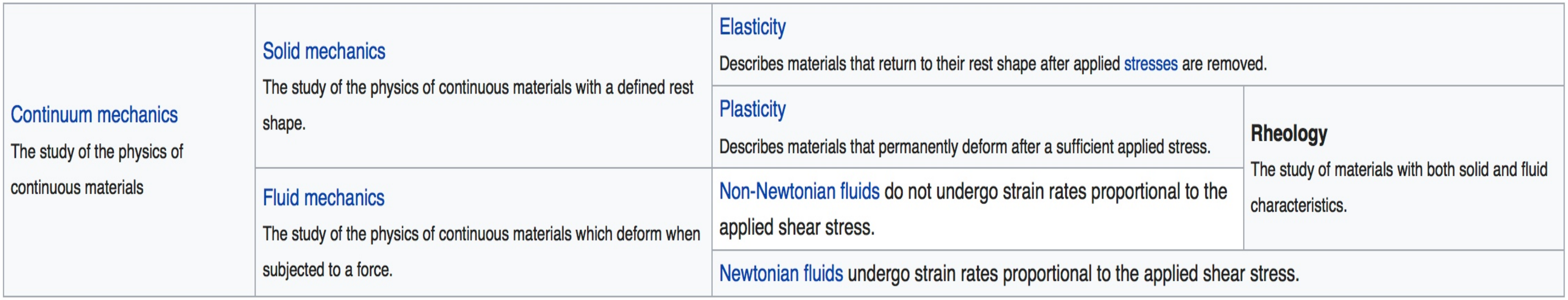


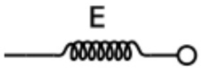
Continuum mechanics The study of the physics of continuous materials	Solid mechanics The study of the physics of continuous materials with a defined rest shape.	Elasticity Describes materials that return to their rest shape after applied stresses are removed.	
		Plasticity Describes materials that permanently deform after a sufficient applied stress.	**Rheology** The study of materials with both solid and fluid characteristics.
	Fluid mechanics The study of the physics of continuous materials which deform when subjected to a force.	Non-Newtonian fluids do not undergo strain rates proportional to the applied shear stress.	
		Newtonian fluids undergo strain rates proportional to the applied shear stress.	

Viscoelasticity

- Fluid and solid character are relevant at long times
  - Apply a constant stress:
  - if the material, after some deformation, eventually resists further deformation, it is considered a solid
  - if, by contrast, the material flows indefinitely, it is considered a fluid

- By contrast, *elastic and viscous* (viscoelastic) behavior is relevant at short times (*transient behavior*):
  - Apply a constant stress:
  - if the material deformation **strain** increases linearly with increasing applied stress, then the material is linear elastic within the range it shows recoverable strains. Elasticity is essentially a time independent processes, as the strains appear the moment the stress is applied, without any time delay.
  - if the material deformation **strain rate** increases linearly with increasing applied stress, then the material is viscous in the Newtonian sense. These materials are characterized due to the time delay between the applied constant stress and the maximum strain.
  - if the materials behaves as a combination of viscous and elastic components, then the material is **viscoelastic**. Theoretically such materials can show both instantaneous deformation as elastic material and a delayed time dependent deformation as in fluids.

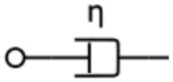
Viscoelasticity



Hook (spring)

elastic

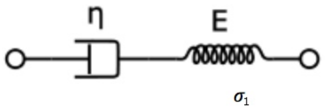
$$\sigma = E\varepsilon$$



Newtonian fluid (dashpot)

viscous

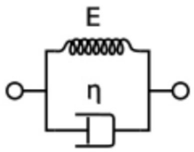
$$\sigma = \eta\dot{\varepsilon}$$



Maxwell element

viscous and elastic elements in series

$$\varepsilon = \varepsilon_1 + \varepsilon_2$$



Kelvin element

viscous and elastic elements in parallel

$$\sigma = \sigma_1 + \sigma_2$$

Recognizing Viscoelasticy in the Earth with Geodesy

Hector Mine
earthquake M7.1
Oct. 16,1999

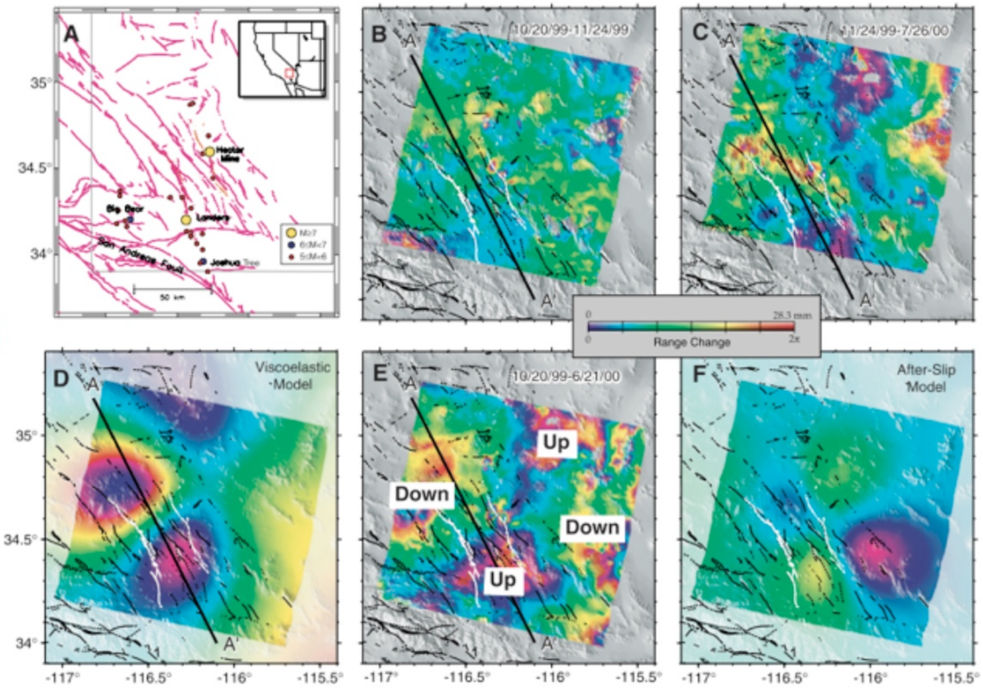


Fig. 1. (**A**) Background map indicating the most substantial earthquakes in the Mojave Desert from 1992 to 2000. Gray lines delineate the area covered in the following subplots. (**B**, **C**, and **E**) Observed ascending orbit wrapped interferograms during various time periods after the Hector Mine earthquake (*9*). One color cycle represents 28 mm of ground displacement away from the satellite with look and track angles (*8*) of 23° and S77°E, respectively. (**D** and **F**) Predictions of range change according to the viscoelastic and afterslip models, respectively, for the time period 20 October 1999 to 21 June 2000. The variance reduction of these models with respect to the observed interferogram in (E) is 67% and −56%, respectively. Peak-to-peak signal is generally slightly greater than 28 mm and is almost entirely captured with one color cycle.

Recognizing Viscoelasticy in the Earth with Geodesy

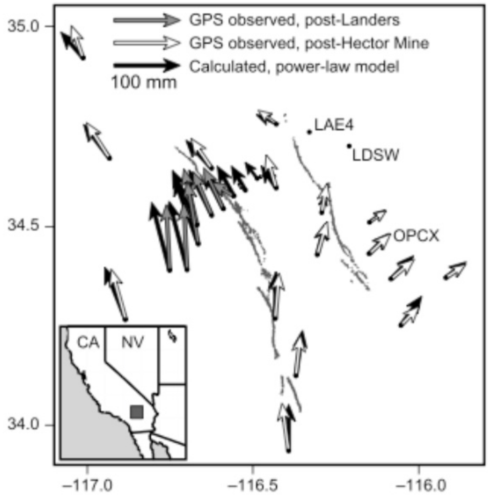


Figure 1 GPS observed and calculated horizontal postseismic surface displacements following the 1992 Landers and 1999 Hector Mine earthquakes in the Mojave desert of southern California. Two separate GPS data sets are used: campaign data following the Landers earthquake[11] and continuous data following the Hector Mine earthquake[12]. The campaign data (grey arrows) are shown relative to station LAE4, while the continuous data (white arrows) are relative to station LDSW. Post-Landers campaign data (Emerson transect) span July 1992 through to February 1998. Post-Hector Mine continuous data span October 1999 through to December 2002. Calculated displacements are based on a finite element model that incorporates a power-law rheology of predominately mantle flow (model 8 in Fig. 2, see Table 1 for power-law parameters).

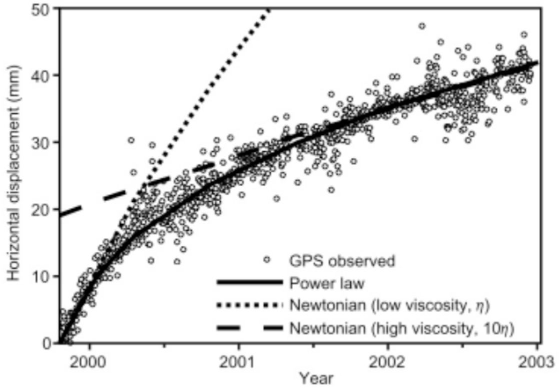
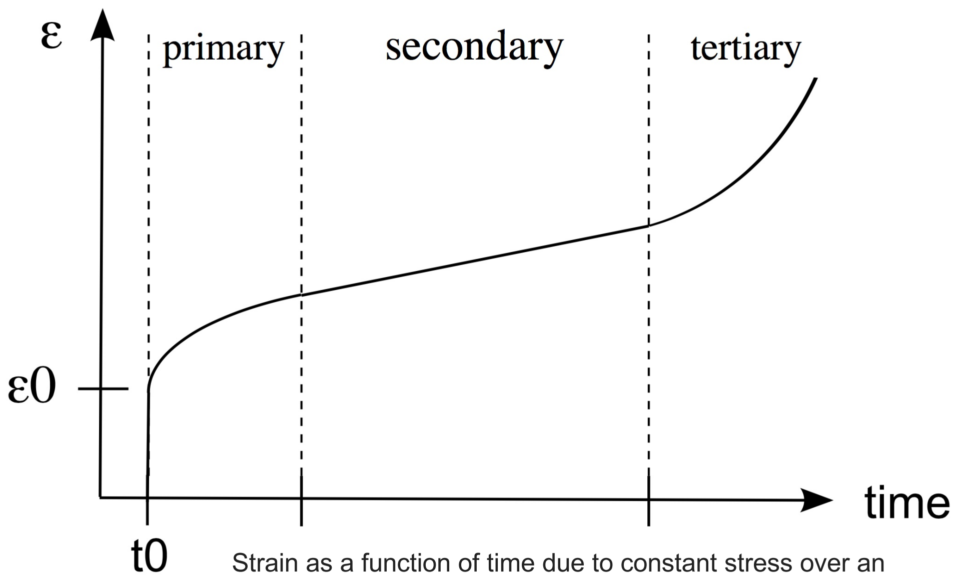


Figure 3 Comparison of representative observed and calculated postseismic displacement time series (station OPCX following the Hector Mine earthquake[12]). Power-law mantle flow model (solid curve) is model 8 in Fig. 2 (aplite, wet olivine, $T_{40\,\mathrm{km}} = 1{,}225\,^{\circ}\mathrm{C}$; power-law parameters listed in Table 1). Newtonian models consider predominately mantle flow with low viscosity (2.5×10^{18} Pa s, dotted curve) and an order of magnitude higher viscosity (2.5×10^{19} Pa s, dashed curve) that match early and late time-series slopes, respectively. The curve associated with the high-viscosity newtonian model has been raised to show where the slope matches the observed time series.

Freed and Burgmann, 2004

Stages of Creep



Strain as a function of time due to constant stress over an extended period for a viscoelastic material.

Primary creep (transient creep)

- strain rate is relatively high, but decreases with increasing time and strain
- → due to strain hardening at lower temperatures.
- ex. the dislocation density increases and, in many materials, a dislocation subgrain structure is formed and the cell size decreases with strain.

Secondary creep (steady-state creep)

- strain rate diminishes to a minimum and becomes near constant (*most understood)
- → due to the balance between strain hardening and annealing (thermal softening).
- no material strength is lost during these first two stages of creep.
- stress dependence of this rate depends on the creep mechanism (diffusion, dislocation, etc.)

Tertiary creep

- strain rate exponentially increases with stress because of necking phenomena
- → internal cracks or voids decreases the effective area of the specimen.
- strength is quickly lost in this stage while the material's shape is permanently changed.
- acceleration of creep deformation this stage eventually leads to material fracture.

Power Law Rheology

$$\boxed{\dot{\varepsilon} = A\sigma^{n} d^{-m} f_{H_2O}^{r} e^{-\left(\frac{Q+pV}{RT}\right)}}$$

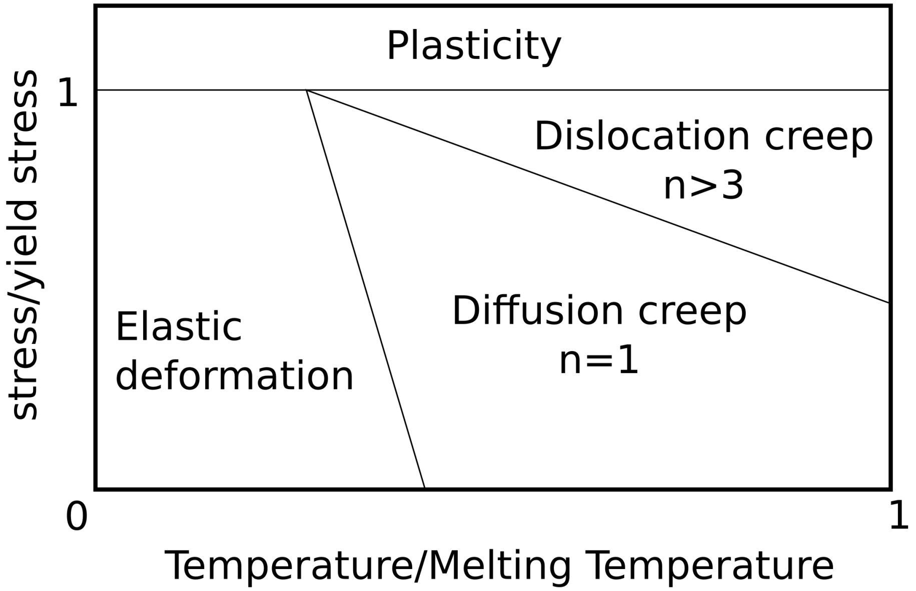
σ = differential stress

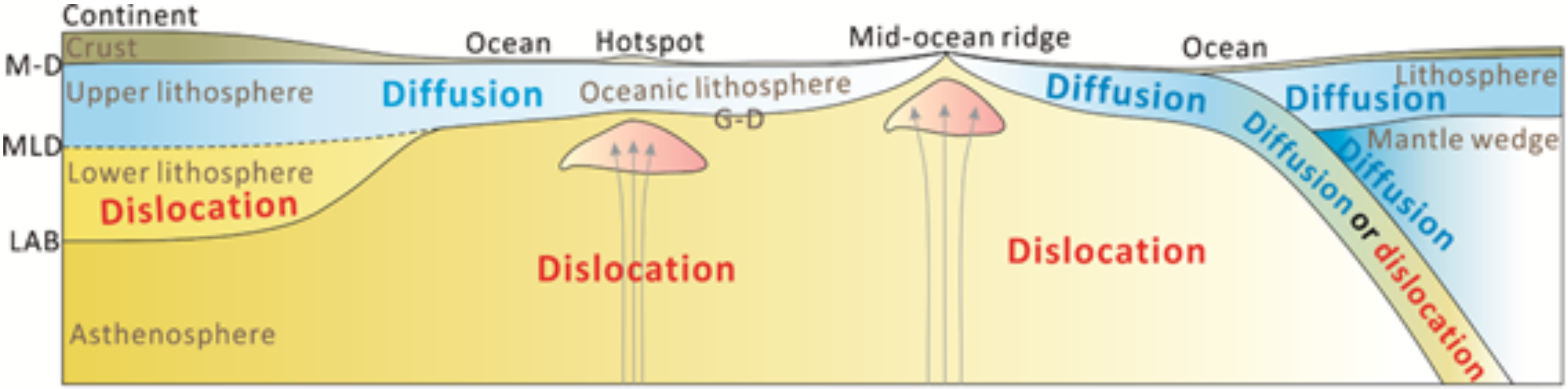
n = 1 implies Newtonian fluid
R = gas constant
T = temperature
p = pressure
Q = activation Energy
V = activation volume
d = grain size
m = grain size dependence
f thingy = fugacity (water concentration)
A = scales it all (constant of diffusion)

- *Laboratory experiments determine many of these properties*

- *Note pressure and temperature dependence are strong functions of depth in the Earth*

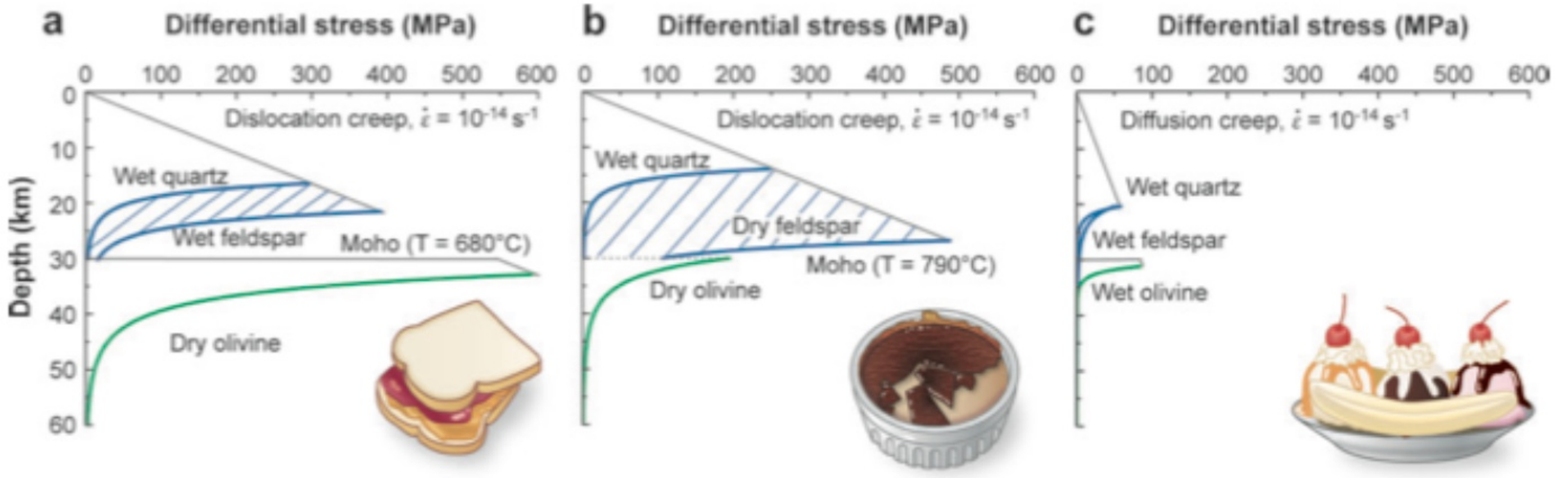
Power Law Creep





M-D: Moho discontinuity. MLD: mid-lithosphere discontinuity. G-D: Gutenberg discontinuity. LAB: lithosphere-asthenosphere boundary.

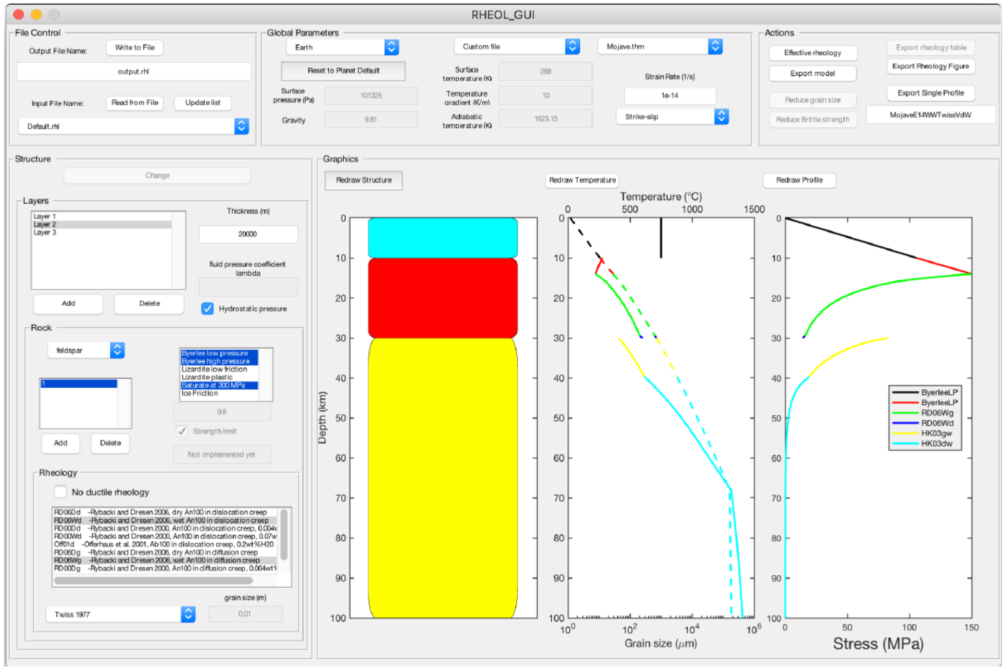
Strength of the Earth's Lithosphere



Burgmann and Dresen, 2008

AN INTEGRATED TOOL FOR DESCRIBING THE RHEOLOGY OF LITHO-TECTONIC BLOCKS AND FAULT ZONES

Laurent Montesi



Output File Name: output.rhl

Input File Name: Default.rhl

Earth

Custom file

Mojave.thm

Surface pressure (Pa) 101325

Gravity 9.81

Surface temperature (K) 288

Temperature gradient (K/m) 10

Adiabatic temperature (K) 1623.15

Strain Rate (1/s) 1e-14

Strike-slip

MojaveE14WWTwissVdW

Layer 1
Layer 2
Layer 3

Thickness (m) 20000

fluid pressure coefficient lambda

☑ Hydrostatic pressure

feldspar

1

Byerlee low pressure
Byerlee high pressure
Lizardite low friction
Lizardite plastic
Saturate at 300 MPa
Ice Friction

0.6

☑ Strength limit

Not implemented yet

☐ No ductile rheology

RD06Dd -Rybacki and Dresen 2006, dry An100 in dislocation creep
RD06Wd -Rybacki and Dresen 2006, wet An100 in dislocation creep
RD00Dd -Rybacki and Dresen 2000, An100 in dislocation creep, 0.004w
RD00Wd -Rybacki and Dresen 2000, An100 in dislocation creep, 0.07w
Off01d -Offerhaus et al. 2001, Ab100 in dislocation creep, 0.2wt%H20
RD06Dg -Rybacki and Dresen 2006, dry An100 in diffusion creep
RD06Wg -Rybacki and Dresen 2006, wet An100 in diffusion creep
RD00Dg -Rybacki and Dresen 2000, An100 in diffusion creep, 0.004wt%

grain size (m) 0.01

Twiss 1977

- Complicated to import rheology into models
- **<u>Goal</u>**: Build RHEL_GUI for SCEC community models
- Matlab code
- Can easily explore model parameters and export visualizations and tables
- Exports figures as PDF file and a rheology table with integrated strength and strain rate
- Uses 2 prepopulated databases planet.mat and rock.mat for global parameters and structural parameters
- Was able to compute the effective rheology and strength profiles for a specific strain using the default stratigraphy with some slight changes and a custom temperature profile provided by Wayne Thatcher