SCEC 2011 Progress Report

"Thermally Driven Shear Localization in Fault Zones"
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A: Summary

We use thermo-hydro-mechanical modeling to investigate strain localization in fluid-saturated gouge materials, driven by thermal processes during rapid shear. Rice and Rudnicki (*in preparation*) considered a system with thermal pressurization and rate-strengthening friction, finding a critical width above which uniform shearing was unstable. They found that a balance between thermal pressurization, frictional-strengthening and diffusion set this critical width. To begin we test the results of this analysis, finding excellent agreement. We then extend their simple model to account for two additional effects, inertia and dilatancy of the gouge material. Using a combination of analytic results and numerical solutions we determine that both effects exert a negligible drag on strain localization at seismic depths, but may influence high-velocity friction experiments that are performed at much lower compressive stresses. Using the path-averaged parameters from Rice [2006] and Rempel and Rice [2006] for the gouge material, and frictional data from low strain experiments (Blanpied et al. [1998]) we predict a localized zone width of 5-40 μm, for a slip rate of 1 ms^{-1} and for ambient temperature and effective normal stress conditions intended to represent a centroidal depth (~ 7 km) of a typical crustal seismogenic zone.

Recent observations (e.g., Brantut et al. [2008]) have shown that thermal decomposition of fault materials may occur during rapid shear. Subsequent modeling (Sulem and Famin [2009], Brantut et al. [2010]) has shown that these endothermic reactions can cap the maximum temperature rise and generate large pore pressures. We investigated how these effects could alter thermally driven strain localization described above. Performing a linear stability analysis we find a critical width as a function of ambient fault temperatures. At low temperatures, when the reaction rate is very small, we recover the prediction of Rice and Rudnicki. However, at high temperature where the reaction is dominant, we see significant additional strain localization. Using the same parameters as before, and the parameters from Sulem and Famin [2009] to model calcite decarbonation, we predict a localized zone width of 2-6 μm, for a slip rate of 1 ms^{-1}.

B: Technical report

1. Localization driven by thermal pressurization

We consider one-dimensional shearing of a fluid-saturated gouge material. Appealing to conservation of energy, pore fluid and momentum (here reduced to equilibrium) we write

$$\frac{\partial \tau}{\partial y} = 0, \quad \frac{\partial \sigma_n}{\partial y} = 0, \quad \tau = f \times (\sigma_n - p),$$

$$\frac{\partial T}{\partial t} = \frac{\tau \dot{\gamma}}{\rho c} + \alpha_{th} \frac{\partial^2 T}{\partial y^2},$$

$$\frac{\partial p}{\partial t} = \Lambda \frac{\partial T}{\partial t} + \alpha_{hy} \frac{\partial^2 p}{\partial y^2}.$$

where σ_n is constant in time. The independent variables are the time t, and fault normal coordinate y, and we solve for the pore pressure, temperature, shear stress, and shear strain. Here we have used the fact that, as commented in Rice [2006], inertial effects are expected to be negligible during seismic events due to the short lengths across which hydraulic and thermal diffusion act. Assuming inertia is unimportant, Rice [2006] also commented that for a constant friction coefficient f, only two types of deformation are allowed, homogeneous shear, and slip on a plane. When the rate-dependence of friction is accounted for, the deformation can localize to a zone of finite width. Extrapolating data taken from low strain rate experiments we choose the steady state friction law,

$$f(\dot{\gamma}) = f_0 + (a-b)\log\left(\frac{\dot{\gamma}}{\gamma_0}\right),$$

where f_0 is the friction coefficient at a reference strain rate, and $(a - b)$ quantifies the rate-dependence of the friction. Previously, Rice and Rudnicki analyzed the stability of the uniform shearing solution presented in Lachenbruch [1980],

$$\tau = \tau_0 \exp\left(-H\dot{\gamma}_0 t\right) \quad , \quad H = \frac{f_0 \Lambda}{\rho c}$$

where τ_0 is the initial shear strength. They found the critical width, above which uniform shearing is unstable,

$$W = \pi^2 \left(\frac{\alpha_{hy} + \alpha_{th}}{HV(z+2)}\right) \quad , \quad z = \frac{f_0}{a-b}$$

We tested these results using numerical simulations, finding excellent initial agreement with the linear stability analysis. Our simulations also let us investigate the role of nonlinear effects, and we find that the exponential growth predicted by Rice and Rudnicki continues until hydraulic and thermal diffusion cap the maximum strain rate.

The analysis of Rice and Rudnicki can be extended to test the importance of other physical effects. When dilatancy is accounted for, with dilatancy modeled as in Segall and Rice [1995], the linear stability can no longer be solved by the classical criterion of the initial growth or decay of an initial perturbation. However, using a frozen coefficient method we can make some predictions, finding that dilatancy retards the initial growth compared with frictional strengthening alone. Furthermore, as thermal pressurization weakens the layer, the effects of dilatancy become more important and can stabilize initially unstable perturbations. Figure 1 shows solutions with and without dilatancy. We clearly see the initial exponential growth for strengthening-only solutions predicted by Rice and Rudnicki, diffusion then capping these solutions to a finite maximum strain rate, and finally the effects of dilatancy significantly limiting strain rate increases. Having quantified the effects of dilatancy we now comment on its role in practical systems. We find that dilatancy produces a negligible drag on localization during seismic events, since the large normal compressive stresses suppress dilatancy. However, in high-velocity friction experiments performed at much lower normal stresses dilatancy may double the observed localized zone width when compared with seismic events. A final investigation was performed to test the importance of inertia in this system, indicating that, as suggested in Rice [2006], inertia is unimportant to it during seismic events. However, we find that some high-velocity friction experiments performed at relatively high slip rates and low normal stresses may be dominated by inertia, and not accurately reproduce seismic conditions.

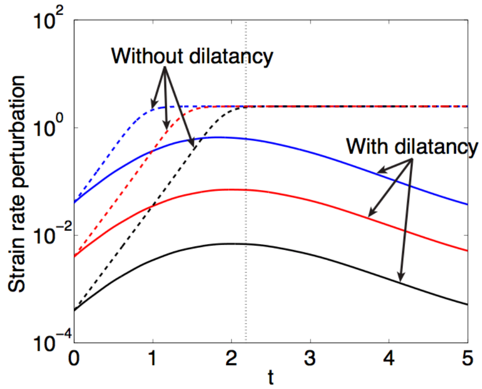

Figure 1, A plot showing the strain rate perturbation versus time for strengthening-only and dilatancy calculations. The solutions with no dilatancy grow exponentially, as predicted by Rice and Rudnicki, until diffusion caps the growth. Dilatancy acts to suppress localization, stabilizing an initially unstable perturbation.

Next we investigated a more physically motivated system than the periodic boundary conditions analyzed by Rice and Rudnicki. Following Rempel and Rice [2006], we consider a finite thickness gouge layer, of width *h*, sheared between two undeformable half-spaces that can conduct heat and pore fluid. A diagram of this is shown in Figure 2. The same equations as before are used, with the strain rate set to zero in the undeformable material. Neglecting dilatancy, we find that the gouge material has an internal length scale, which the strain rate localizes to,

$$W \approx 9.4 \frac{a-b}{f_0} \frac{\rho c}{\Lambda f_0} \frac{\alpha_{hy} + 1.9\alpha_{th}}{V}$$

The form of this formula is almost identical in from to the linear stability results of Rice and Rudnicki, and clearly illustrates the physical balance between thermal pressurization and diffusion. When *h* is less than *W*, the deformation is stable and we observe uniform shearing. However, for *h* greater than *W*, the straining localizes dramatically within the gouge material. An example is shown in Figure 3. Here the

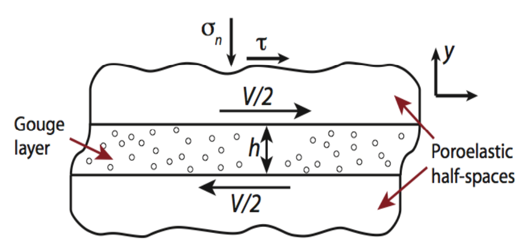

Figure 2, A sketch showing shear of a finite thickness gouge layer.

straining in a 2 mm wide gouge layer localizes to a zone approximately 58 μm wide. This is in good agreement with the linear stability prediction of 41 μm for the parameters assumed.

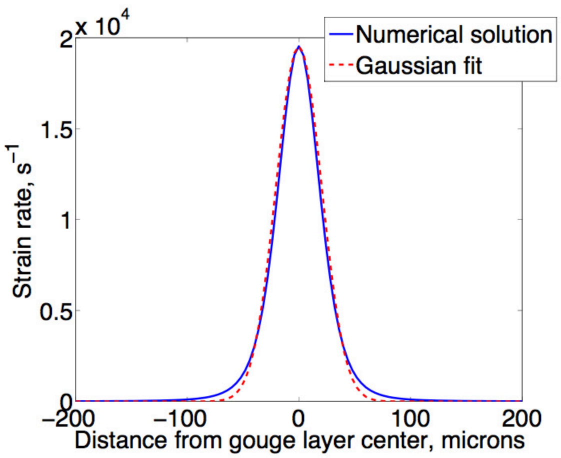

Figure 3, A Plot showing the straining profile for the damaged parameters in Rice [2006] and Rempel and Rice [2006], and a 2 mm wide gouge layer. The dotted red line shows the fit using Gaussian functions, allowing us to estimate a width of 58 μm. This is comparable to the linear stability prediction of 41 μm.

2. The importance of thermal decomposition

Recent observations from high-velocity friction experiments have indicated that thermal gouge materials, such as calcite or hydrated clays, may undergo thermal decomposition during seismic events. As mentioned before, these reactions typically act as temperature sinks, but pore pressure sources. Theoretical studies (Sulem and Famin [2009], Brantut et al. [2010]) have shown how these reactions could interact with pore pressure and temperature, finding that the endothermic nature of the reaction caps the maximum temperature rise and the pore pressure source leads to significant dynamic weakening, beyond that expected from thermal pressurization alone. We have been analyzing how thermal decomposition could interact with our localization framework.

Following Sulem and Famin [2009], we model thermal decomposition using the equations,

$$\frac{\partial T}{\partial t} = \frac{\tau\dot{\gamma}}{\rho c} + \alpha_{th}\frac{\partial^2 T}{\partial y^2} - E_r\frac{\partial \xi}{\partial t},$$

$$\frac{\partial p}{\partial t} = \Lambda\frac{\partial T}{\partial t} + \alpha_{hy}\frac{\partial^2 p}{\partial y^2} + P_r\frac{\partial \xi}{\partial t},$$

$$\frac{\partial \xi}{\partial t} = A(1-\xi)\exp\left(-\frac{Q}{RT}\right).$$

Here ξ is the reaction extent, E_r is the total temperature buffered, and P_r the total pore

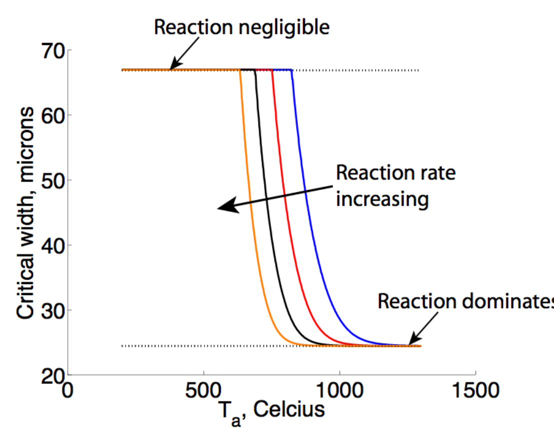

Figure 4, A plot showing the linear stability prediction for the critical width of shear localization in calcite as a function of ambient fault temperature. Note the two limits at extreme temperature values. Each line corresponds to an order of magnitude increase of the reaction rate constant A, and the limits are independent of A.

pressure rise if the reaction goes to completion. We assume the reaction rate is equal to the amount of reactant left, multiplied by a reaction rate with Arrhenius temperature dependence, an activation energy Q, and rate constant A. Neglecting reactant depletion and linearizing the reaction kinetic about an ambient fault temperature allows us to perform a linear stability analysis, finding a critical width above which uniform shearing is unstable. Tracking this as a function of the ambient fault temperature produces the results shown in Figure 4. At low temperatures, when the reaction is negligible, we recover the results from Rice and Rudnicki. However, at high temperatures, where the reaction dominates, we see a new balance between the reaction parameters and hydraulic diffusion. Linear stability predicts,

$$W = \frac{E_r \alpha_{hy} \pi^2}{P_r V} \frac{\rho c(a-b)}{f_0^2}$$

Note that this width is independent of the rate constant A, and the reaction kinetics just select the critical temperature at which thermal decomposition becomes important. Using the gouge parameters from before, and the Sulem and Famin [2009] parameters for the decomposition of calcite, we predict a localized zone width of 2-6 μm at a slip rate of 1 ms^{-1}. Examining other fault materials we find thermal decomposition always leads to additional strain localization, with the severity varying from material to material.

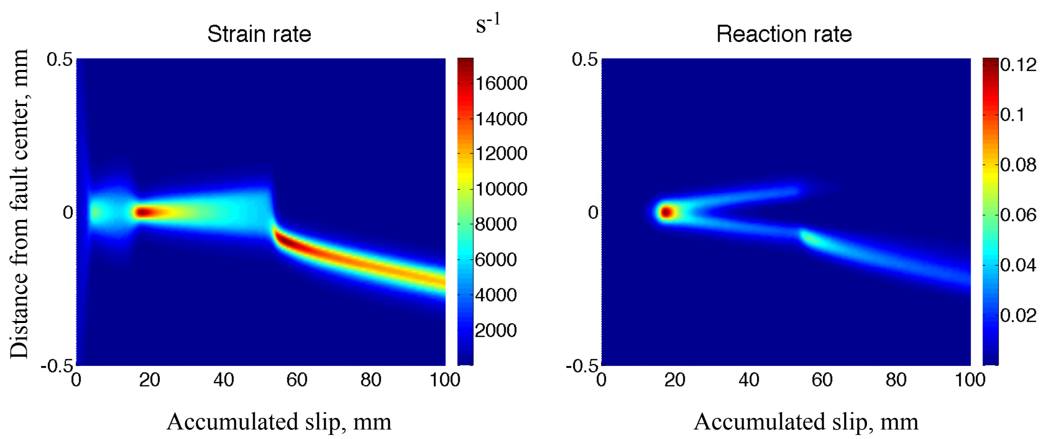

Figure 5, A plot evolution of strain rate and reaction rate with slip. Note the additional strain rate localization when the reaction commences. As the reaction depletes the decomposable material the maximum reaction rate moves off the centre of the gouge layer. Eventually this causes the maximum pore pressure to also move off the centre, and the zone of localized straining migrates across the gouge layer. The reaction rate and the strain rate are locked together during this migration.

As before also performed numerical simulations to test the predictions of the linear stability analysis. We found reasonable agreement between the observed localized zone widths and the predictions from linear stability. The linear stability prediction tends to be slightly thinner than observations, since the nonlinear simulations never make it all the way to the high temperature limit shown in Figure 4, and stop in the transition region between the two limits. As predicted, the observed width is relatively insensitive to changes in the rate constant A, with a three order of magnitude change in A leading to just a factor of two change in the localized zone width. Nonlinear simulations also allow us to test the influence of depletion. Due to the large pore pressures generated by decomposition, when the reactant is totally depleted at a given location the straining is forced to migrate towards fresh material. This produces results like the ones in Figure 5. The strain rate and reaction rate are locked together, and the reaction progresses across the gouge material.

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D: Broader impacts

A study by Chester and Chester [1998] examined a section of the Punchbowl, California, fault, inferred to have undergone of order 40 km of slip. They observed a thin ultracataclasite layer, ~20 cm wide, contained within a wider damage zone, ~15m, and noted that the ultracataclasite hosted an extremely thin feature which they called the "principal slip surface" (PSS) for the fault. Their subsequent thin-section laboratory studies in 2003 showed that the PSS corresponded to a shear zone of ~ 1 mm width with truly large relative displacements apparently taking place on localized features of order 100-300 microns wide within it [Rice, 2006]. Also, Heermance et al. [2003] drilled into the Chelungpu fault, which ruptured in the September 1999 Chi-Chi, Taiwan M_w 7.6 earthquake. They likewise found a localized slip surface, constrained to be 50-300 microns wide, which they interpreted as the fault rupture surface. Another study by De Paolo et al. [2008] analyzed a series of faults in the Northern Apennines, Italy. On all faults they found a nested structure, with a highly localized band of less than 100 microns, contained within a broad damage zone. Faults that had undergone more slip had broader damage zones, but the localized zone width was comparable for all faults.

Further evidence for strain localization during rapid shear comes from high-velocity friction experiment. Microstructural analysis performed by Brantut et al. [2008] indicated the presence of an "ultralocalized deformation zone", interpreted as the main slipping zone of the experiment. This was observed to be 1-10 microns wide. A similar approach by Kitajima et al. [2010] found a highly deformed zone measuring 150-350 microns. This structure had a distinct banded structure, possibly indicating even more localized slip surface within the highly deformed zone.

Our work is aimed at explaining what processes may cause the extreme localization observed in gouge material subjected to rapid shear. The quantitative nature of our work allows us to make predictions for localized zone thicknesses, and show how the physical properties of the gouge material combine to set this critical width. Estimating the width of slip surfaces under different conditions is crucial for future theoretical studies, since the amount of slip required to obtain a given strength drop via thermal pressurization is controlled by the slipping zone width. Rempel and Rice [2006] showed how the width of the slipping zone influences the maximum temperature rise. Another study by Noda et al. [2009] showed how increasing the width of the slip zone causes the rupture to transition from a crack, to a growing slip pulse, and finally to an arresting slip pulse. This occurred as the width of the slipping zone increased from 40 to 100 microns, keeping all other parameters in the problem constant.

E: Recent presentations and publications related to theme of this project:

Papers in semi-final draft form, to be submitted:

Rice, J. R, and J. W. Rudnicki, "Stability and localization of rapid shear in fluid-saturated gouge, 1. Linearized stability analysis", to be submitted to *Journal of Geophysical Research.*

Platt, J. D., J. W. Rudnicki, and J. R. Rice, "Stability and localization of rapid shear in fluid-saturated gouge, 2. Numerical simulations and nonlinear effects", to be submitted to *Journal of Geophysical Research.*

Other reports, abstracts, talks:

Brantut, N., and J. R. Rice, "Decomposition-induced overpressures and fault zone dilation during earthquake slip", Abstract T23G-06 (oral) presented at 2011 Fall Meeting, AGU, San Francisco, Calif., 5-9 Dec., 2011.

Platt, J. D., J. R. Rice, and J. W. Rudnicki, "Strain localization within a fluid saturated fault gouge layer during seismic shear", Abstract 12122, EGU General Assembly, Vienna, Apr. 2011.

Platt, J. D., N. Brantut, and J. R. Rice, "Strain localization driven by thermal decomposition during seismic shear", Poster A-092, 2011 SCEC Annual Meeting.

Platt, J. D., N. Brantut, and J. R. Rice, "Strain localization driven by thermal decomposition during seismic shear", Abstract T22A-09 (oral) presented at 2011 Fall Meeting, AGU, San Francisco, Calif., 5-9 Dec., 2011.

Rice, J. R., "Frictional shear in fluid-saturated (and thermally decomposing) fault gouge", at Workshop on Stick-slip Dynamics, from Nano to Geophysical Scales, Institute for Advanced Studies, Hebrew University of Jerusalem, 2-5 May 2011.

Rice, J. R., "Thermal weakening in earthquake rupture and new perspectives on stress levels along mature faults", Geodynamics Seminar, Lamont-Doherty Earth Observatory, Columbia University, 16 May 2011.

Rice, J. R., "Earthquake rupture dynamics with strong thermal weakening", at Symposium in honor of Professor L. Ben Freund, New Frontiers of Solid Mechanics – From Earthquakes to Single Molecules, Providence, RI, 1-3 June 2011.

Rice, J. R., "Thermal weakening in seismic slip and some consequences for earthquake dynamics", Université Joseph Fourier, Institut des Sciences de la Terre, Grenoble, 26 January 2012.

Rice, J. R., "Thermal weakening of faults in earthquake rupture", joint seminar, Department of Civil and Environmental Engineering and Department of Mechanical Engineering, MIT, 14 February 2012.