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

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1. INTRODUCTION

Rheology is a complex concept to incorporate in community models. Rheology may refer to the stress needed to deform under a certain set of conditions, which define the strength of that rock (Kohlstedt and Hansen, 2015). At its most basic level, rocks deform according to two regime: brittle or ductile. Brittle strength depends on pressure but, to first order, is independent on temperature and strain rate. The opposite is true in the ductile regime. Brittle strength is often described by Byerlee's law (Byerlee, 1978), which prescribes a universal strength regardless of rock type, with serpentine being a notable exception to the law (Reinen et al., 1994; Amiguet et al., 2014). Ductile strength, on the other hand, depends dramatically on rock type and grain size, water fugacity, and probably oxygen fugacity (Evans et al., 1995). Many formulations have been proposed based on laboratory data (Burgmann and Dresen, 2008). Because of these various dependencies, rheology in the lithosphere cannot exist independently from information on rock type (stratification), chemical environment, temperature. Some of this information will be available from other SCEC community models, such as the Geological Framework (GF) and the Community Thermal Model (CTM).

As a result from this project, I am contributing to the SCEC community RHEOL_GUI, a matlab-based graphical user interface that serves two purposes. Given a stratigraphic model and a temperature profile, RHEOL_GUI:

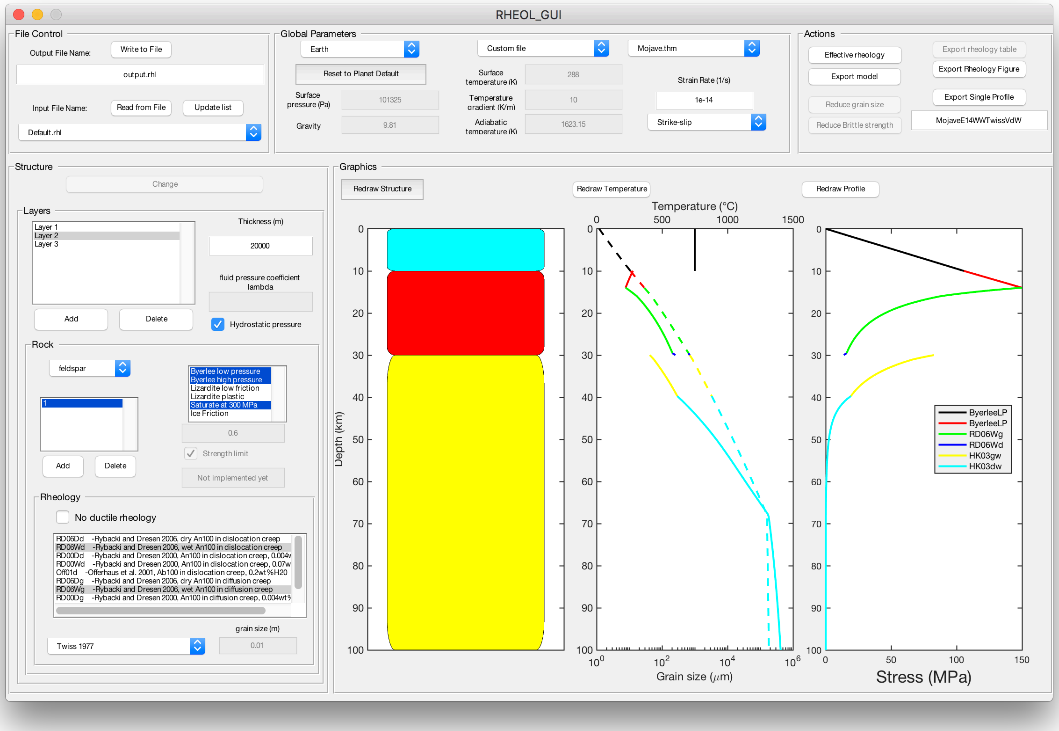
1) Determine which rheology dominates over each depth range for a given strain rate (Brace and Kohlstedt, 1980) and visualize the profile of strength through the lithosphere
2) Integrate strength for various strain rate for provide an effective rheology relevant for the lithosphere as a whole.

Having this tool available as a graphical user interface (GUI) allows for the rapid exploration of model parameters, such as:

- The specific flow laws taken from the literature describe ductile creep.
- The grain size in each stratigraphic layer
- the strain rate applied on the lithosphere
- The specific rock types at each depth
- The thickness of each strata
- The depth to which the strength profile is integrated
- The temperature profile through the lithosphere

RHEOL_GUI can also export predefined visualizations and a table summarizing the effective rheology. The strength profile for the current strain rate can be exported in the form of a matlab structure that contains information on stratigraphic layers and rheological sublayers, their depth limits and the associated strain rate or stress functions. The stratigraphic information can stored as a human-readable *.rhl* file that, in principle, can be used to automatically load information provided by external models. That functionality is not yet fully implemented, as the GF is not yet widely available. It is possible, however, to convert CTM excel spreadsheet into a thermal profile *.thm* file for import into RHEOL_GUI using the following matlab function (not distributed with RHEOL_GUI)

```
function CTM2THM(CTMname);
% convert CTM excel spreadsheet to thm file for use in RHEOL_GUI
[CTMpath,CTMroot,CTMext] = fileparts(CTMname); % used to change extension
A=xlsread(CTMname);
A(:,1)=A(:,1)*1000; %convert to meters
save(sprintf('%s.thm',CTMroot),'A','-ascii');
```


RHEOL_GUI

File Control
Output File Name: output.rhl
Input File Name: Default.rhl

Global Parameters
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

Actions
MojaveE14WWTwissVdW

Structure
Layers: Layer 1, Layer 2, Layer 3
Thickness (m): 20000
fluid pressure coefficient lambda
☑ Hydrostatic pressure

Rock: 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

Rheology
☐ 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%
Twiss 1977
grain size (m): 0.01

Figure 1: Screenshot of the RHEOL_GUI interface for an example structure of a 30 km crust (10 km quartz, 20 km feldspar) over a 70 km mantle, with an example temperature profile coming from CTM.

2. USING RHEOL_GUI

1) Installation and startup

RHEOL_GUI is a [Matlab](https://www.mathworks.com)-based [graphical user interface](https://en.wikipedia.org/wiki/Graphical_user_interface) built using GUIDE (Figure 1). The package (version 1.0) is available at https://github.com/montesi/RHEOL_GUI/. To install and run RHEOL_GUI:

1) Downloading the package. To do that, either click on the green *clone or download* button on GitHub or, if git is installed on your computer, type `git clone https://github.com/montesi/RHEOL_GUI` in a terminal or console window
2) Start Matlab
3) Type in the command window: `>> RHEOL_GUI`

The utility need access to two matlab binaries provided with the package: `planet.mat` and `rock.mat`. They contain prepopulated databases of planet data (default gravity, surface pressure, surface temperature, interior temperature, surface geotherm) and rock information (density, published flow laws). The GUI also uses several attendant matlab scripts provided with the distribution. Default parameter file `Default.rhl` and `Default.thm` is also provided.

2) Naming conventions

- Files describing the input stratigraphy use extension `.rhl`. (standing for RHeoLogy) This extension is also used by default to save modified stratigraphy files. These file are simple human-readable text files. To avoid formatting issues, it is recommended to use emacs, nano, vim, or notepad to edit these files.
- Files containing a custom temperature profile use extension `.thm`. (standing for THerMal). They are human-readable text file with two columns: depth (in meter) and temperature (in °C)
- Figures are exported as PDF
- The effective rheology is exported as a `.rht` file (standing for Rheology Table). It is a simple human-readable text file with two columns: strain rate (in s^{-1}) and integrated strength (in MPa·km)

3) Description of the GUI

There are several sections to the GUI

File control

Includes the name of available `.rhl` files. Use this section to save work as a new `.rhl` file.

Global parameters

Control the environment of the model: gravity, temperature, strain rate, and whether the tectonic regime is extension (assumed to be uniform with depth), compression, or strike-slip faulting. Default values are taken from `planet.mat`

Options for temperature include a pre-programmed analytical formulae (linear or error function) or custom file: table of depth - temperature pairs.

Structure

The model contains a stratigraphy with an arbitrary number of layer (see *Structure* drawing in the GUI). Each layer in the structure is characterized by

- A thickness. Changes in thickness are accommodated by pushing material downward.
- An assumption on pore fluid pressure (hydrostatic or a fraction λ of lithostatic).
- A rock type (at this point, mixtures are not implemented). Each rock type has a unique color in the **Structure** drawing. The density of each rock is taken from the `rock.mat`.

The GUI allows adding a layer (duplicating the next layer down for initialization) or deleting the current layer.

For each rock included in the layer, you need to select at least one rheology. You can select as many rheologies as you want (hold the control key or command key for multiple selections)

- Brittle strength
    - Byerlee's law
    - Laws for serpentine, also corresponding to a reduced coefficient of friction of 0.25 (Reiner et al., 1994) or a plastic limit of 100 MPa (Amiguet et al., 2014)
    - Brittle laws for ice
- Ductile rheologies
    - A series of strain-rate dependent flow laws. Some have pressure, grain size, and/or water fugacity dependence. Water fugacity is assumed to be at saturation.
    - If you don't want any ductile rheology, check the box above the list of rheologies.
- Grain size

  - You can select a predefined piezometer
  - By selecting *input*, grain size is fixed to value specified in the input text box.

If you change any parameters, you need to push the button *Changes UNSAVED* at the top of the structure section to record your modifications. When working with several layers, you must save each layer before switching to the next one, or the parameters actually used are probably not the ones you intended.

Actions

Several actions are predefined:

- *Single profile*: Identify the rheology that predicts the lowest strength at each depth (in practice the structural layer is divided in rheological layers where a single rheology dominates). Plots the strength profile in the *Strength* figure, the temperature (dashed) and grain size (solid) in the *Temperature* figure. Run by default after saving a change in the structure
- *Export Model*: Save the matlab structure *model* as a matlab binary *root*.mat. *model* contains information for each structural layers and each rheological sublayer. The root is specified in the text input window and is the same as the `.rhl` file per default.
- *Export Single Profile*: prints a PDF figures with the temperature, grain size, and strength profile. The file name is *root*_profile.pdf.
- *Effective rheology*: Loops over strain rate from 10^{-20} to 10^{-8} s^{-1}. For each strain rate, the structure is divided in rheological sublayers and the strength is integrated with depth. The effective rheology is defined as the (numerical) relation between strain rate and integrated strength, plotted in the *Strength* figure.
  - After the effective rheology is calculated, you can export it as a figure *root*_rheology.pdf or and ascii table *root*_rheology.rht.

3. DEMONSTRATION

As an example, I loaded the stratigraphy in Default.rhl but increases the thickness of layer 3 (mantle) to 70 km. I changed mantle rheology to the wet variants of the dislocation creep and diffusion creep flow laws of Hirth and Kohlstedt (2004). I then loaded a custom temperature profile containing a 1D steady state CTM geotherm for the Mojave block, provided by Wayne Thatcher.

For this demonstration, I considered four alternative assumptions for the rheologies used: the lower crust can be wet or dry (using the corresponding diffusion creep and dislocation creep flow laws for Feldspar from Rybacki et al., 2006) and using either a fixed grain size of 2 cm or a piezometric relationship for the lower crust (Twiss, 1977) and the mantle (van der Wal et al., 1993). For each case, I compute the effective rheology (Figure 2) and show example strength profiles for a strain rate of 10^{-14} s^{-1} (Figure 3).

These calculation show that the effective rheology is highly non-linear The effective stress exponent $n \equiv \frac{d\ln(\dot{\varepsilon})}{d\ln(\sigma)}$ is generally larger than 10. This is because much the strength is accommodated by brittle failure (perfectly plastic). Even though ductile creep is active over the largest depth range, it contributes little to the total force required for motion of the lithosphere. Changes in the rheology dominating at each depth results in changes of slope in the integrated rheology. Grain size reduction and hydration of the lower crust both can change the strain rate (and therefore the viscosity) expected for a given stress by several orders of magnitude. This effect is important for regional scale modeling of the stress and deformation fields in Southern California (e.g., Bird, 2009).

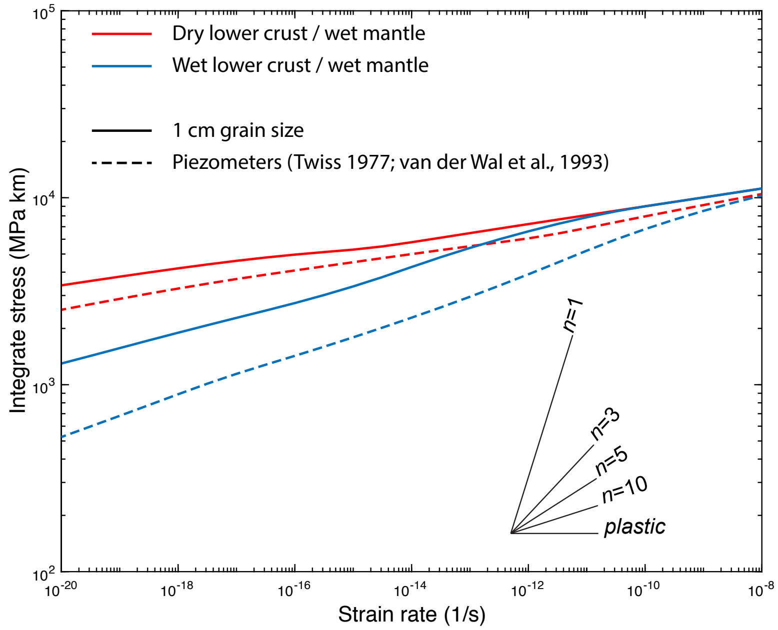


Figure 2: Example calculation of the effective rheology of the lithosphere, defined as a relation between integrated stress and strain rate for the stratigraphic structure as in Figure 1. Red lines assume a dry lower crust and blue lines a wet lower crust (flow laws of Rybacki et al., 2006) while the mantle is always assumed to be wet (flow laws of Hirth and Kohlstedt, 2004). The 10 km quartz layer is always brittle in this model. Dashed lines assume that grain size obeys the piezometer of Twiss (1977) in the lower crust and van der Wal et al. (1993) in the mantle, while the solid lines assume a grain size of 1cm throughout the lower crust and upper mantle. Effective rheologies are highly nonlinear, with an apparent stress exponent between 10 and 30. Therefore, a small change in applied force results in a large change in strain rate. Grain size reduction, and especially hydration of the lower crust can significantly increase strain rate.

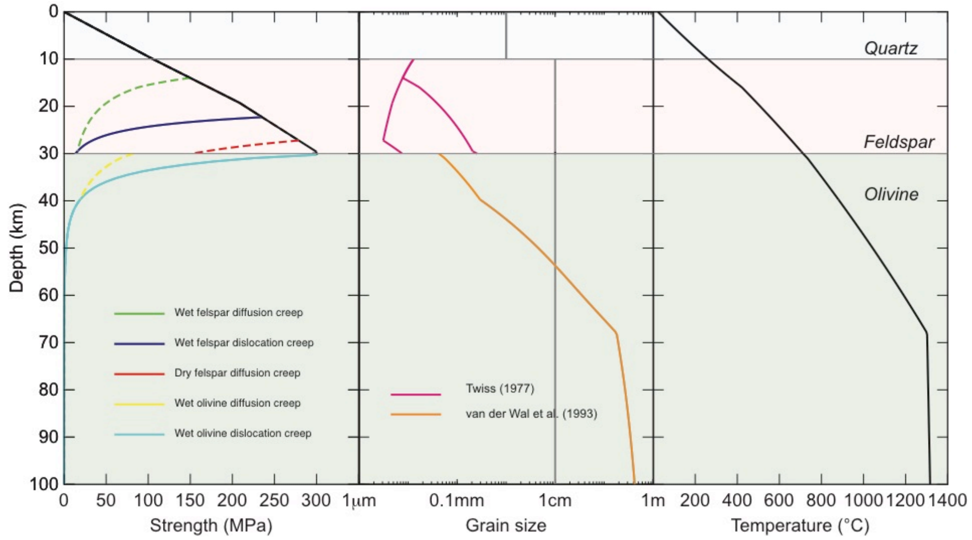


Figure 3: Strength envelopes, grain size, and temperature for the four rheological models associated with Figure 2 but for a given strain rate of 10^{-14} s^{-1}. We see that hydration changes the lower crust behavior from brittle to ductile while grain size reduction reduces the maximum strength of the lithospheric profile where the lithosphere is ductile. Grain sizes are comparable to shear zone samples. The temperature profile was taken from the CTM.

REFERENCES

Amiguet , E., B. van de Moortèle, P. Cordier, N. Hilairet, and B. Reynard (2014), Defomation mechanisms and rheology serperntine in experiments and in natureLimits on lithospheric stress imposed by laboratory experiments, *J. Geophys. Res.*, 119, 4640-4655, doi:10.1002/2013JB010791.

Bird, P. (2009), Long-term fault slip rates, distributed deformation rates, and forecast of seismicity in the western United States from joint fitting of community geologic, geodetic, and stress direction data sets*, J. Geophys. Res.*, 114, B11403, doi:10.1029/2009JB006317.

Brace, W. F., and D. L. Kohlstedt (1980), Limits on lithospheric stress imposed by laboratory experiments, *J. Geophys. Res.*, 85, 6248-6252.

Bürgmann, R., and G. Dresen, (2008), Rheology of the Lower Crust and Upper Mantle: Evidence from Rock Mechanics, Geodesy, and Field Observations: *Annual Review of Earth and Planetary Sciences*, 36, 531-567.

Byerlee, J., (1978), Friction of rocks, *Pure Appl. Geophys.*, 116, 615-626, doi:10.1007/BF00876528

Evans, B., and D. L. Kohlstedt, (1995), Rheology of Rocks, in *Rock Physics & Phase Relations: A Handbook of Physical Constants* (ed T. J. Ahrens), American Geophysical Union, Washington, D. C.. doi: 10.1029/RF003p0148

Hirth, G. and D. Kohlstedt (2004) Rheology of the Upper Mantle and the Mantle Wedge: A View from the Experimentalists, in *Inside the Subduction Factory* (ed J. Eiler), American Geophysical Union, Washington, D. C., doi:10.1029/138GM06.

Kohlstedt, D.L., and L.B. Hansen (2015) Constitutive equations, rheological behavior, and viscosity of rocks, *Treatise of Geophysics, 2nd edition*, 2, 441-472.

Reinen, L. A., J. D. Weeks, and T. E. Tullis (1994), The frictional behavior of lizardite and antigorite serpentinites: experiments, constitutive models, and implications for natural faults, *Pure Appl. Geophys*., 143, 317–358.

Rybacki, E., M. Gottschalk, R. Wirth, and G. Dresen (2006), Influence of water fugacity and activation volume on the flow properties of fine-grained anorthite aggregates, *J. Geophys. Res.*, 111, B03203, doi:10.1029/2005JB003663.

Twiss, R. J. (1977), Theory and applicability of a recrystallized grain size paleopiezometer, *Pure and Applied Geophysics*., 115, 227 – 244.

Van der Wal, D., P. Chopra, M. Drury, and J. D. Fitz Gerald (1993), Relationships between dynamically recrystallized grain size and deformation conditions in experimentally deformed olivine rocks, *Geophys. Res. Lett.*, 20, 1479–1481, doi:10.1029/93GL01382.