SCEC 2013 Progress Report

Thermally Driven Shear Localization in Fault Zones (Project 13011)

PI: J. R. Rice, $32,000 for 1 Feb 2013 to 31 Jan 2014
James R. Rice and John D. Platt, Harvard University, 11 May 2014

ABSTRACT:

In continuation of our FY 2012 SCEC project, we have focused on identifying physical mechanisms controlling the thermal weakening and related localization of rapid shear in fault gouge.

The major goal is to understand the materials physics and dynamics which allows earthquakes on maturely sheared fault zones to occur at low overall driving stresses, and with the majority of deformation accommodated in a principal shear zone that is generally less than 1mm to 1 cm wide, within a much broader fault core composed of gouge and ultracataclasite, and pervasively cracked rock.

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, and our major accomplishment in the current grant period was to prepare two papers for publication (now accepted at JGR) on that, as discussed below.

Also, we have continued the studies initiated in the prior year which recognize, based on recently published experiments and field observations, 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 also been partly supported, starting 1 July 2013, by a 3-year NSF grant, NSF-EAR Geophysics Program Grant EAR-1315447: "Materials physics of rapidly sheared faults and consequences for earthquake rupture dynamics".

TECHNICAL REPORT

Again, the goal is to understand the materials physics and dynamics which allows earthquakes on maturely sheared fault zones to occur at low overall driving stresses, and with the majority of deformation accommodated in a principal shear zone generally less than 1mm to 1 cm wide, within a much broader fault core composed of gouge and ultracataclasite, and pervasively cracked rock.

We have developed a physical understanding of dynamic thermal weakening and strain localization. We studied strain localization based on thermo-poro-mechanical descriptions of gouge that is fluid-saturated, whether with native groundwater or volatiles from thermal decomposition. In the simplest analyses, a layer with a finite thickness h is

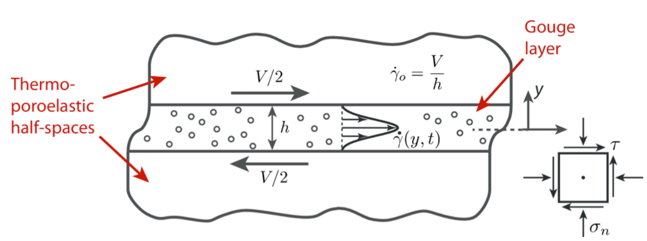

Figure 1 Sketch showing shear of a gouge layer of thickness h between two poroelastic half-spaces moving relative to each other at a slip rate V.

sheared at a rate $\dot{\gamma}$ between two undeforming poroelastic half-spaces moving relative to each other at a slip rate *V,* as in Figure 1. That model is one-dimensional, in that all variations occur in the across-fault direction *y*. Following ideas in Lachenbruch [1980], Mase and Smith [1987], Rice [2006], and Sulem and Famin [2009], we model conservation of energy and pore fluid mass, accounting for thermal pressurization and thermal decomposition, by

$$\frac{\partial T}{\partial t} = \frac{\tau\dot{\gamma}}{\rho c} + \alpha_{th}\frac{\partial^2 T}{\partial y^2} - E_r\frac{\partial m_d}{\partial t} \quad , \quad \frac{\partial p}{\partial t} = \Lambda\frac{\partial T}{\partial t} + \alpha_{hy}\frac{\partial^2 p}{\partial y^2} + P_r\frac{\partial m_d}{\partial t} \quad , \quad \frac{\partial m_d}{\partial t} = A(m_d^0 - m_d)\exp\left(-\frac{Q}{RT}\right)$$

Here, α_{th} is the thermal diffusivity, α_{hy} is the hydraulic diffusivity, ρc is the specific heat, and Λ is a thermal pressurization constant. E_r and P_r are the total temperature rise buffered and pressure generated by a completed reaction of a pure material. The decomposition reaction is controlled by a rate constant A, an activation energy Q, the gas constant R and m_d, the mass of volatiles released per unit volume. For typical gouge layers thicknesses inertial effects can be expected to be negligible (Rice [2006], Platt et al. [2014]), allowing us to use the conditions for mechanical equilibrium at that thickness scale, i.e., $\partial\tau/\partial y = 0, \partial\sigma_n/\partial y = 0$, within the gouge layer The shear stress in the gouge layer is linked to the normal stress through a friction coefficient and the Terzaghi effective stress by setting $\tau = f(\dot{\gamma})(\sigma_n - p)$, and we assume the rate-strengthening friction law $f(\dot{\gamma}) = f_0 + (a-b)\log(\dot{\gamma}/\dot{\gamma}_0)$ with $(a-b) > 0$.

Rice et al. [2013], Platt et al. [2013], and Platt et al. [*in preparation*] show how a linear stability analysis can be used to predict a localized zone thickness as a function of the gouge properties. The analysis points to two regimes, one at lower temperatures when thermal decomposition is slow enough to be neglected, and another at high temperatures where thermal decomposition dominates thermal pressurization. This leads to a high and a low temperature predictions for the localized zone thickness,

$$W^{LT} = \pi^2\frac{\alpha_{th}+\alpha_{hy}}{\Lambda}\frac{(a-b)\rho c}{f_0^2 V} \quad , \quad W^{HT} = \pi^2\frac{\alpha_{hy}E_r}{P_r}\frac{(a-b)\rho c}{f_0^2 V}$$

Using hydraulic and thermal parameters from Rice [2006] and Rempel and Rice [2006], frictional parameters from Blanpied et al. [1998], and parameters modeling decarbonation of calcite from Sulem and Famin [2009], we predicted W^{LT} = 44 μm and W^{HT} = 2-30 μm, where the width in the high temperature limit depends on the specific decomposition reaction activated. The onset of decomposition typically leads to additional strain rate localization.

Our work has also shown the dramatic effect strain rate localization has on dynamic weakening. Figure 2 shows the evolution of shear stress for a uniformly sheared gouge layer and for a gouge layer within which straining is allowed to localize. We found that the onset of localization triggers an abrupt drop in shear stress. As straining localizes the frictional heating is focused into a narrower zone, accelerating the dynamic weakening

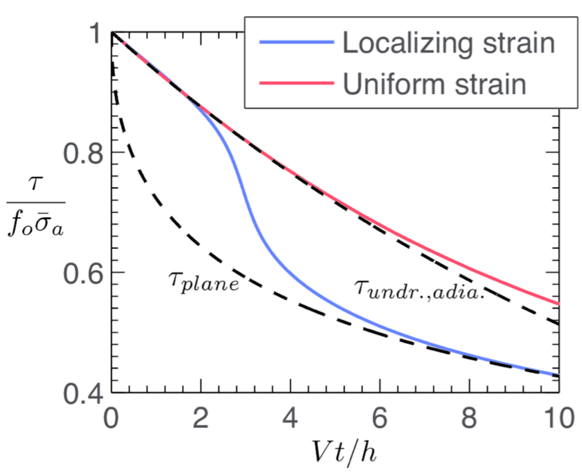

Figure 2: The evolution of shear stress for a gouge layer that localizes compared to a gouge under uniform strain. The onset of localization causes intensified dynamic weakening.

from thermal pressurization and decomposition. From this we conclude that strain rate localization is crucial in setting the rate of dynamic weakening during seismic shear.

Co-seismic migration of the shear zone: For uniform fault properties, the symmetry about the center of the gouge layer forces strain rate localization to initially form in the center of the layer. However, we have found that at later times a variety of mechanisms can drive migration of the localized shear zone across the gouge layer. Our predictions of shear zone migration are in agreement with observations from high-velocity friction experiments (Yao et al. [2013]). One mechanism is the combination of thermal pressurization and hydrothermal diffusion. Using a Green's function approach, Rice [2006, App. B3] showed how thermal diffusion could move the location of maximum pore pressure off the center of the gouge layer. In our model the peak strain rate occurs in the location of maximum pore pressure so when the location of peak pore pressure moves the shear zone will migrate. Another mechanism is reactant depletion during thermal decomposition, which causes straining to focus in areas with the fastest reaction rates. As the reactant depletes the peak reaction rate moves off the center of the layer, causing shear zone migration.

Co-seismic migration of the shear zone has two important consequences. First, it is a crucial consideration when interpreting field observations of highly localized shear zones (Chester and Chester [1998]; Heermance et al. [2003]; De Paola et al. [2008]) in terms of in-situ strain rates. The width of highly deformed material may reflect the distance the shear zone has migrated and not the momentary width of the zone of localized shearing. Second, shear zone migration distributes frictional heating over a broader region of the gouge layer leading to a significantly lower temperature rise than if the shear zone is fixed in a single location. This is important when quantifying the likelihood that weakening mechanisms such as thermal decomposition or melting will be activated. Typically we find maximum temperature rises several hundred degrees Celsius lower than those that would occur without migration.

Finally we have also established how pre-existing heterogeneities within the gouge layer may control the final strain profile (Platt et al., *in progress*). Numerical simulations show that straining quickly migrates towards zones more susceptible to strain rate localization, where that susceptibility is interpreted using our linear stability results shown above. For example a zone of low hydraulic diffusivity attracts straining. Also, once thermal decomposition is active, straining will jump towards reactant-rich zones. We find that the final strain profiles are dominated by the initial heterogeneities, providing a possible explanation for the variability found in field observations of shear zone thickness (Chester and Chester [1998]; Boullier et al. [2009]). Heterogeneities also play an interesting role in determining the dynamic weakening behavior. Deformation initially occurs in the region of the gouge most susceptible to localization. The properties of this zone control the initial dynamic weakening. At larger slips, the distance over which hydrothermal diffusion operates can become larger than the width of heterogeneity causing the background properties of the fault to control dynamic weakening.

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PUBLICATIONS

We completed a coordinated pair of papers on these studies to J. Geophys. Res. - Solid Earth on 25 September 2013, and both were accepted, following minor revisions, on 17 April 2014. The papers (both listed as "submitted" in the SCEC data base) and download links to the accepted pre-publication versions, are:

• Rice J. R., J. W. Rudnicki, and J. D. Platt (2014), **Stability and localization of rapid shear in fluid-saturated fault gouge: 1. Linearized stability analysis**, J. Geophys. Res. - Solid Earth, 119, doi:10.1002/2013JB010710. (SCEC Contribution number is 1825)

Abstract: Field observations of major earthquake fault zones show that shear deformation is often confined to principal slipping zones that may be of order 1-100 **μ** m wide, located within a broader gouge layer of order 10-100 mm wide. This paper examines the possibility that the extreme strain localization observed may be due to the coupling of shear heating, thermal pressurization and diffusion. In the absence of a stabilizing mechanism, shear deformation in a continuum analysis will collapse to an infinitesimally thin zone [Rice , 2006]. Two possible stabilizing mechanisms, studied in this paper, are rate-strengthening friction and dilatancy. For rate-strengthening friction alone, a linear stability analysis shows that uniform shear of a gouge layer is unstable for perturbations exceeding a critical wavelength. Using this critical wavelength we predict a width for the localized zone as a function of the gouge properties. Taking representative parameters for fault gouge at typical centroidal depths of crustal seismogenic zones, we predict localized zones of order 5-40 **μ** m wide, roughly consistent with field and experimental observations. For dilatancy alone, linearized strain rate perturbations with a sufficiently large wavelength will undergo transient exponential growth before decaying back to uniform shear. The total perturbation strain accumulated during this transient strain rate localization is shown to be largely controlled by a single parameter dimensionless parameter E, which is a measure of the dilatancy of the gouge material due to an increase in strain rate.

Download link to pre-publication version:
http://esag.harvard.edu/rice/250_RiceRudnickiPlatt_ThermLocalizPart1_Linear_JGR14.pdf

• Platt, J. D., J. W. Rudnicki, and J. R. Rice (2014), **Stability and localization of rapid shear in fluid-saturated fault gouge: 2. Localized zone width and strength evolution**, J. Geophys. Res. - Solid Earth, 119, doi:10.1002/2013JB010711. (SCEC Contribution number is 1826)

Abstract: Field and laboratory observations indicate that at seismic slip rates most shearing is confined to a very narrow zone, just a few tens to hundreds of microns wide, and sometimes as small as a few microns. Rice et al. [2013] analyzed the stability of uniform shear in a fluid-saturated gouge material. They considered two distinct mechanisms to limit localization to a finite thickness zone, rate-strengthening friction and dilatancy. In this paper we use numerical simulations to extend beyond the linearized perturbation context in Rice et al. [2013], and study the behavior after the loss of stability. Neglecting dilatancy we find that straining localizes to a width that is almost independent of the gouge layer width, suggesting that the localized zone width is set by the physical properties of the gouge material. Choosing parameters thought to be representative of a crustal depth of 7 km, this predicts that deformation should be confined to a zone between 4 and 44 **μ** m wide. Next, considering dilatancy alone we again find a localized zone thickness that is independent of gouge layer thickness. For dilatancy alone we predict localized zone thicknesses between 1 and 2 **μ** m wide for a depth of 7 km. Finally we study the impact of localization on the shear strength and temperature evolution of the gouge material. Strain rate localization focuses frictional heating into a narrower zone, leading to a much faster temperature rise than that predicted when localization is not accounted for. Since the dynamic weakening mechanism considered here is thermally driven, this leads to accelerated dynamic weakening.

Download link to pre-publication version:
http://esag.harvard.edu/rice/251_PlattRudnickiRice_ThermLocalizPart2_Nonlin_JGR14.pdf

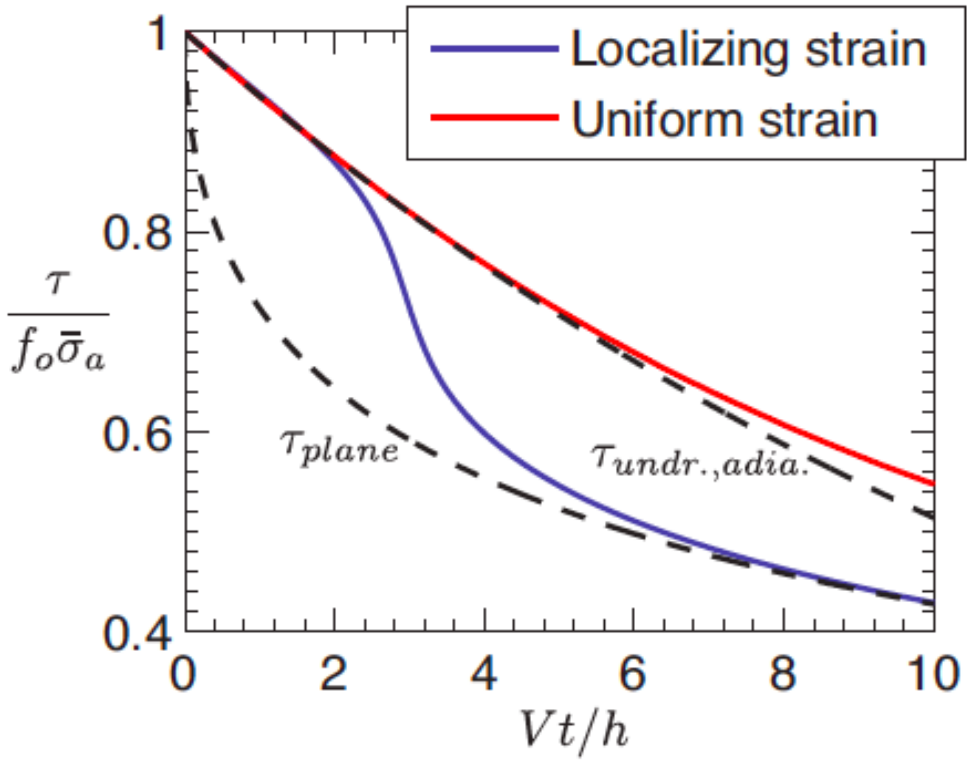
INTELLECTUAL MERIT

Our studies contribute towards the goal of understanding the materials physics and dynamics which allows earthquakes on maturely sheared fault zones to occur at low overall driving stresses, and with the majority of deformation accommodated in a principal shear zone generally less than 1mm to 1 cm wide, within a much broader fault core composed of gouge and ultracataclasite, and pervasively cracked rock.

BROADER IMPACT

An impact, not yet fully realized, is that this level of understanding of the faulting process will help us to interpret, and understand the significance in terms of causative processes, of fault zone observations in the field and in laboratory specimens. The work also takes steps towards understanding how the materials physics of fault zone processes interact with rupture dynamics.

EXEMPLARY FIGURE



This is Figure 8 of Platt, Rudnicki and Rice [2014] (in press), for a layer of thickness *h* of rate-strengthening fault gouge, with boundaries forced to shear relative to one another at a constant rate *V*. The plot shows how the strength of the gouge layer evolves, normalized by the initial strength, for localizing shear (in blue, the actual response) and, as a comparison (in red), for non-localized uniform shear - which is shown to be an unstable deformation mode, despite the rate-strengthening. These simulations were produced using path-averaged parameters modeling a damaged material, intended to represent a strike slip fault at ~ 7 km depth. Here V = 1 m/s, a typical average slip-rate in an earthquake, and h = 1 mm. The sudden drop in strength coincides with the onset of localization. The initial deformation, before diffusion and localization have had time to act, is well described by the solution for uniform shear under undrained and adiabatic condition [Lachenbruch, 1980] . At large slips the solution is no longer influenced by the small yet finite width of the shearing zone and the strength is well approximated by the solution for slip on a plane [Mase and Smith, 1987; Rice, 2006]. The two limits for undrained adiabatic deformation and slip on a plane are shown above by the dashed black lines. Note that the undrained adiabatic solution from Lachenbruch [1980] differs from our simulation of a uniformly sheared layer because our numerical simulations allow for diffusion of heat and fluid into the surroundings.