SCEC 2013 Progress Report

Spontaneous Rupture Propagation With Strong Dynamic Weakening

(Project 13012)

PI: J. R. Rice, $30,000 for 1 Feb 2013 to 31 Jan 2014

James R. Rice and John D. Platt, Harvard University, 11 May 2014

ABSTRACT

A companion SCEC 2013 study (Thermally Driven Shear Localization in Fault Zones, Project 13011) focused on identifying physical mechanisms controlling the thermal weakening and related localization of rapid shear in fault gouge. The goal in this work was to see the implications, for dynamic rupture propagation, of those new views of how the histories of slip and stress on a fault are related to one-another - such being an essential input for analysis of spontaneous dynamic rupture.

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".

The main contributions in this phase of the work are being made by John D. Platt, as a part of his Ph.D. thesis in preparation. His work is being summarized in a manuscript "Steadily propagating slip pulses driven by thermal decomposition" in preparation by Platt, in combination with Robert C. Viesca (a former Ph.D. student in our group, now at Tufts University) and Dmitry I. Garagash (a former sabbatical visitor to our group, from Dalhousie Univ.), to be submitted to *J. Geophys. Res*. That work seems to be the first modeling of propagating dynamic rupture in cases for which thermal decomposition is a part of the process, it being assumed to follow a preliminary phase of frictional heating and related weakening by thermal pressurization of native ground fluids. Previously, Garagash [2012] has presented such an analysis of propagating slip pulses for the case of fault weakening solely by thermal pressurization of native fluids.

Their approach is to solve for self-healing slip pulses propagating at a constant rupture velocity. Results show that for fixed fault properties there are two ways to propagate a slip pulse. One is a pulse with small slip that never triggers thermal decomposition and the other is a pulse with large slip and significant weakening due to thermal decomposition. Thermal decomposition leads to a distinctive along-fault slip rate profile, with peak slip rates coinciding with the onset of the reaction. The study establishes how the total slip and rupture velocity vary for slip pulses with and without thermal decomposition. Before submitting the manuscript, Platt plans to add a results section showing how model outcomes like total slip, rupture velocity, etc. vary with the reaction parameters (e.g., with E_r, P_r, A, m_d and Q) in the equation set within the report).

TECHNICAL REPORT

Our aims fit within the framework of the companion report (Project 1301) of which the goal was “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". Here, however, the focus is on what that new understanding implies for the mode of rupture (e.g., self-healing versus enlarging crack) and patterns of slip development during spontaneously propagating dynamic rupture, i.e., in earthquakes.

We have developed a physical understanding of dynamic thermal weakening and strain localization, which provide a new basis for expressing the history of stress sustained along a fault as a functional of the history of slip. 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 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.

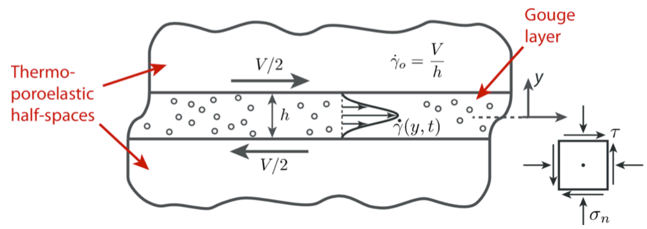

Figure 1 Sketch showing shear of a gouge layer of thickness h between two poroelastic half-spaces moving relative to each other at a slip rate V.

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. [2014], Platt et al. [2014], and Platt et al. [*in preparation,* 2014] 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 low-temperature (LT) and high-temperature (HT) predictions for the localized zone thickness W,

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

which are seen to become insensitive to the initial thickness h of the sraring zone.

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.

Assuming a fixed thickness h (which seems to become irrelevant to results at large slip, the above system of differential equations, together with the rate-strengthening (because of the elevated T) friction law, thus provides the system which relates a history of slip rate V on the fault to a history of shear stress τ. Coupling that relation to a description of the linearized elastodynamics of the region exterior to the fault zone, and devising appropriate numerical methodology for that, has led to the results of Platt et al. [*in preparation,* 2014], summarized in the following figures.

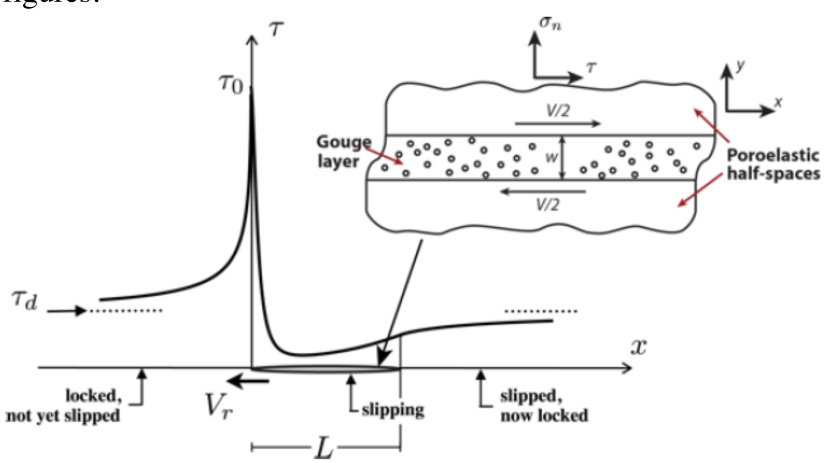

Figure 1. Plot showing the slip pulse geometry.

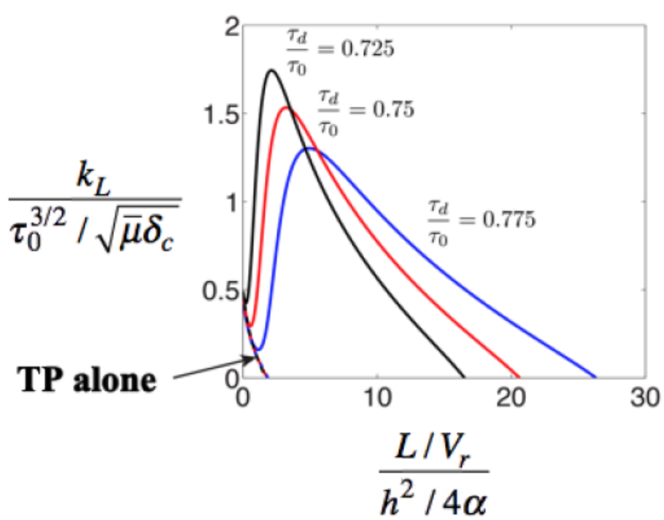

Figure 2. Plot showing k_L as a function of slip duration for three different driving stresses. (k_L = trailing edge stress intensity factor; k_L = 0 at pulse end -- at right here)

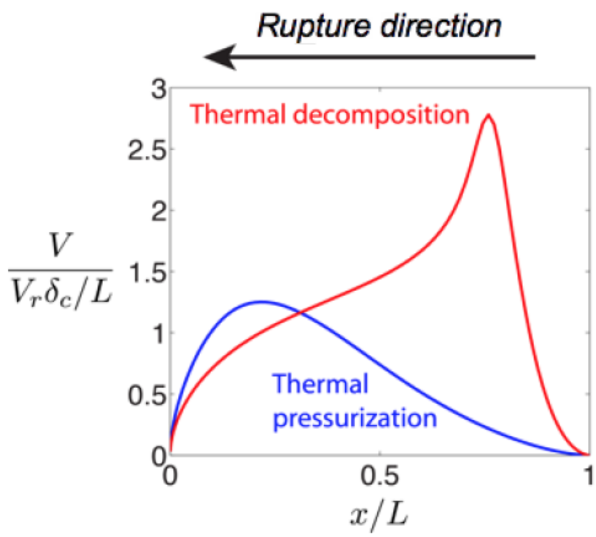

Figure 3. Plot showing the along fault slip rate profile for solutions with and without thermal decomposition.

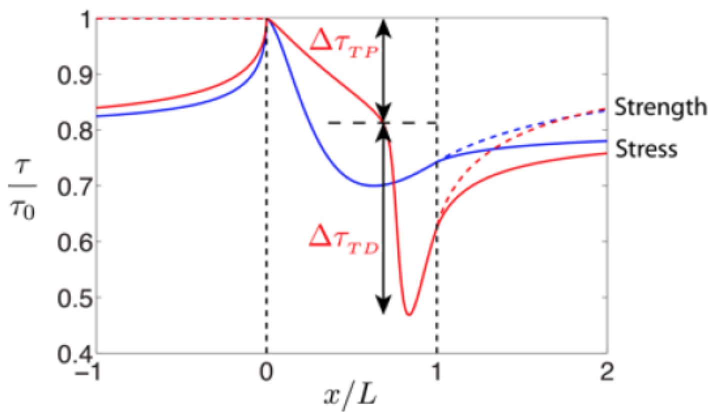

Figure 4. Plot showing the stress and strength evolution for solutions with and without thermal decomposition.

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PUBLICATIONS

Nothing published on this project. Paper in preparation for publication [Platt, J. D., R. C. Viesca, and D. I. Garagash (*in preparation,* 2014), Steadily propagating slip pulses driven by thermal decomposition] is listed among references.

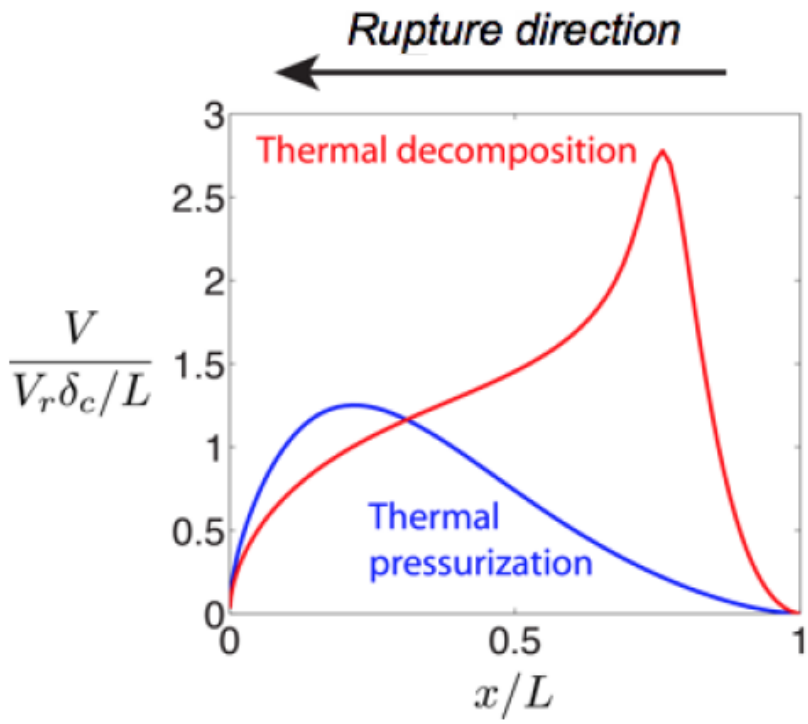
INTELLECTUAL MERIT

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 figure, from Platt, Viesca and Garagash [2014] (in preparation; see reference list) shows the distribution of sliding velocity V along a propagating rupture in the form of a self-healing slip pulse, of length L, which is advancing steadily, at propagation speed V_r, along a planar fault under plane strain conditions. The case of weakening by thermal pressurization of native ground water (in blue) is contrasted with that of an initially dry fault zone (in red) in which a fluid phase is introduced, as a volatile component, by thermal decomposition of the fault zone material.