SCEC 2012 Progress Report

"Thermally Driven Shear Localization in Fault Zones"

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SUMMARY: We have focused on identifying physical mechanisms controlling the thermal weakening and related localization of rapid shear in fault gouge. The particular processes identified involve weakening through frictional heating and the consequent pressurization of pore fluids. In our earliest studies, those were in-situ pore fluids, i.e., groundwater, but recently published experiments and field observations led us to understand that fluids released by the thermal decomposition of fault gouge components may also be important sources of weakening and localization, and these too are considered in our most recent work. The studies have been partly supported by a no-cost extension, to 31 December 2012, of a multi-year NSF grant, EAR award 0809610, and partly supported by this SCEC grant. A similar text has been sent to NSF on 1 February 2013 as part of a report of progress on the NSF award.

TECHNICAL REPORT: Recent mechanical concepts of the earthquake process that we have pursued assume that mature faults are statically strong, but weaken dramatically during slip. Several dynamic weakening mechanisms have been proposed (e.g., Rice [2006], Rice and Cocco [2007], Rice et al. [2009]). In our most recent prior work on NSF-EAR grant 0809610, we focused on two key ones, thermal pressurization of in-situ pore fluids (Lachenbruch [1980]; Mase and Smith [1987]) and of volatiles resulting from thermal decomposition (Han et al. [2007]; Brantut et al. [2008]; Sulem and Famin [2009]; Brantut et. al [2010], Brantut and Sulem [2012]). Since these mechanisms are driven by temperature rise, the width of the localized shear zone plays an unexpectedly large importance in theoretical calculations, where it can control not only the fault zone temperature rise (Rempel and Rice [2006]), but also the total slip and rupture velocity of a dynamically propagating rupture (Garagash [2012], Platt et al. [2012]), and the mode of propagation as pulse *vs.* crack (Noda et al. [2009]); a narrower shear zone focuses frictional heating leading to larger temperature rises and more rapid dynamic weakening.

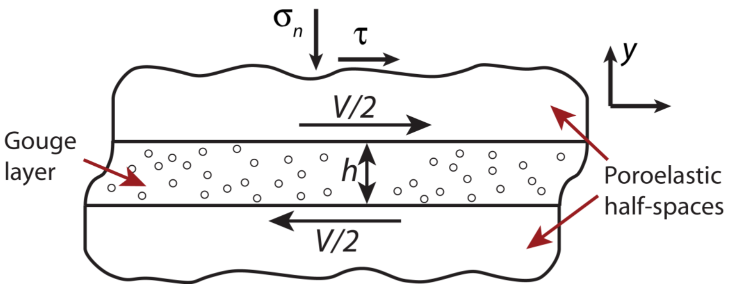

Figure 1 A sketch showing shear of a gouge layer of thickness *h* between two poroelastic half-spaces moving relative to each other at a slip rate *V*.

Thermal pressurization is driven by thermal expansion of the pore fluid as the gouge material is heated; if the pore fluid cannot drain from the gouge material then the pore pressure will increase. The pore pressure change (in the undrained, adiabatic limit) is proportional to the temperature rise, $\Delta p = \Lambda \Delta T$. At seismic depths thermal decomposition reactions typically act as an energy sink and a pore pressure source (Sulem and Famin [2009]; Brantut et al. [2010]). An Arrhenius kinetic relation controls the reaction rate and dynamic weakening due to thermal decomposition is only important once the reaction rate reaches a critical value; this corresponds to an effective triggering temperature for the reaction. This highlights the key qualitative difference between thermal pressurization and thermal decomposition; thermal pressurization provides a small pore pressure increase for every small temperature increase, while thermal decomposition generates pore pressures only once the temperature reaches a critical value.

Having recognized the importance of shear zone width, we have been using theoretical approaches to try and constrain that width during seismic shear. We considered a simple one-dimensional model for shear of a fluid-saturated gouge layer of width h sheared between two poroelastic half-spaces moving relative to each other at a slip rate V and at fixed normal stress σ_n, as shown in Figure 1. Extending ideas from Lachenbruch [1980], Mase and Smith [1987], Sulem and Famin [2009] and Sulem et al. [2009], we use conservation of pore fluid and energy to write

$$\frac{\partial T}{\partial t}=\frac{\tau\dot{\gamma}}{\rho c}+\alpha_{th}\frac{\partial^2 T}{\partial y^2}-\tilde{m}E_r\frac{\partial \xi}{\partial t}\ ;\quad \frac{\partial p}{\partial t}=\Lambda\frac{\partial T}{\partial t}-\frac{\varepsilon}{\beta\dot{\gamma}}\frac{\partial \dot{\gamma}}{\partial t}+\alpha_{hy}\frac{\partial^2 p}{\partial y^2}+\tilde{m}P_r\frac{\partial \xi}{\partial t}\ ;\quad \frac{\partial \xi}{\partial t}=A(1-\xi)\exp\left(-\frac{Q}{RT}\right).$$

Here α_{th} is the thermal diffusivity, α_{hy} is the hydraulic diffusivity, ρc is the specific heat, β is the pore fluid storage capacity, Λ is the thermal pressurization constant discussed, and ε measures the dilatant properties of the gouge in the Segall and Rice [1995] model. The decomposition reaction is controlled by a rate constant A, an activation energy Q, the gas constant R, the mass fraction $\tilde{m}$ $(0 \le \tilde{m} \le 1)$ of material susceptible to decomposition, and the temperature rise $\tilde{m}_r E_r \mathrm{d}\xi$ buffered and pore pressure $\tilde{m}_r P_r \mathrm{d}\xi$ generated in reaction advance $\mathrm{d}\xi$ where ξ $(0 \le \xi \le 1)$ is the reaction progress; $\xi = 0$ represents a fresh material and $\xi = 1$ a fully completed reaction. Rice [2006] noted that inertial effects are expected to be negligible within the gouge layer due to the small distances associated with hydrothermal diffusion. Based on that we assume the conditions for mechanical equilibrium, and relate the shear stress and effective stress using a friction coefficient f,

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

The first means that the shear stress is constant across the deforming gouge layer, and thus a function of time alone. Rice [2006] showed that for a constant f, and neglecting dilatancy, only two forms of deformation are possible: homogeneous shear of the gouge layer, or slip on a mathematical plane. However, if the friction

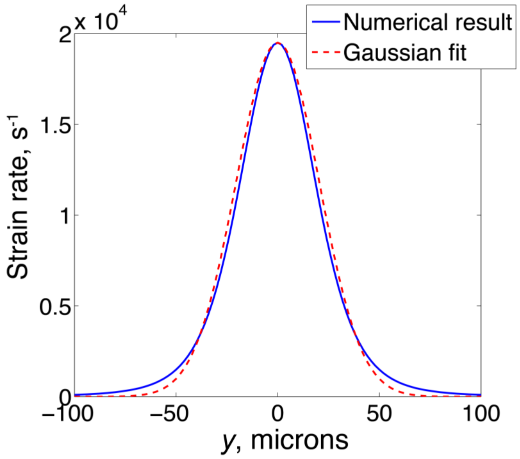

Figure 2 A plot showing the numerical strain profile in blue, and the Gaussian fit in red, based on the path-averaged material parameter values for a damaged fault wall in Rempel and Rice [2006], a h = 2 mm (2,000 microns) wide gouge layer, and a slip rate of V = 1 ms^{-1}. The straining localizes to a zone W (taken as twice the r.m.s. width of the best-fitting Gaussian) approximately 41 microns wide, i.e., ~2% of h.

coefficient can vary across the gouge layer, because of dependence of f on strain rate or other variables, then straining can localize to a finite width zone. Motivated by experiments in Blanpied et al. [1998] showing rate-strengthening behavior for temperatures above 300-400°C, we assumed a rate-strengthening friction law for a rapidly shearing (and hence heating) gouge,

$$f(\dot{\gamma}) = f_o + (a-b)\log\left(\dot{\gamma}/\dot{\gamma}_o\right) \ , \quad \dot{\gamma}_o = V/h \quad , \quad (a-b) > 0 \, .$$

Here f_o is the friction coefficient at the nominal strain rate $\dot{\gamma}_o$, and $(a-b)$ measures the rate-strengthening component of friction. Since the shear stress is constant across the gouge layer, regions of low effective stress must have a high coefficient of friction, leading to high strain rates in regions of high pore pressure. Neglecting dilatancy and linearizing the Arrhenius kinetic about an ambient fault temperature, we performed a linear stability analysis and predicted a critical gouge layer width W such that uniform shear is unstable when $h > W$. At low temperatures the reaction is negligible and all dynamic weakening is due to thermal pressurization, but-above the triggering temperature the reaction is rapid and thermal decomposition dominates thermal pressurization.

This leads to low and high temperature predictions, denoted by subscripts LT and HT respectively, for the localized thickness, based on the growth vs. decay of linearized perturbations from uniform shear:

$$W_{LT} = \pi^2 \frac{(a-b)\rho c}{f_o \Lambda\left(f_o + 2(a-b)\right)} \frac{\alpha_{th} + \alpha_{hy}}{V} \quad , \quad W_{HT} = \pi^2 \frac{(a-b)\rho c E_r}{f_o^2 P_r} \frac{\alpha_{hy}}{V} \quad .$$

A balance between frictional strengthening, diffusion and whichever dynamic weakening mechanism is active at that instant sets these localized zone widths.

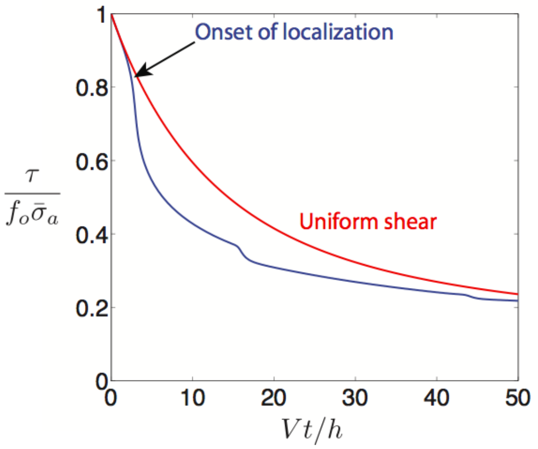

Figure 3 A plot showing the evolution of gouge layer shear strength for localizing (blue) and uniform (red) shear. A dramatic drop in strength coincides with the onset of localization, showing the strong link between localization and fault weakening; this link is also observed in experiments (Kitajima et al. [2010]).

Interestingly the reactant mass fraction and reaction kinetics only select the critical temperature at which thermal decomposition is triggered, but do not influence the localized zone width. The hydraulic parameters are poorly constrained, but using the path-averaged fault gouge values provided in Rempel and Rice [2006], and with $f_o = 0.6$ and $(a-b) = 0.025$ we predict a localized zone thickness W_{LT} of 5 to 41 microns. Table 1 shows values of E_r and P_r for a range of common fault materials and the values of W_{HT} using the Rempel and Rice [2006] poro-thermo-mechanical

Mineral	$-E_r$ (K)	P_r (MPa)	W_{HT} (μm)	T_c (°C)
Calcite	3093	3064	13	900
Lizardite	228	374	8	550
Kaolinite	3627	545	83	500
Talc	496	206	30	800
Gypsum	89	582	2	100

Table1 Thermal decomposition parameters (Platt et al. [2011]); reaction significant when $T > T_c$.

parameters for a damaged material. These E_r and P_r correspond to groupings of terms in Sulem and Famin [2009] and Brantut and Sulem [2012], evaluated with thermodynamic data from Bose and Ganguly [1994], Holland and Powell [1998), L'vov and Ugolkov [2005], Llana-Fúnez et al. [2007], and Ballirano and Melis [2009]. Some of the predictions are approaching representative gouge particle sizes, suggesting that in the thinnest shear zones grain-scale effects may help set the width of the deforming zone.

Complimentary full numerical simulations (i.e., without linearization in perturbation size) were performed for a finite gouge layer of width *h* sheared between two undeforming but conducting half-spaces, as in Rempel and Rice [2006]. Solving from initially uniform shear, we observe strain localization within the gouge layer for $h \gg W_{LT}, W_{HT}$. The resulting strain rate profile is well described by Gaussian functions allowing us to infer a width of the localized zone, as shown in Figure 2. Neglecting thermal decomposition, a parameter sweep leads to a formula for the localized zone thickness at peak localization; this formula is similar in form to the linear stability prediction, suggesting our linearized estimates for the localized zone thickness were good ones. Accounting for thermal decomposition in the full numerical simulations, we again found good agreement between the observed width and the linear stability predictions. The observed shear zone width is found to be very weakly dependent on the reaction kinetics, as already suggested by the linear stability analysis.

As mentioned, previous analyses have shown the link between shear zone widths and thermally driven dynamic weakening (Lachenbruch [1980]; Rempel and Rice [2006]; Noda et al. [2009]; Garagash [2012]). Motivated by that we compared (see Figure 3), for the case of thermal pressurization, our full numerical simulations that allow possible strain rate localization to the solution for a gouge layer that is forced to shear uniformly. A significant drop in strength accompanies the onset of localization as frictional heating is focused into a narrower zone, leading to accelerated weakening.

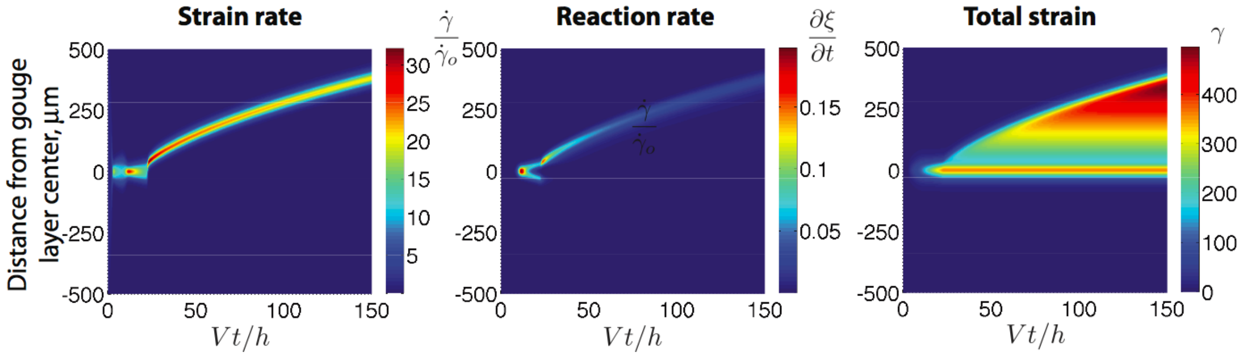

Figure 4 Depletion of reactant causes reaction rate profiles to evolve during slip; deforming zone location is not fixed in a specific location and moves across the gouge layer, leaving laminated strain pattern.

For large slip events reactant depletion can become important, as shown in Brantut et al. [2010]. That leads to localized zone migration. Figure 4 shows how the strain rate and reaction rate profiles evolve during slip; the deforming zone is not fixed in a specific location and moves across the gouge layer as the layer deforms. When the reacting material in the centre of the gouge layer is depleted the reaction proceeds fastest in the adjacent material, which has the most favorable balance of available reactant and high temperatures. Since the reaction drives localization, this leads to migration of the deforming zone across the gouge layer. Integrating the strain rate profiles we find complex final strain patterns, and a final deformed zone thickness that is an order of magnitude wider than W_{HT}. The width of the final deformed zone is set by a combination of how thick the deforming zone is at a given instant and how far that zone migrates.

Even when thermal decomposition is neglected and localization is driven by thermal pressurization alone, we noticed a tendency for the deforming zone to become unstable and migrate across the gouge layer. Returning to our equation for conservation of pore fluid mass, we showed that the mechanism for this destabilization is thermal diffusion and thermal pressurization combining to move the peak pore pressure away from the center of the gouge layer. Our equations for mechanical equilibrium and the rate-strengthening friction law force the peak strain rate to coincide with the peak pore pressure leading to migration of the deforming zone across the gouge layer. As expected, in the idealized case of zero thermal diffusion, our simulations show no movement of the localized zone.

It is left to our continuing work to investigate how the physical properties of the gouge material control the final strain profile and maximum temperature rise.

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OUTREACH ACTIVITIES: These have been outreach to the larger scientific community. During 2012 Rice has lectured on this research, on the thermal and materials physics of fault zones in rapid shear and consequences for earthquake dynamics, on 14 February at a joint seminar of the departments of Mechanical and of Civil and Environmental Engineering at MIT, on 27 June at a conference on the Dynamic Deformation of Solids in Symi, Greece, on 3 July at an International Union of Theoretical and Applied Mechanics Symposium on "Fracture Phenomena in Nature and Technology" in Brescia, Italy, and on 10 October at the Society of Engineering Science Annual Meeting in Atlanta, GA.

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No papers published or currently in review.

Published abstract:

Platt, J. D., R. C. Viesca, and D. I. Garagash (2012), Self-healing slip pulses driven by thermal decomposition: Towards identifying dynamic weakening mechanisms in seismic observations, Abstract S14A-02, presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-7 Dec., 2012.

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

Rice, J. R, J. W. Rudnicki, and J. D. Platt, "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. Localized zone width and implications for strength evolution", to be submitted to *Journal of Geophysical Research.*

Oral presentations:

Rice, J. R., McGill Univ., Montreal, Earth Science Seminar, 23 March 2012: "Thermal weakening of faults in earthquake rupture"

Rice, J. R., European Geosciences Union (EGU) 2012 General Assembly, Vienna, Louis Néel Medal Lecture, 24 April 2012: "Materials physics of faults in rapid shear and consequences for earthquake dynamics"

Rice, J. R., Symposium on the Dynamic Deformation of Solids, Symi, Greece (to honor the scientific contributions and the retirement of Rod Clifton), invited lecture, 27 June 2012: "Materials physics of faults in rapid shear and consequences for earthquake dynamics"

Rice, J. R., International Union of Theoretical and Applied Mechanics, Symposium on “Fracture Phenomena in Nature and Technology”, Brescia, Italy, invited "lectio magistralis", 3 July 2012: "Materials physics of faults in rapid shear and consequences for earthquake dynamics"

Rice, J. R., Society of Engineering Science Annual Meeting, Atlanta, GA, invited presentation, 10 October 2012: "Thermal weakening in seismic shear of fluid-infiltrated fault gouge"

Rice, J. R., Institut de Physique du Globe de Paris, Seismology Seminar, 20 November 2012: "Materials physics of faults in rapid shear and consequences for earthquake dynamics"