Experimentalists

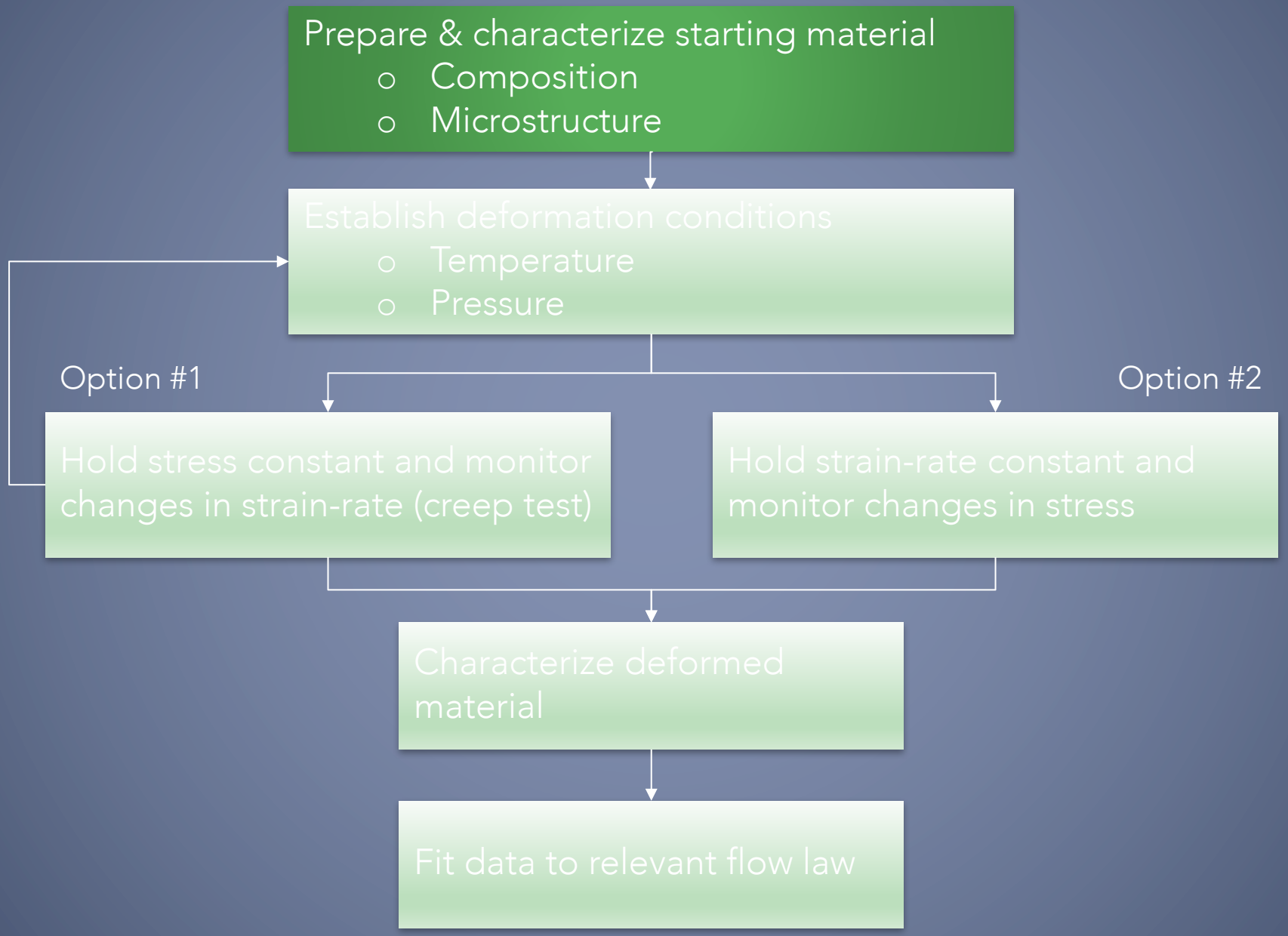
Greg Hirth

Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

David Kohlstedt

Department of Geology and Geophysics, University of Minnesota, Minneapolis, Minnesota

Experimental Rock Deformation

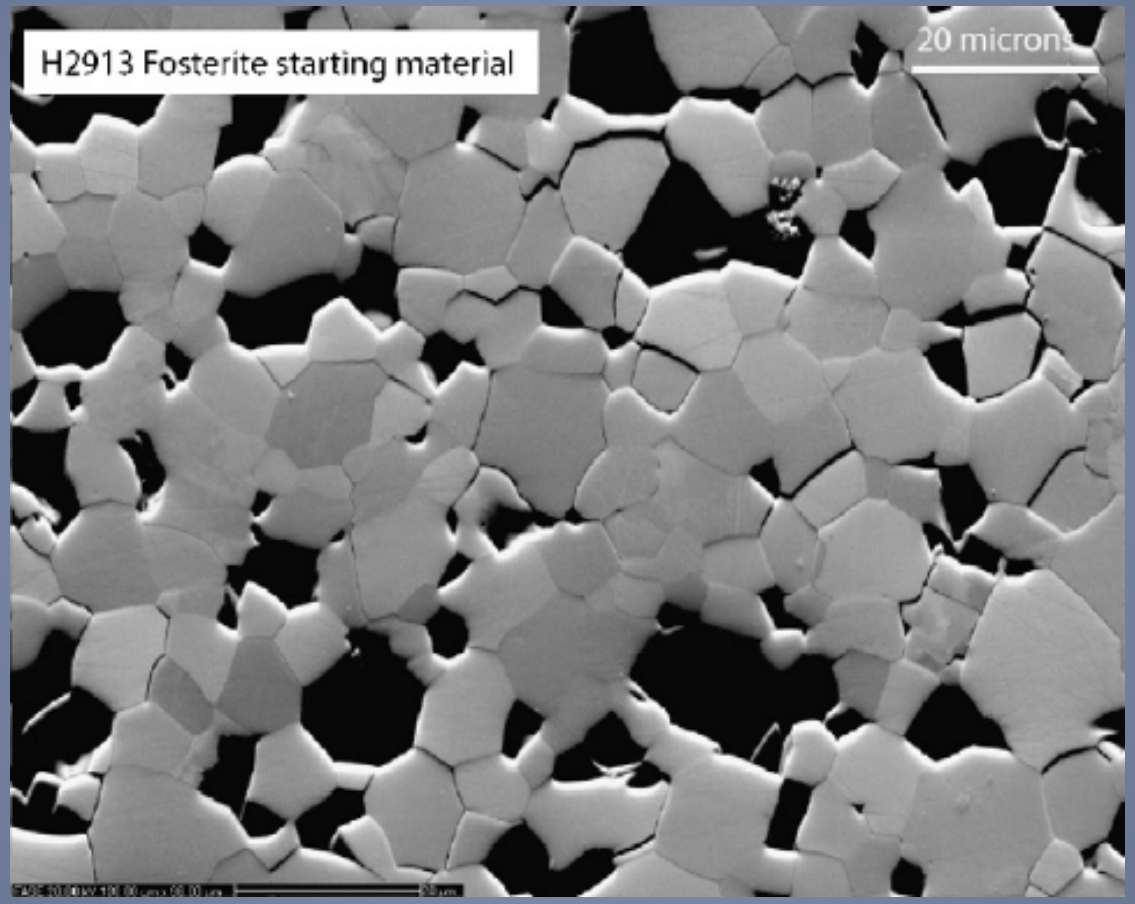


Xenoliths or other natural rocks

Gem-quality olivine crystals

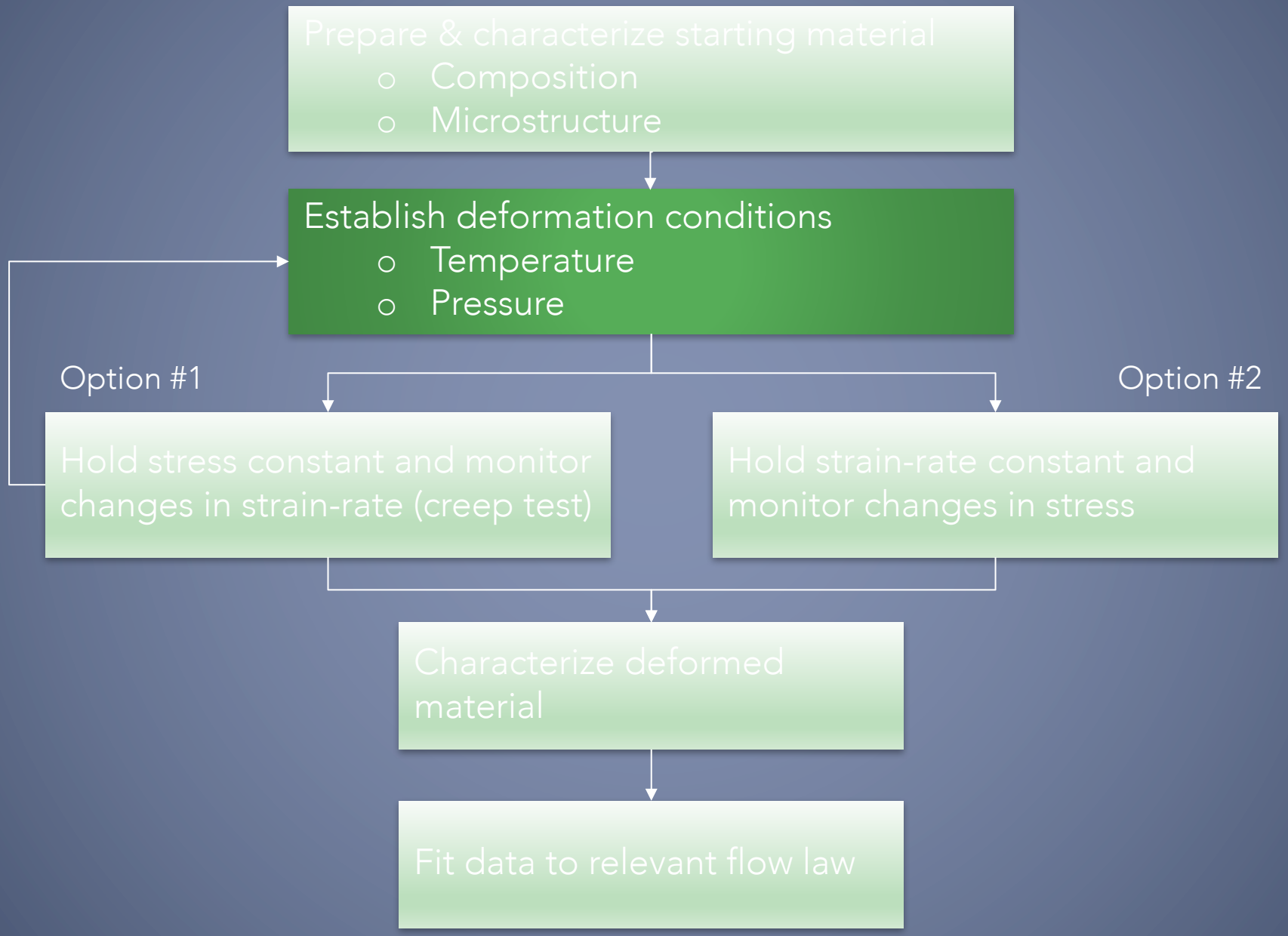
Ground to fine-grained powder

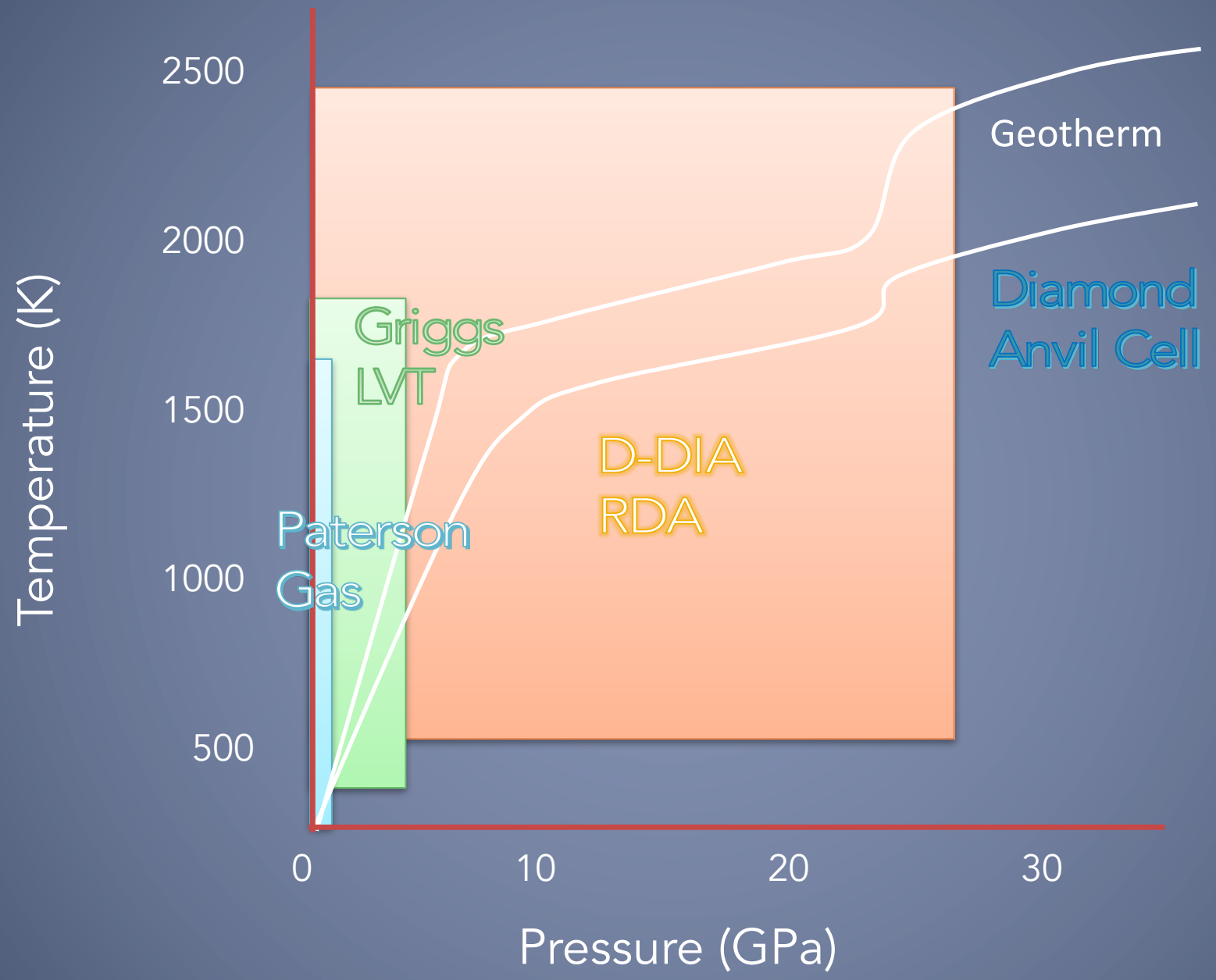
Hot-pressed to make a dense, homogeneous, fine-grained polycrystal



Demouchy et al (2011)

Experimental Rock Deformation





modified from SERC

Paterson Apparatus

Deformation specimen

Alumina spacers

Iron jacket

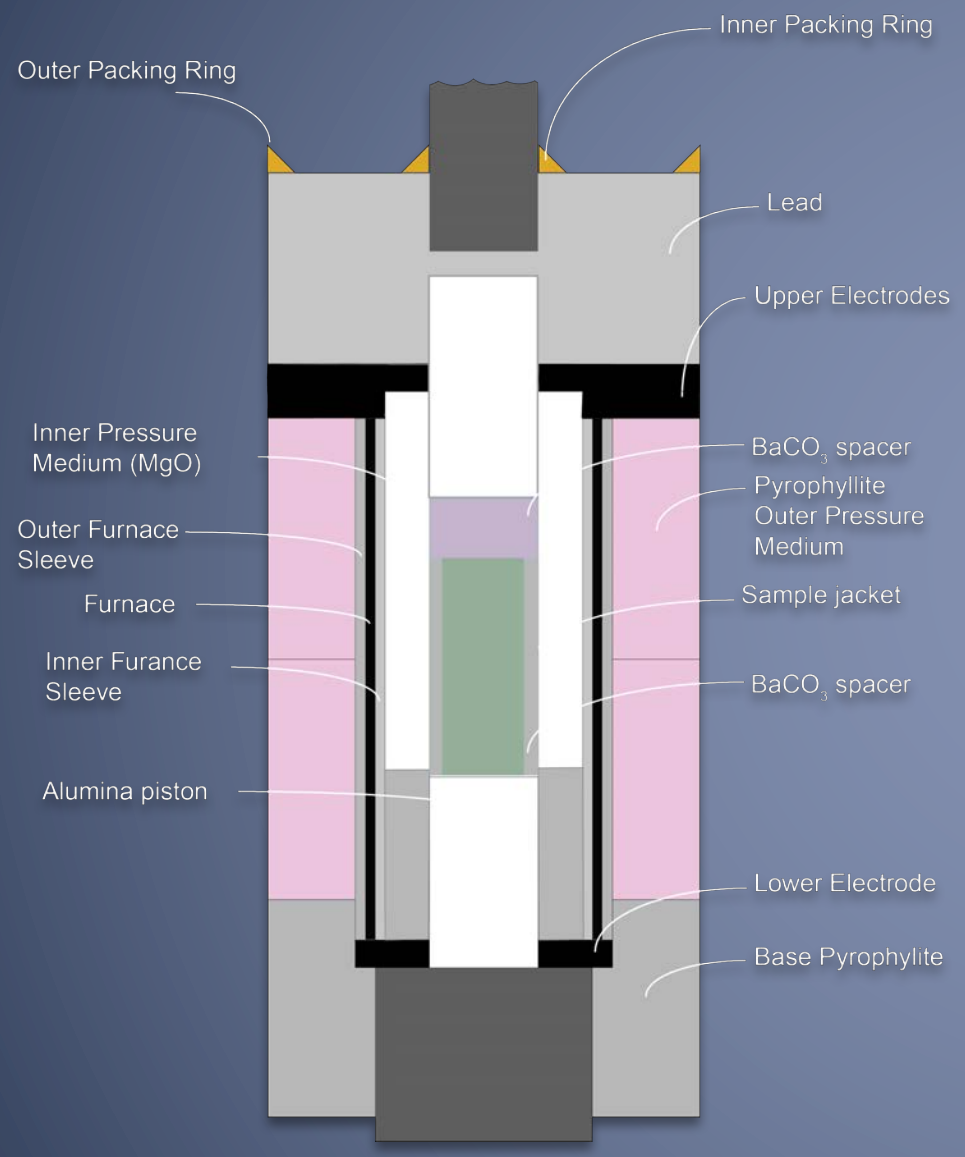
Yttria-stablized zirconia

Photo credit: SERC

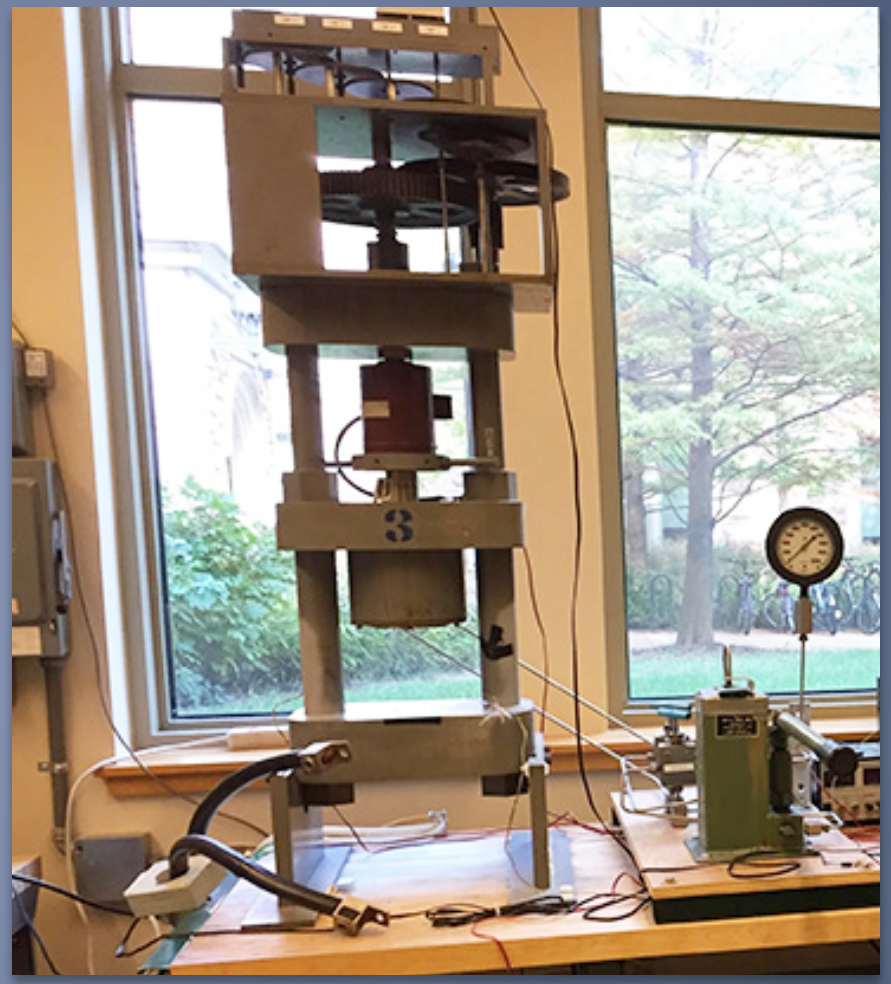
Kohlstedt Lab, University of Minnesota

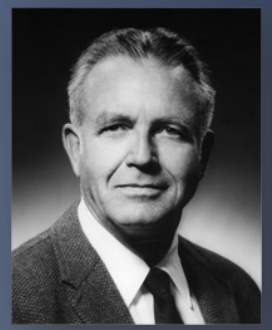
- Low pressure (P<300 Mpa)
- Excellent stress resolution
- Low or high strain (depends on instrument)
- Large sample volume

Griggs Apparatus



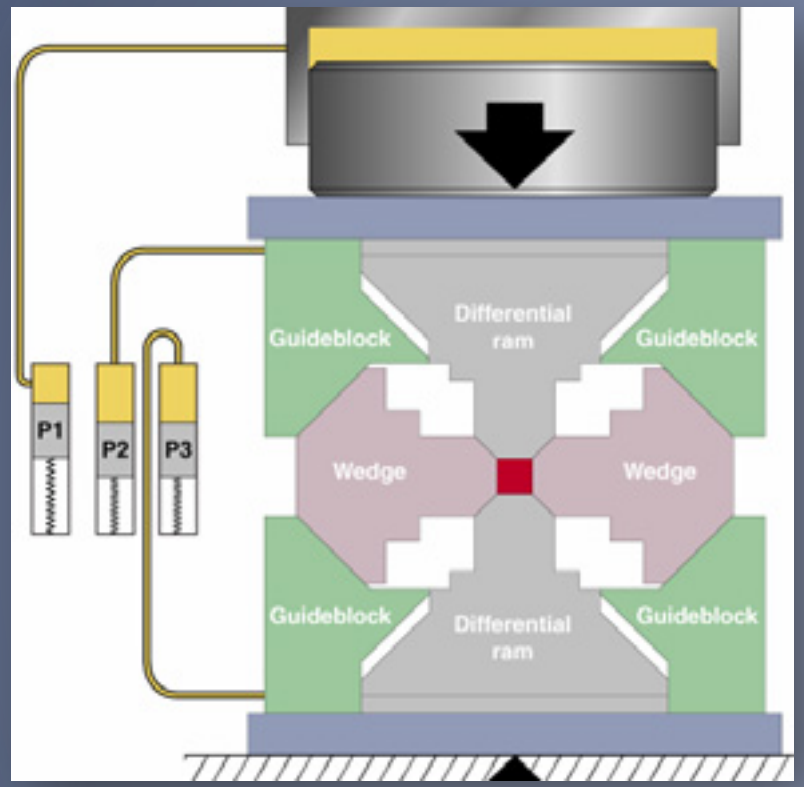
Washington University in St. Louis



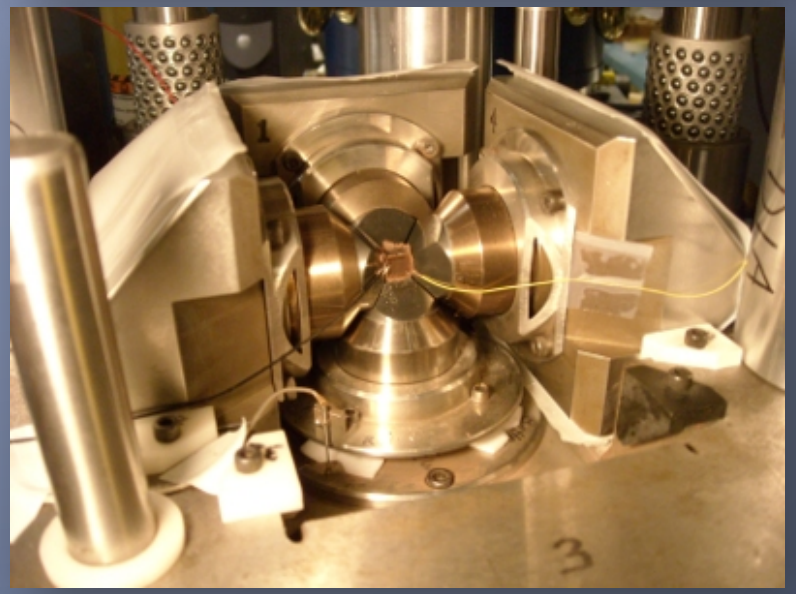


- Moderate pressure / temperature
- Poor stress resolution
- Moderate strain
- Moderate sample volume

D-DIA Apparatus



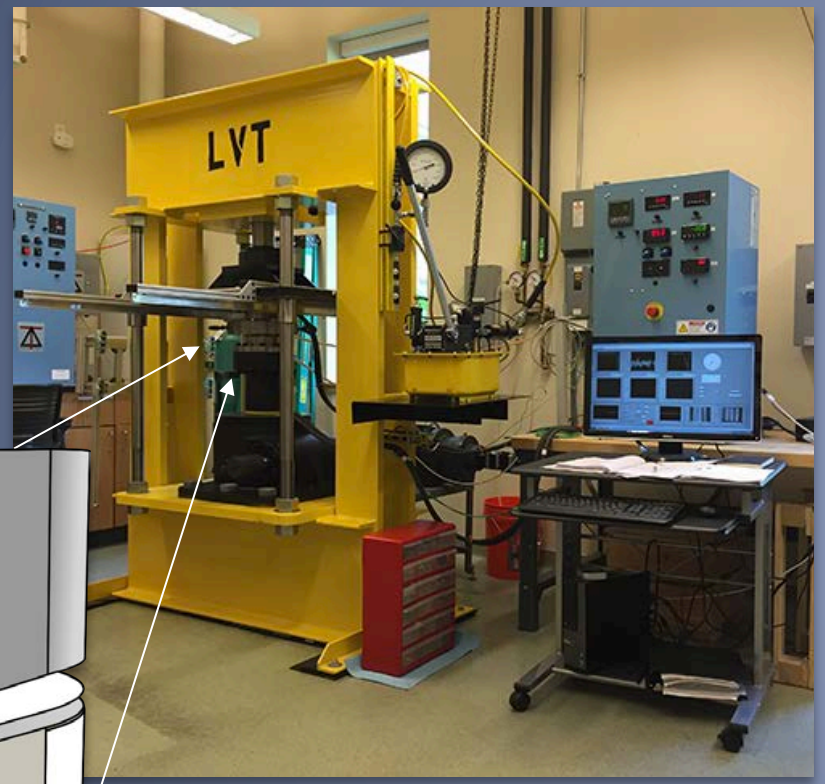
APS

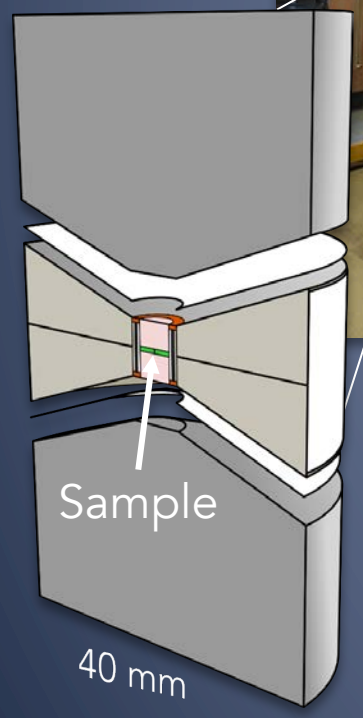


- High pressure and temperature
- Good stress resolution
- Low strain
- Small sample volume

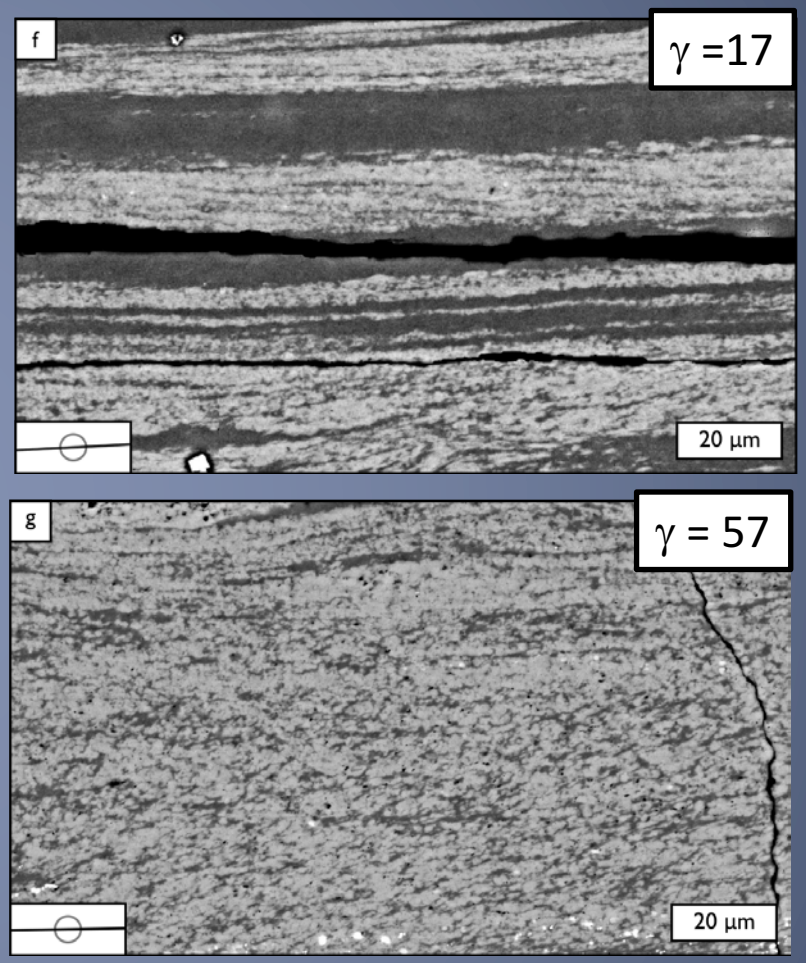
Large Volume Torsion Apparatus (LVT)

Washington University in St. Louis





- Moderate pressure / temperature
- Poor stress resolution
- Large strains
- "large" sample volume

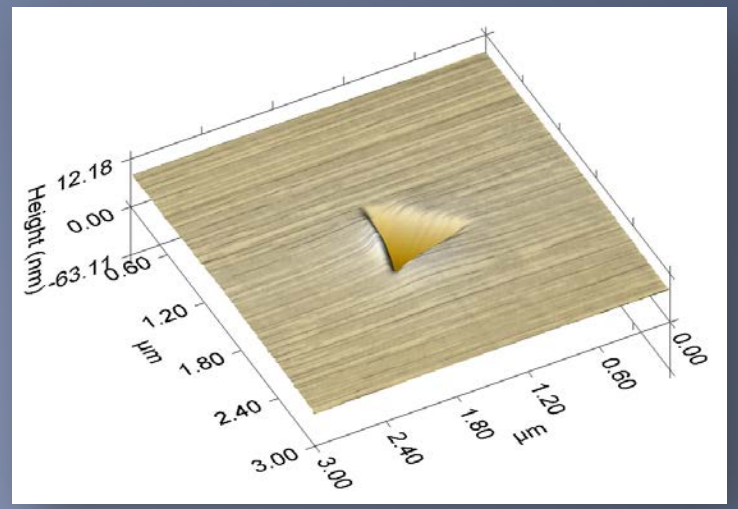


2-phase mixtures of calcite and anhydrite

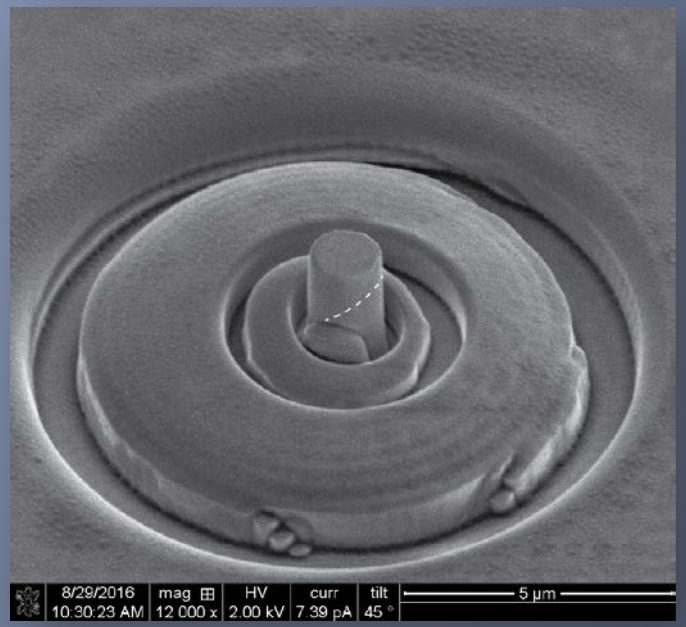
Cross & Skemer (2017) JGR

Nano-indentation / Micropillar Compression Testing

Hysitron Nanoindenter



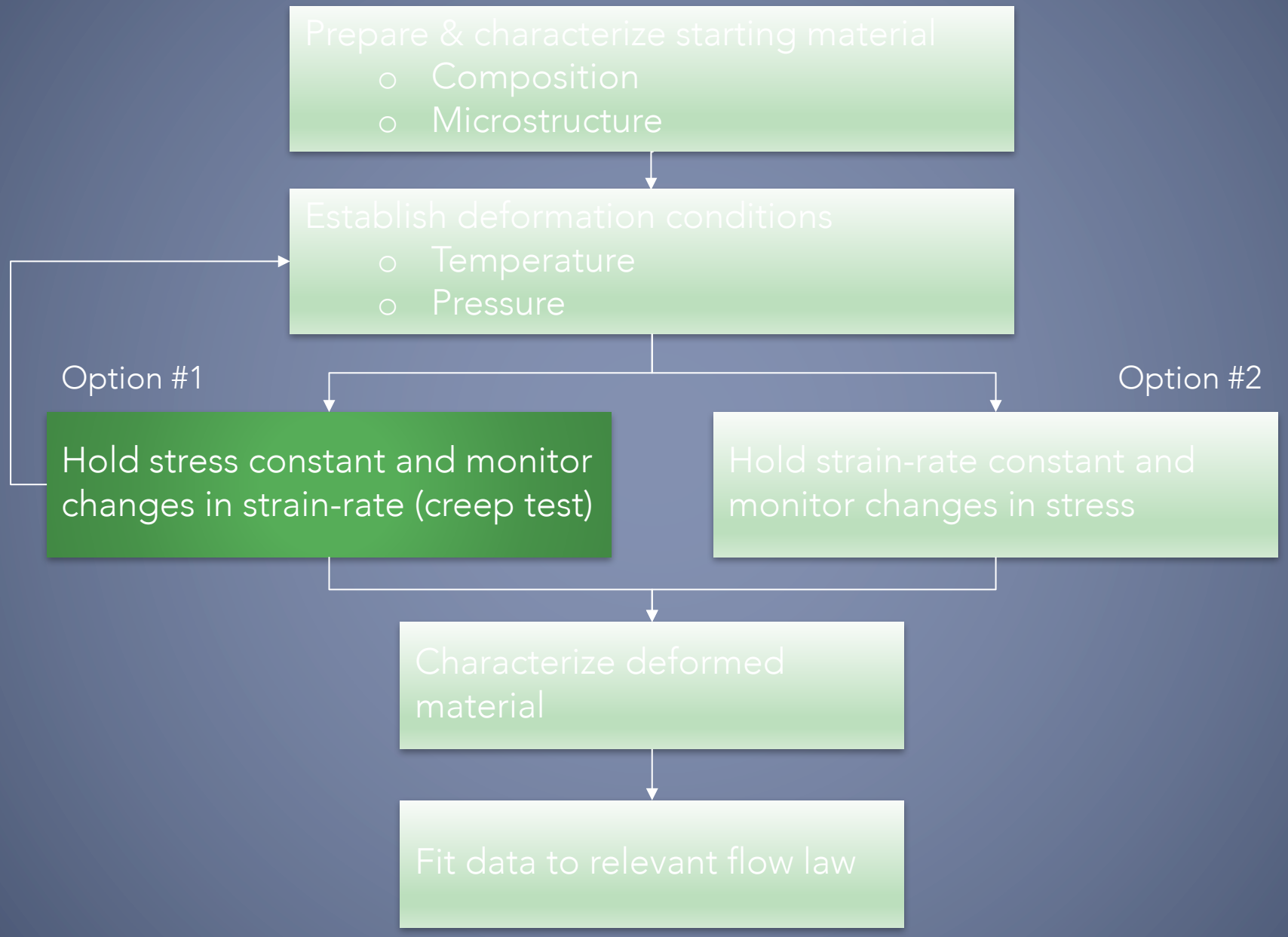
Kranjc et al (2016)



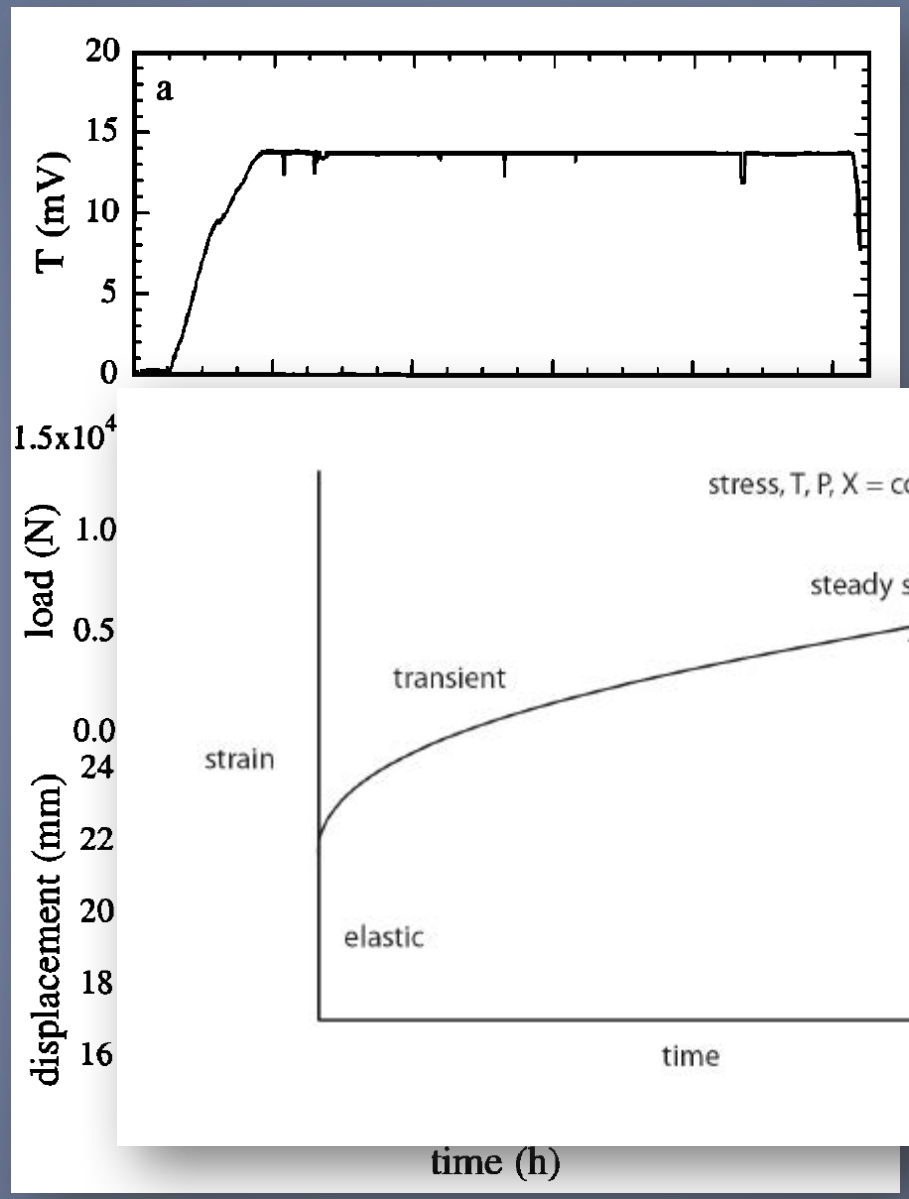
Kranjc et al (in prep)

- High ‘pressure’ and moderate temperature
- Excellent stress resolution
- Low strain
- Sub-micron sample volume

Experimental Rock Deformation



Raw data recorded by deformation apparatus

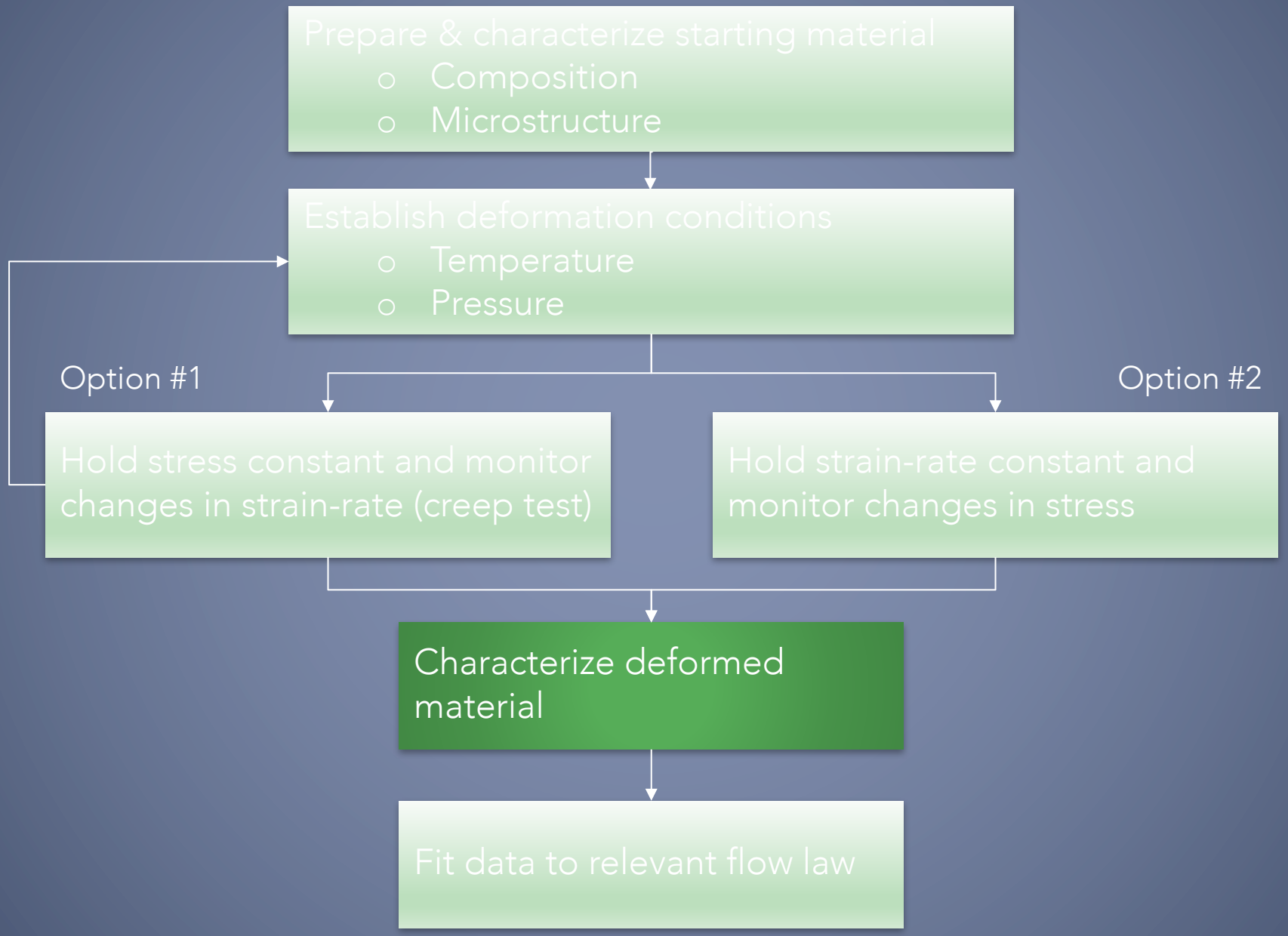


1250

Temp (C)

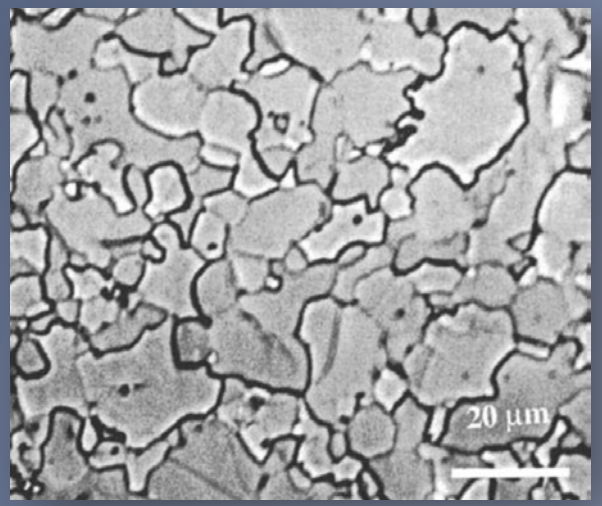
Mei and Kohlstedt (2000)

Experimental Rock Deformation



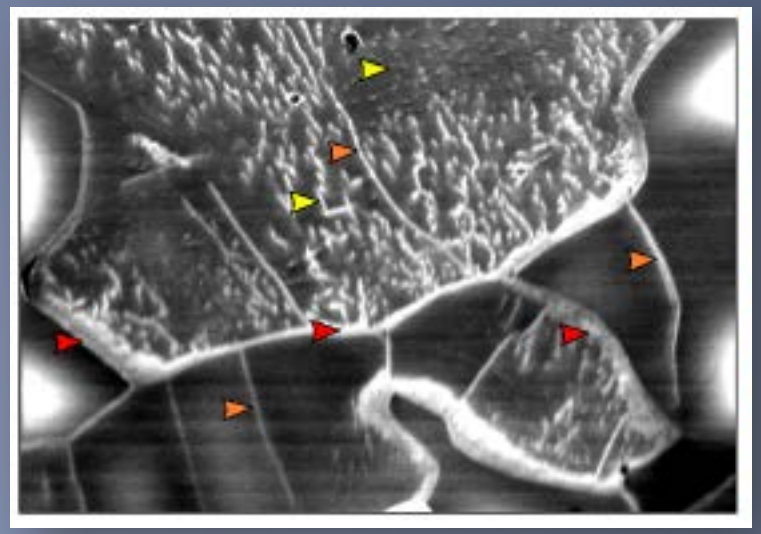
Microstructural Analysis

Grain-size



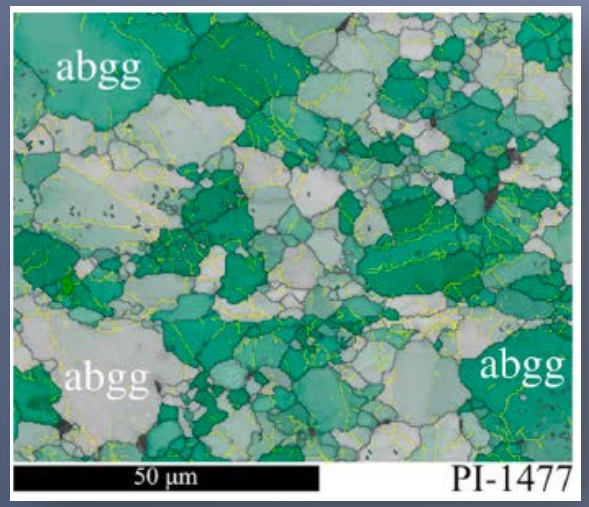
Mei and Kohlstedt, 2000

Dislocations



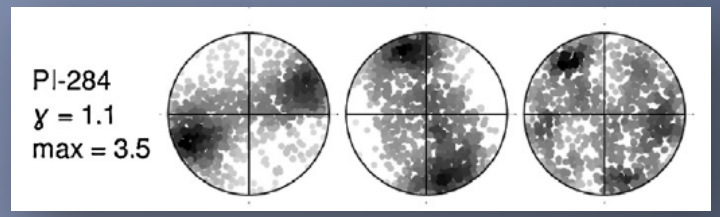
Wallis et al 2016

Grain Scale Microstructures (EBSD)



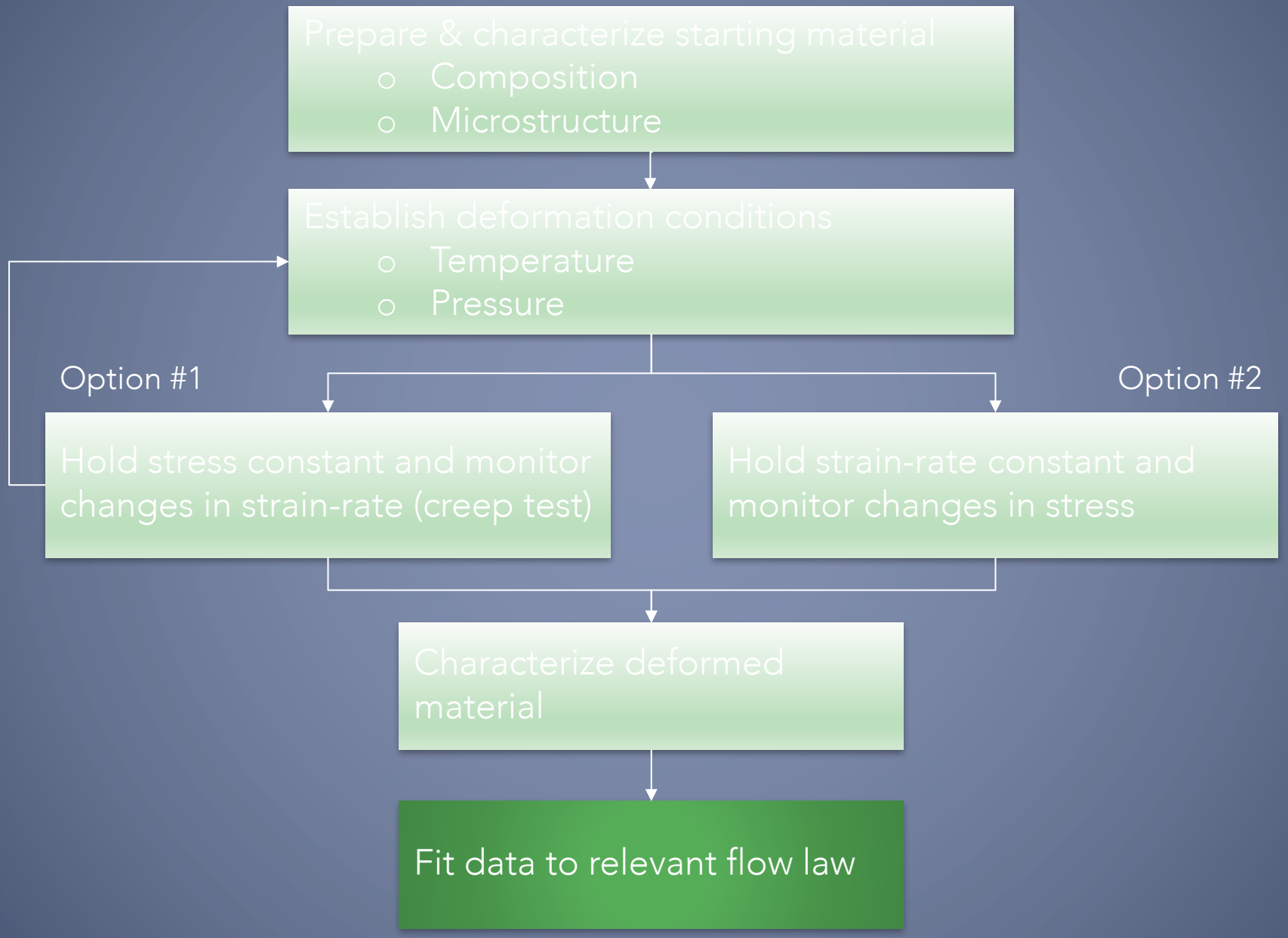
Hansen et al 2011

Lattice Preferred Orientation

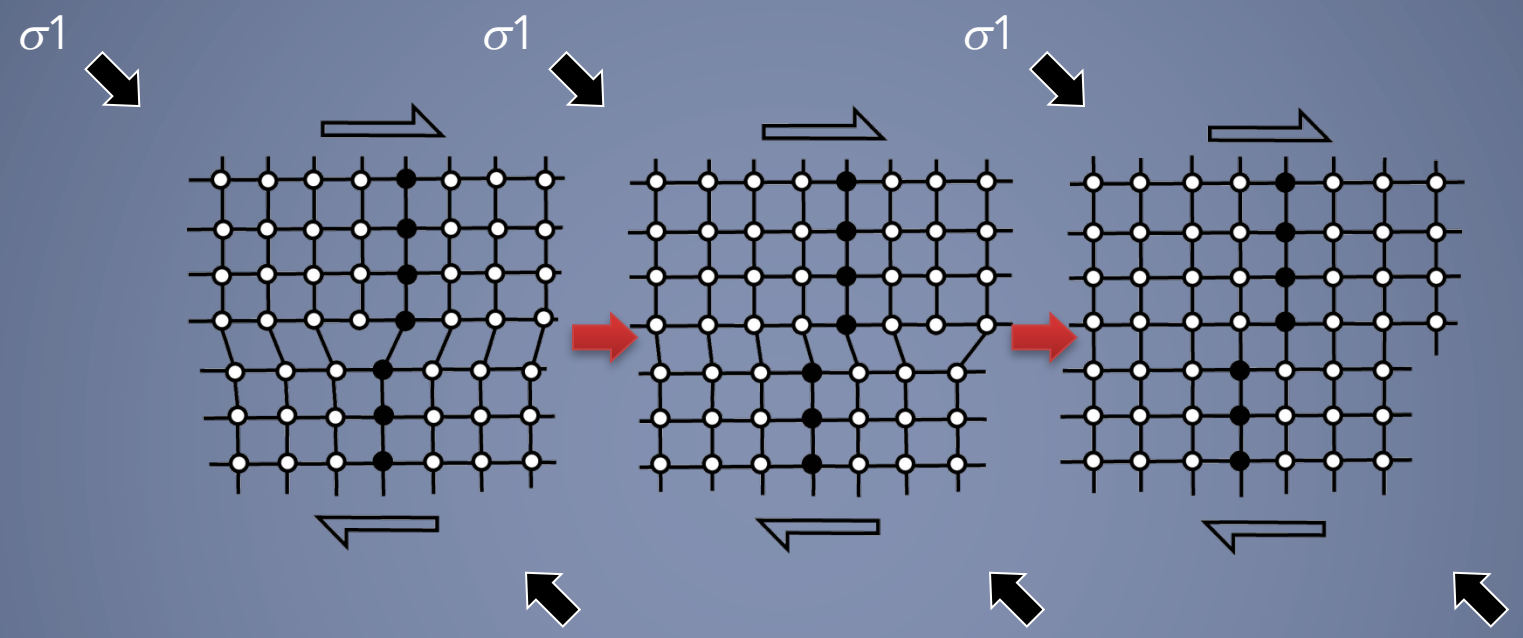


Hansen et al 2014

Experimental Rock Deformation



Dislocation Creep



$$\dot{\varepsilon} \propto \frac{\sigma^n}{d^m}$$

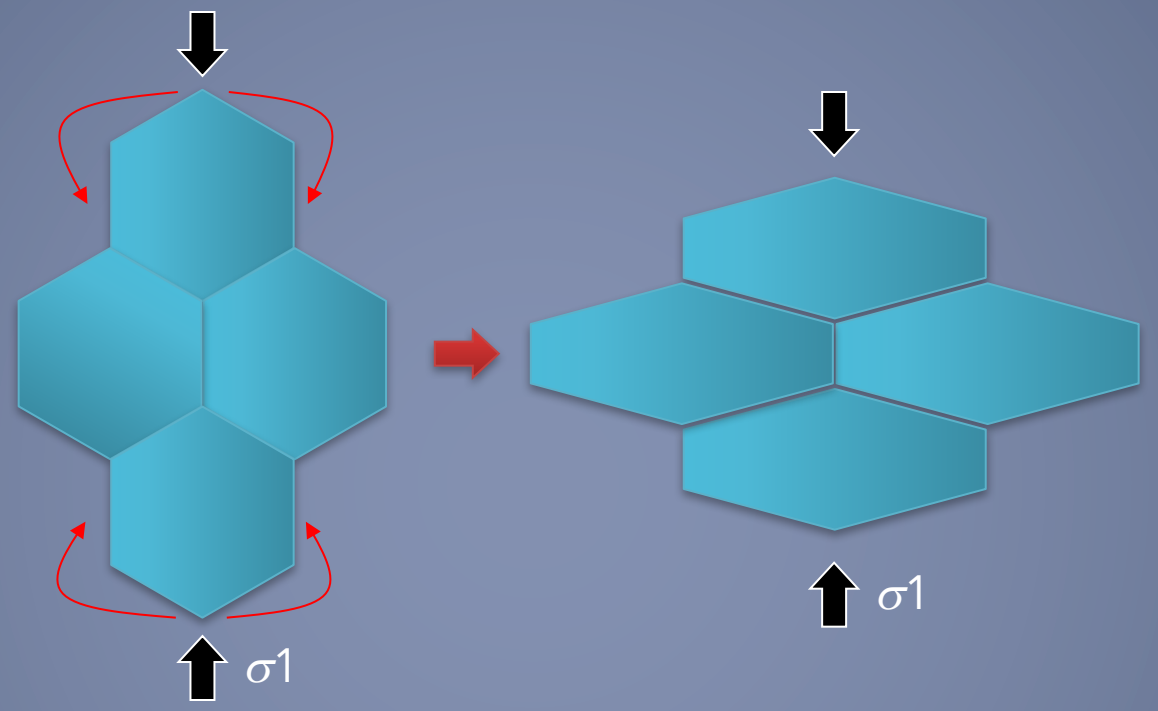
n = 3-5

m = 0

Microstructural Effects:

1. Changes grain size and shape
2. Produces LPO

Diffusion Creep



$$\dot{\varepsilon} \propto \frac{\sigma^n}{d^m}$$

n = 1

m = 2-3

Microstructural Effects:

1. Changes grain shape, not size
2. Does not produce LPO

Constitutive Expressions for High PT Deformation

stress

grain size

melt fraction

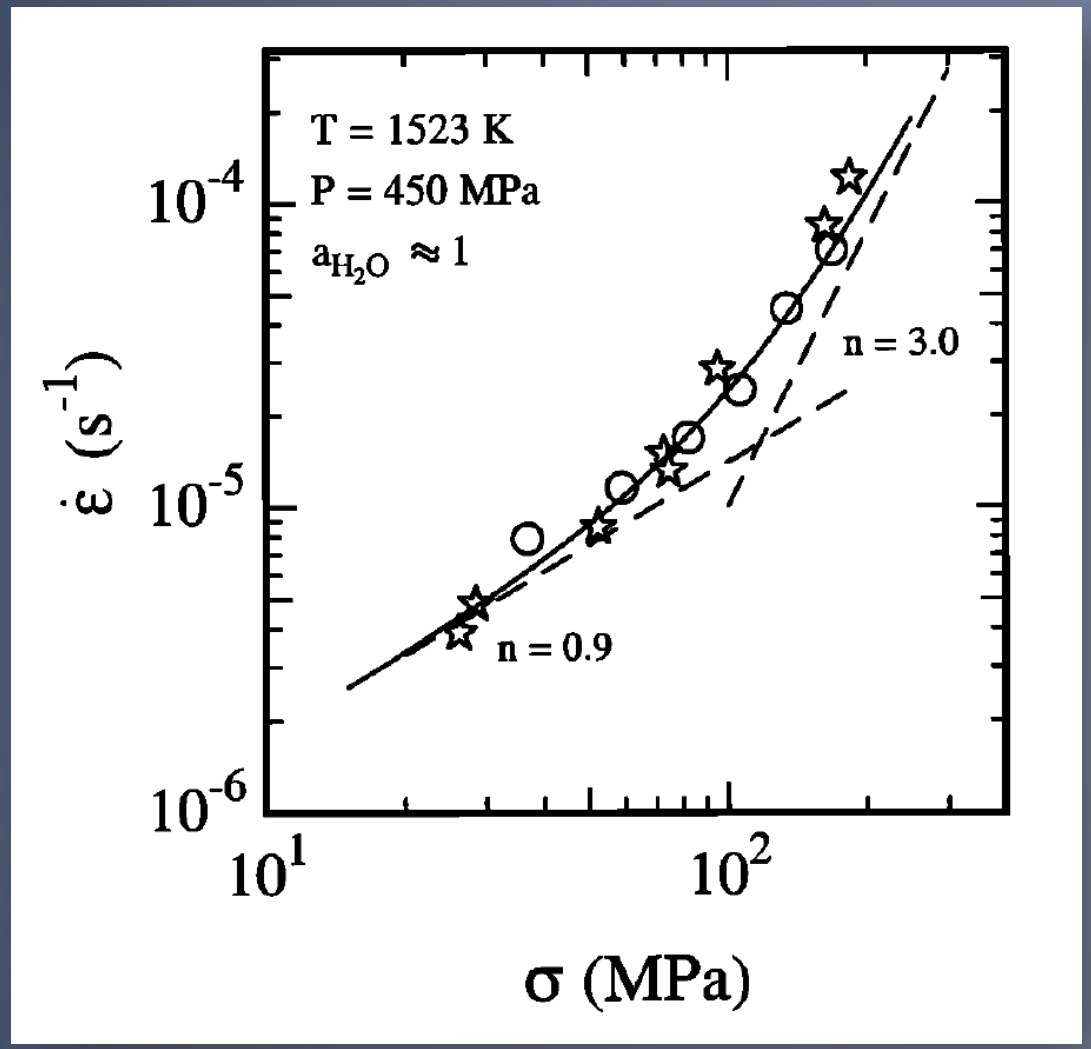
$$\dot{\varepsilon} = A\sigma^n F(\gamma) d^{-m} C_{OH}^r \exp(\alpha\varphi) \exp\left(-\frac{E + PV}{RT}\right)$$

strain dependent viscous anisotropy

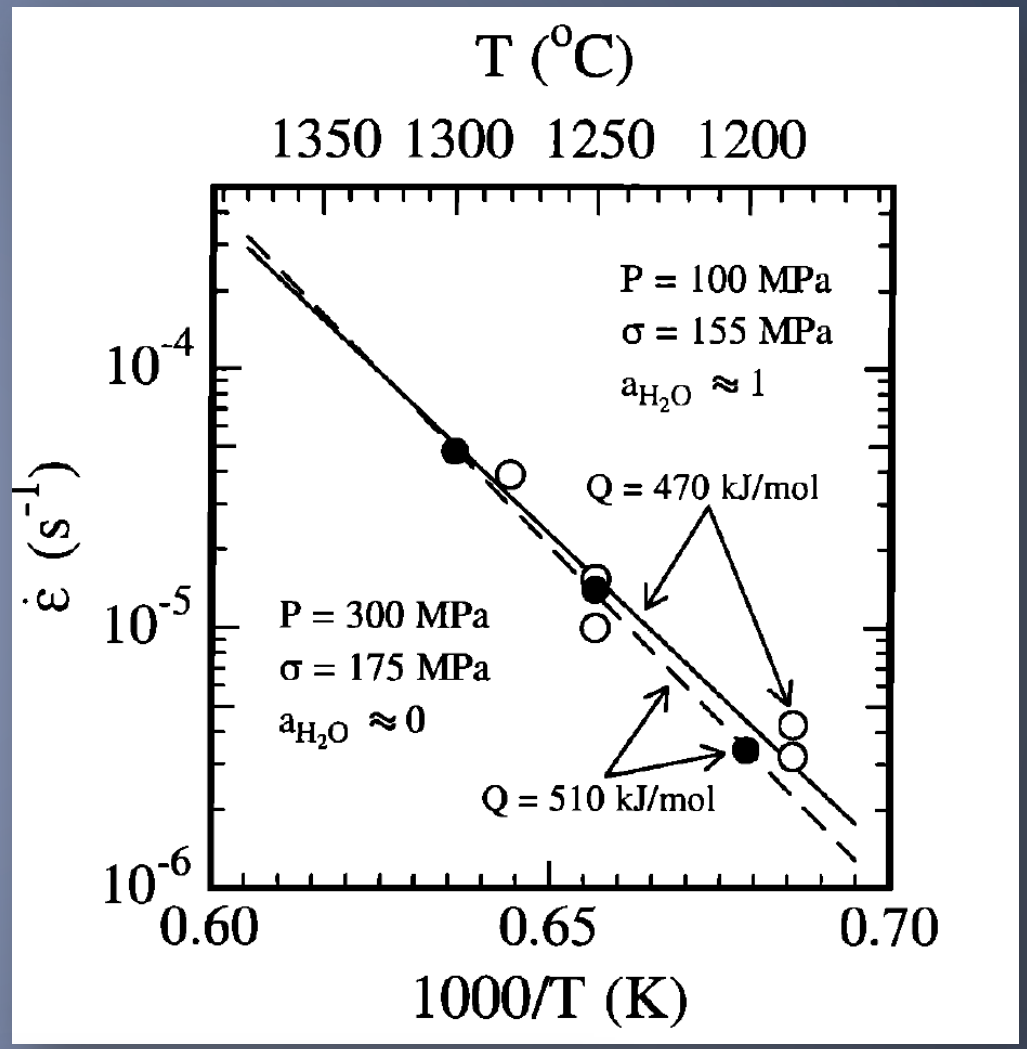
water concentration

temperature and pressure

Stress Dependence



Temperature Dependence



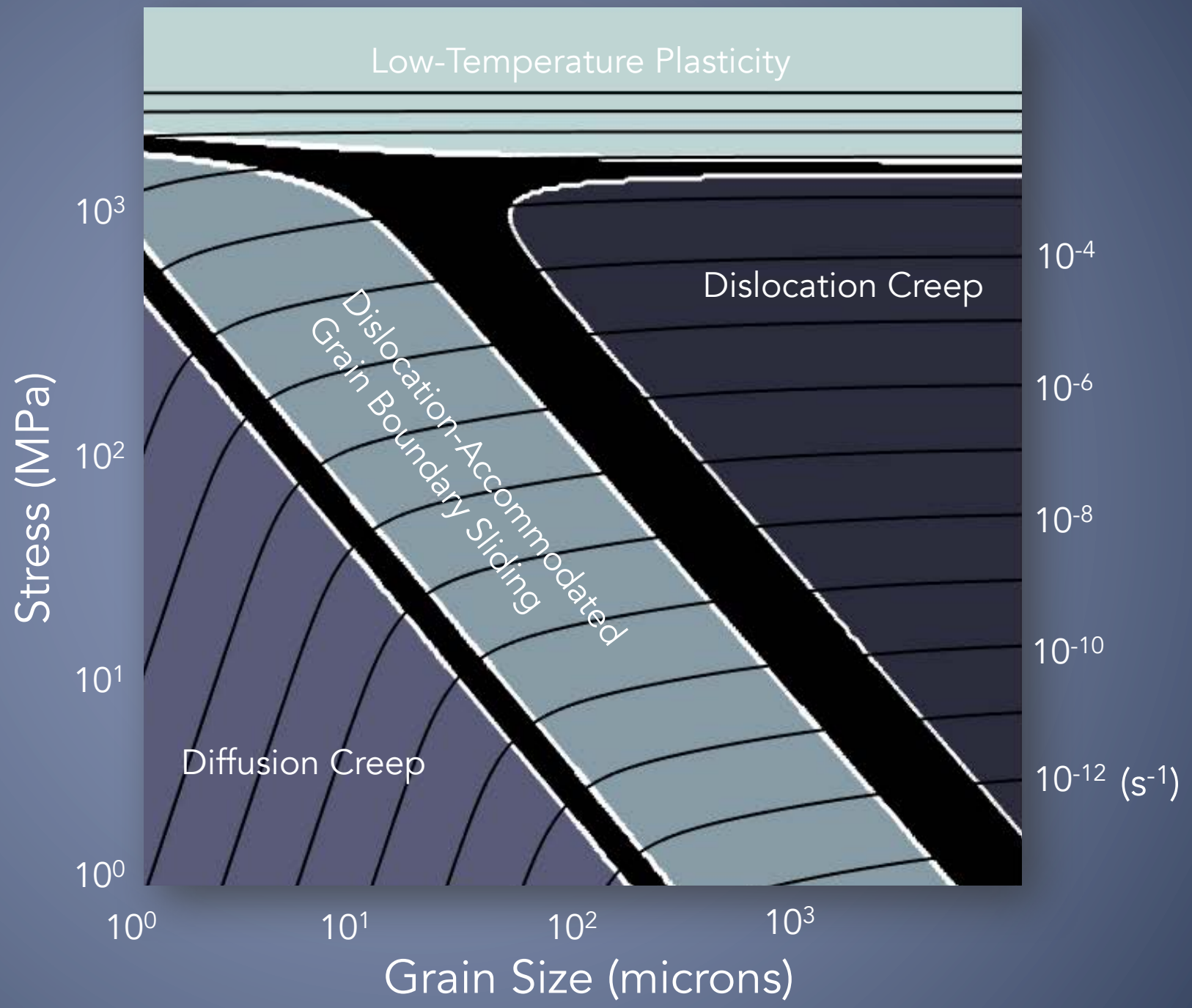
$$\dot{\varepsilon} = A\sigma^n F(\gamma) d^{-m} C_{OH}^r \exp(\alpha\varphi) \exp\left(-\frac{E+PV}{RT}\right)$$

Mei and Kohlstedt (2000)

Olivine Deformation Mechanism Map

- T = 1200°C
- P = 300 MPa
- Mg # ~ 90
- C_{OH} = dry
- Melt ϕ = 0

Hirth and Kohlstedt (2003)
Hansen et al. (2011)
Kranjc et al. (2016)



Deformation regime boundaries

Strain-rate contours

Rheology Tutorial

McCone 365

Portable Rock Analog Deformation Apparatus (PRADA)

- Dead weight creep apparatus
- Room pressure
- Room temperature

Rheology Tutorial

McCone 365

- 10 apparatus available
- Samples of paraffin are already prepared
- Each group will complete and analyze 2-3 creep tests
- We will compile our data to see if the rheology of paraffin wax at room T is linear or non-linear