SCEC award #118062196: Numerical modeling of weakening and strain localization on faults experiencing multi-physical mechanisms

Duration: 2019-2020
Investigators: Hadrien Rattez, Manolis Veveakis
Institution: Duke University

FINAL REPORT

The main goal of the SCEC award #118062196 was to investigate the role of different weakening mechanisms on the phenomenon of strain localization inside fault zones and the influence of each of them on the frictional response during seismic slip. It was done by developing a rate-and-state (visco-plastic) model encompassing internal lengths from multi-physical couplings, to provide qualitative assessments on the parameters dominating a fault's response. The model was implemented in a numerical code, allowing quantifying the role of each of these mechanisms during the seismic slip process. In particular, we aimed at providing scaling laws with respect of the role of each process in seismic slip sequence. The framework was indeed implemented, and in addition to the numerical results, experimental results were obtained to accompany some of the main conclusions of this work. The main scientific outcomes of the award were the following, listed by tasks:

A. Importance of chemo-mechanical couplings on faults' friction experiments. The project started by developing a visco-plastic approach accounting for thermo-chemo-mechanical couplings. As a first step, the results of the model in terms of steady states have been compared to experimental observations of friction experiments conducted over the full range of velocities experienced by a fault during seismic events. A drastic decrease of the friction has been observed for velocities closed to the maximum slip velocity independently of the material considered (Di Toro et al. 2011), but the physical mechanisms accompanying this rapid weakening are different for each rock type. The common feature of the weakening mechanisms inferred from microstructural observations is a thermal weakening and a thermally activated phase transformation like mineral decomposition (Veveakis et al. 2010) nanoparticle lubrication (Han et al. 2007), or melting (Di Toro, Pennacchioni, and Teza 2005).

By introducing flash heating and weak phase production in the visco-plastic law, the thermo-chemo-mechanical model was able to reconcile experimental results of all available rock types (Figure 1). Through this process, we identified the main chemical transformations driving the mechanical behavior of each material and constrain the parameters of the model to reproduce the experimental results (Rattez and Veveakis 2020). It was shown that the dominant parameters influencing the shearing resistance of laboratory-scale faults are: 1) the sensitivity of the mechanical response (expressed through the viscosity of the visco-plastic law) to the weak phase production, which affects directly the friction coefficient of the material when weak phases are being produced during shearing at high velocities, therefore causing the seismic slip; 2) the thickness of the shear-band (gouge), which controls the amount of mechanical work that is dissipated in heat, verifying that thinner gouges are admitting higher temperatures and being more prone to chemo-mechanical softening(Rice 2006).

After identifying the dominant parameters of the model, we performed mechanical tests focusing on the observation of the shear band thickness for a granular material presenting a constant (in time) grain size distribution. The main scope of this work was to identify which parameter of the grain size distribution controls the shear band thickness, so that one of the dominant parameters influencing the response of the model (the shear band thickness) can be further constrained.

Journal publications from this task: Rattez, H., Veveakis, M. Weak phases production and heat generation control fault friction during seismic slip. *Nature Communications*, 11, 350 (2020).

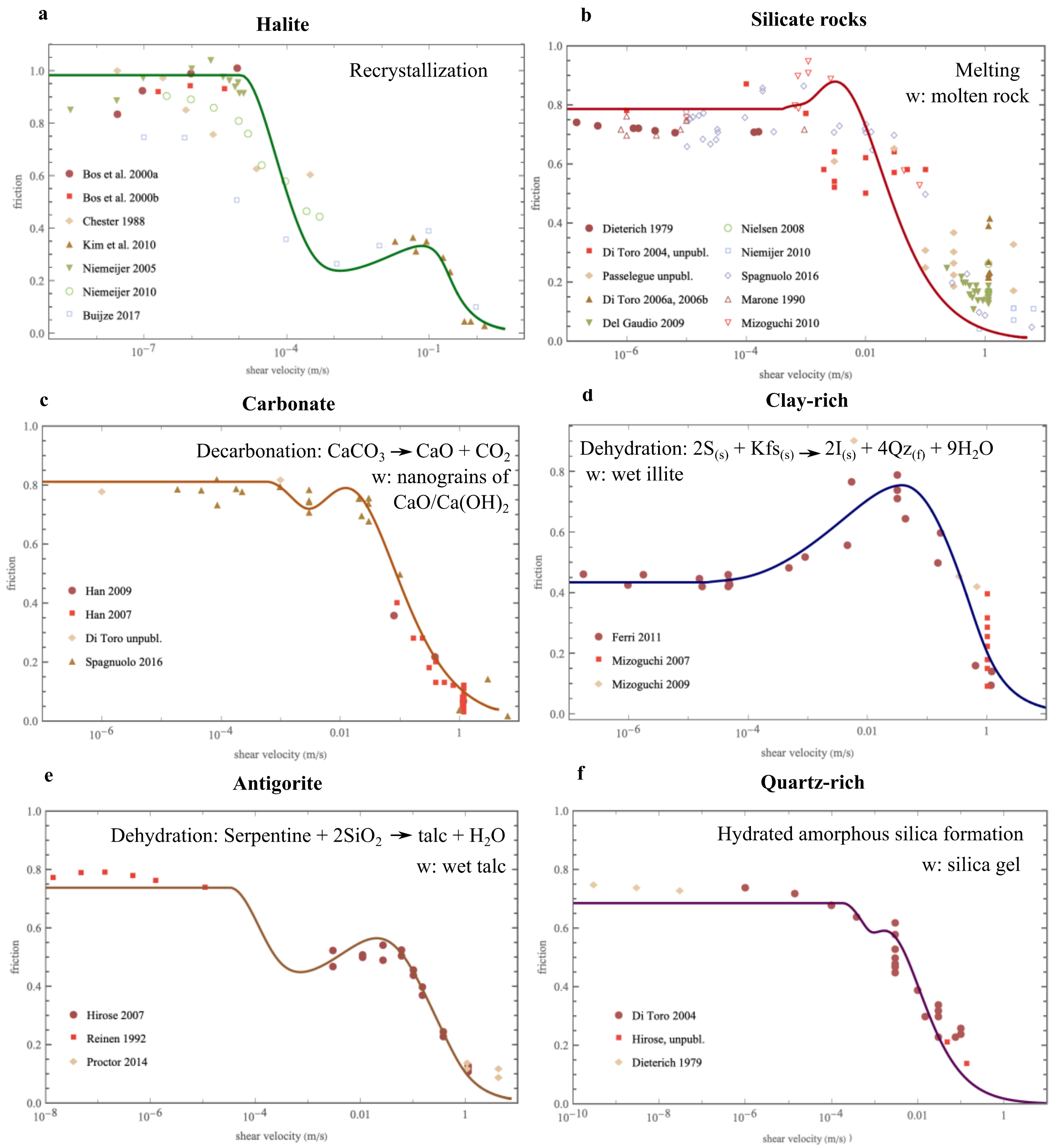

Figure 1. Model (solid lines) results plotted against experimental data from the literature (dots) for different materials. Figure from (Rattez and Veveakis 2020) *and data retrieved from* (Buijze et al. 2017; Ferri et al. 2011; Hirose and Bystricky 2007; Spagnuolo et al. 2016; Di Toro et al. 2011; Di Toro, Goldsby, and Tullis 2004).

B. Effect of grain size on shear band thickness. We have conducted an experimental study on the influence of the microstructure size on the shear band thickness and in particular the impact of different particle size distributions. Specifically, the aim of the work was to identify the parameters controlling the shear band thickness, and complement previous studies focusing on sands presenting a narrow distribution compared to the distributions observed, for example, in fault zones (Rice 2006).

To this end, triaxial experiments have been conducted on granular materials presenting uniform, graded and fractal particle distributions in order to investigate how the broadness of the distribution affects the phenomenon of strain localization. The shear band thickness evolution was assessed by Digital Image Correlation using 3 cameras placed at different angles around the triaxial cell. From the field of deformation, a gaussian distribution has enabled to fit the data satisfactorily and determine the shear band width evolution (Figure 2a-b).

The shear band thickness evolves soon after peak stress, exhibiting a rapid decrease until reaching a residual value (Figure 2c), which depends only on the mean grain size D_{50} (Figure 2d). The ratio of the residual thickness to the mean grain size exhibits a value between 9 and 20 and this ratio is not influenced by a broader distribution (Figure 2d).

This analysis enables to show that D_{50} is the information to insert into a constitutive law that aims at capturing the strain localization phenomenon. However, since the average grain size is known to evolve during seismic slip (Einav 2007; Platt, Rudnicki, and Rice 2014; Sammis and Ben-Zion 2008), it also raises the question "*how would grain size evolution –and therefore evolution of the shear band thickness- affect seismic slip?"*. This question was attempted to be answered in the next task.

Journal publications from this task: Rattez H., et al. ***Geotechnical Testing Journal***, *submitted*; Rattez H., et al. ***Geotechnique***, *submitted*

C. Evolving grain-size/shear band thickness. The next step was to investigate the effect of different grain size distributions on the rate dependency of a granular material. To do so, velocity stepping experiments have been conducted for a synthetic calcite gouge with an annular shear apparatus and observe how the rate and state parameters are modified by different microstructures. To alter the microstructure, dissolution by an acid before conducting the mechanical test has enabled us to modify the particle size distribution of the gouge material and the roughness of the particles. It induces an increase of the mean grain diameter and a decrease of the fractal number. These modifications are due to the removal of the small particles from the grain size distribution, in the same way that grain crushing makes the fractal number increase and the mean grain size to decrease due to the creation of more small particles.

We have observed a more pronounced velocity weakening of the carbonate gouge for specimens subjected to dissolution in the case of dry experiments and a less pronounced for saturated experiments. These experiments have enabled us to examine the importance of an initial microstructure on the rate dependency of the material. However, in these experiments many mechanisms are triggered (pressure solution(B. a. Verberne et al. 2013; Zhang and Spiers 2005), grain breakage (Karimpour and Lade 2010), water lubrication(B. A. Verberne et al. 2014)) that make the microstructure evolve and affect the rate dependency. Thus, these tests cannot be modelled by a constant grain size framework and a more thorough study looking also at the evolution of the microstructure is required.

Journal publications from this task: Rattez H., et al. ***Geomechanics for Energy and the Environment***, *submitted*.

D. Developing a model accounting for (mechanical) internal length. The visco-plastic model with multiphysical couplings has been implemented in the Moose finite element framework and is currently being tested for the problem of an infinite layer in shear representing a fault. The model was qualitatively juxtaposed against the results of the triaxial experiments performed with a constant (in time) grain size distribution to reproduce the stress-strain behavior and the shear band thickness. Preliminary results are shown in Figure 3 and show that this model enable to obtain a shear band size that is approximately ten times the internal length and is therefore expected to reproduce the observations of the triaxial tests (Figure 2).

The next steps of this work involve constraining an evolution law for the grain size distribution and the mechanical parameters (elastic moduli, shear strength etc) during seismic slip. As already discussed, evolution of the grain size will also trigger an evolving shear-band (gouge) thickness, which in turn will drastically affect the response of the fault against thermally driven multi-physical mechanisms.

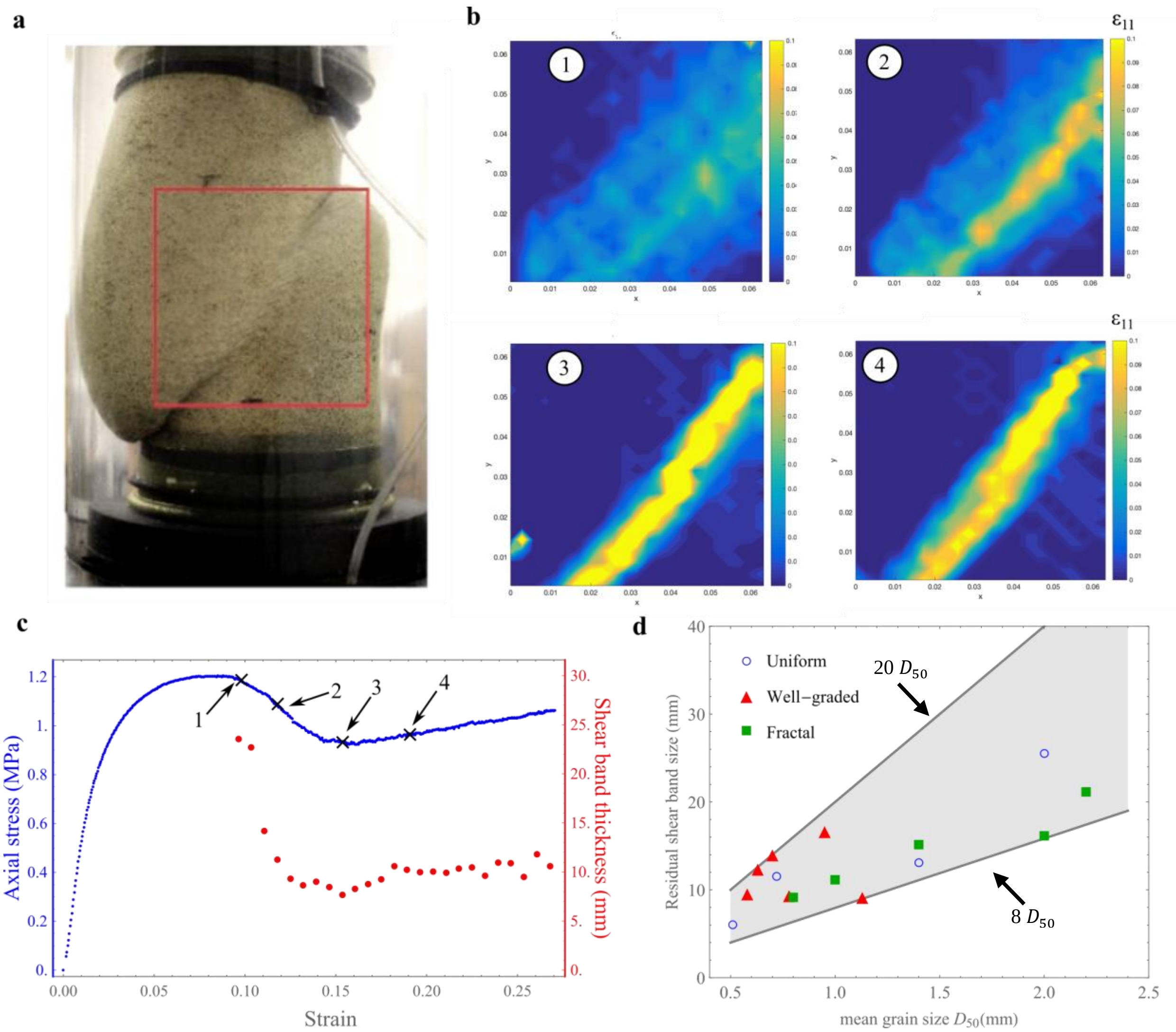

Figure 2. Example of mechanical behavior observed for a triaxial tests (300 kPa confinement) and results in terms of deformation at different stages with the apparent shear band (left). Residual shear band thickness for the different distributions as a function of the D_{50} (right).

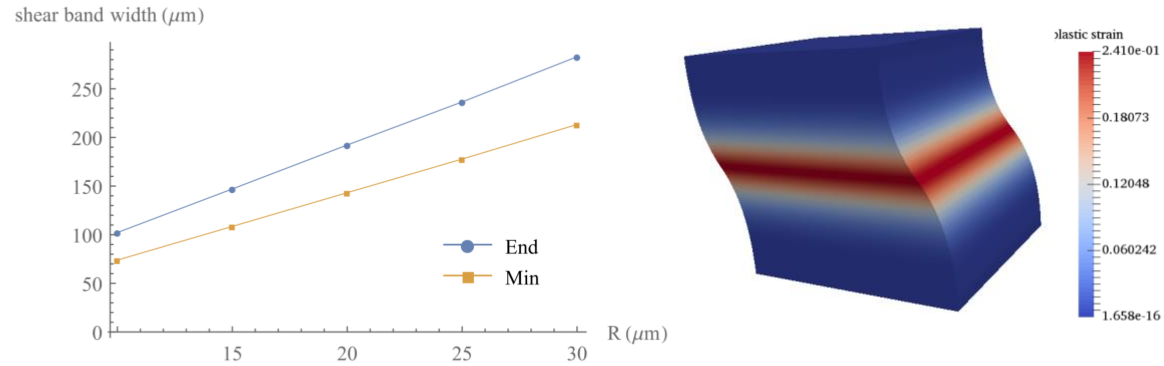

Figure 3. Results from the numerical simulations of an infinite sheared layer (left) for the effect of the internal length of the model on the minimum and residual shear band thickness (left). Example of simulation with the localization of the plastic deformation (right).

Relevant publications produced during SCEC AWARD #118062196 (link to preprint is provided, when publisher allows it):

A. Journal Publications:

1. Rattez, H., Veveakis, M., 2020. Weak phases production and heat generation control fault friction during seismic slip. ***Nat Commun* 11,** 350 https://doi.org/10.1038/s41467-019-14252-5
2. Rattez H., Disidoro F, J. Sulem, M. Veveakis, 2019. Effect of carbonate dissolution on the reactivation of faults. ***Geomechanics for Energy and the Environment***, *submitted, doi: https://doi.org/10.31223/osf.io/b8xuh*
3. Rattez H., Y. Shi, A. Sac-Morane, T. Klaeylé, B. Mielniczuk and M. Veveakis. Digital image correlation applied to the evaluation of the shear band thickness evolution during triaxial tests of sands. ***Geotechnical Testing Journal***, *submitted*.
4. Rattez H., Y. Shi, A. Sac-Morane, T. Klaeylé, B. Mielniczuk and M. Veveakis. Effect of particle size distribution on the shear band thickness evolution in sand during triaxial experiments. ***Geotechnique***, *submitted*

B. Conference Proceedings (Refereed):

1. H Rattez, A Sac, T Klaeylé, B Mielniczuk, M Veveakis (2020). Observation of strain localization by Digital Image Correlation to study the influence of particle size distribution, 54th US Rock Mechanics/Geomechanics Symposium, Golden, Colorado, USA, 28 June-1 July 2020
2. H Rattez, and M Veveakis (2020). A thermo-chemo-mechanical model for fault friction, 54th US Rock Mechanics/Geomechanics Symposium, Golden, Colorado, USA, 28 June-1 July 2020
3. H Rattez, A Sac, T Klaeylé, B Mielniczuk, M Veveakis (2019). Digital Image Correlation and numerical simulations to study the influence of grain size distribution on strain localization, AGU Fall Meeting 2019, San Francisco
4. H Rattez, and M Veveakis (2019). Weak phases production controls fault friction and heat generated during seismic slip, AGU Fall Meeting 2019, San Francisco

References

Buijze, Loes et al. 2017. "Friction Properties and Deformation Mechanisms of Halite(-Mica) Gouges from Low to High Sliding Velocities." *Earth and Planetary Science Letters* 458: 107–19. http://dx.doi.org/10.1016/j.epsl.2016.09.059.

Einav, Itai. 2007. "Breakage Mechanics—Part I: Theory." *Journal of the Mechanics and Physics of Solids* 55(6): 1274–97.

Ferri, Fabio et al. 2011. "Low- to High-Velocity Frictional Properties of the Clay-Rich Gouges from the Slipping Zone of the 1963 Vaiont Slide, Northern Italy." *Journal of Geophysical Research: Solid Earth* 116(9): 1–17.

Han, Raehee et al. 2007. "Ultralow Friction of Carbonate Faults Caused by Thermal Decomposition." *Science* 316(5826): 878–81.

Hirose, Takehiro, and Misha Bystricky. 2007. "Extreme Dynamic Weakening of Faults during Dehydration by Coseismic Shear Heating." *Geophysical Research Letters* 34(14): 10–14.

Karimpour, Hamid, and Poul V. Lade. 2010. "Time Effects Relate to Crushing in Sand." *Journal of Geotechnical and Geoenvironmental Engineering* 136(9): 1209–19.

Platt, John D, John W. Rudnicki, and James R. Rice. 2014. "Stability and Localization of Rapid Shear in Fluid-Saturated Fault Gouge : 2 . Localized Zone Width and Strength Evolution." *Journal of Geophysical Research: Solid Earth*.

Rattez, Hadrien, and Manolis Veveakis. 2020. "Weak Phases Production and Heat Generation Control Fault Friction during Seismic Slip." *Nature Communications* 11(350).

Rice, James R. 2006. "Heating and Weakening of Faults during Earthquake Slip." *Journal of Geophysical Research: Solid Earth* 111(5).

Sammis, Charles G., and Yehuda Ben-Zion. 2008. "Mechanics of Grain-Size Reduction in Fault Zones." *Journal of Geophysical Research: Solid Earth* 113(2): 1–12.

Spagnuolo, E., S. Nielsen, M. Violay, and Giulio Di Toro. 2016. "An Empirically Based Steady State Friction Law and Implications for Fault Stability." *Geophysical Research Letters* 43(7): 3263–71.

Di Toro, Giulio et al. 2011. "Fault Lubrication during Earthquakes." *Nature* 471(7339): 494–98. http://www.nature.com/doifinder/10.1038/nature09838.

Di Toro, Giulio, David L. Goldsby, and Terry E. Tullis. 2004. "Friction Falls towards Zero in Quartz Rock as Slip Velocity Approaches Seismic Rates." *Nature* 427(Jan 2004): 436–39.

Di Toro, Giulio, Giorgio Pennacchioni, and Giordano Teza. 2005. "Can Pseudotachylytes Be Used to Infer Earthquake Source Parameters? An Example of Limitations in the Study of Exhumed Faults." *Tectonophysics* 402(1-4 SPEC. ISS): 3–20.

Verberne, B. a. et al. 2013. "Frictional Properties and Microstructure of Calcite-Rich Fault Gouges Sheared at Sub-Seismic Sliding Velocities." *Pure and Applied Geophysics*. http://link.springer.com/10.1007/s00024-013-0760-0 (April 24, 2014).

Verberne, B. A. et al. 2014. "Frictional Properties and Microstructure of Calcite-Rich Fault Gouges Sheared at Sub-Seismic Sliding Velocities." *Pure and Applied Geophysics* 171(10): 2617–40.

Veveakis, E et al. 2010. "Chemical Reaction Capping of Thermal Instabilities during Shear of Frictional Faults." *Journal of the Mechanics and Physics of Solids* 58(9): 1175–94. http://www.sciencedirect.com/science/article/pii/S0022509610001262 (September 21, 2015).

Zhang, X., and C. J. Spiers. 2005. "Compaction of Granular Calcite by Pressure Solution at Room Temperature and Effects of Pore Fluid Chemistry." *International Journal of Rock Mechanics and Mining Sciences* 42: 950–60.