Earthquake Instabilities On Fluid Saturated Faults

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Final Report

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Technical Abstract

This study represents an initial investigation of the interaction of slip weakening friction and pore fluid fluctuations in controlling earthquake instabilities. Pore compaction and thermal pressurization due to shear heating act to increase pore pressure, whereas dilatancy and fluid flow decrease pore pressure. Linearized analysis of a lumped parameter, spring-slider system shows that slip is unstable if the spring stiffness is less than a critical value which depends on hydraulic diffusivity. For undrained conditions earthquakes can not nucleate if the pore pressure exceeds some fraction of the normal stress

Non-Technical Project Summary

An improved understanding of the physics of earthquake nucleation could potentially lead to prediction strategies. Two distinct views have emerged among researchers. In one view earthquakes nucleate due to loss of frictional strength, in the other the effect of porefluids within the fault zone is most important. This study represents the first rigorous attempt to understand earthquake nucleation including both important processes.

Investigations

Earthquake nucleation requires that frictional fault strength decrease with increasing slip or slip speed. Possible instability mechanisms include: (1) loss of strength due to change in coefficient of friction at fixed effective normal stress ("slip weakening") and (2) loss of strength due to increased pore-pressure through shear-heating and thermal pressurization ("shear heating"). Laboratory experiments show that for rock surfaces in frictional contact under drained conditions μ is a function of slip rate and past slip history. consistent with widely used rate and state dependent frictional constitutive laws (a form of slip weakening). With rate and state dependent friction Ruina [1983] showed that a single degree of freedom spring-slider system is unstable if the spring stiffness is less than

$$k_{crit} = (\sigma - p\ (b - a)/d_c \qquad (1)$$

where a measures direct velocity strengthening, b - a measures steady-state velocity weakening, and d_c is the critical distance scale over which weakening occurs.

Dilatancy under shear tends to decrease pore-pressure and is therefore stabilizing. A number of processes may act to compact pores during the interseismic period tending to raise pore-pressures between earthquakes. The effects of both dilatancy and compaction may be mitigated by pore-pressure diffusion. On the other hand, thermal pressurization of pore-fluids due to shear heating can lead to dramatic loss of frictional strength, depending on the amount of pore-pressure dissipation due to dilatancy and fluid diffusion.

In this study we developed constitutive laws for porosity, consistent with drained laboratory tests, and consider stability of simple lumped parameter (spring-slider) models. We first considered isothermal, dilatant faults with rate- and state dependent friction. The analysis quantifies the strengthening effect of dilatancy and shows how the critical system stiffness varies between drained and undrained limits. We then investigated nonisothermal systems, and considered whether shear-heating instabilities can occur when the fault friction is stable to drained deformation (i.e., velocity strengthening).

Results

We develop two constitutive models for fault zone dilation. We postulated the existence of a steady state drained porosity φ_{ss} of the fault gouge which depends on slip velocity as

$$\varphi_{ss} = \varphi_0 + \epsilon ln(v/v_0) \qquad (2)$$

over the range of velocities considered, where v is sliding velocity and ϵ and v_0 are constants. Laboratory evidence suggests that porosity evolves toward steady state over the same distance scale, d_c, as "state", such that

$$\varphi = -v/d_c,(\varphi - \varphi_{ss}) \qquad (3)$$

where φ refers to inelastic changes in pore volume and ϵ is a "dilatancy coefficient." Modifications of this law are presented that restrict the range of φ to $0 \leq 0 \leq 1$. A feature of the constitutive law represented by (2) and (3) is the absence of compaction on a stationary fault. Other laboratory data indicate compaction under stationary, but non-hydrostatic conditions. A second form of the porosity constitutive relation was developed that predicts compaction under stationary contact. In this form porosity is a function of the fault "state", θ which evolves according to the state evolution law proposed by Ruina [1983]

$$\varphi = \varphi_0 - \epsilon \ln(v_0\theta/d_c). \qquad (4)$$

The steady state porosity is identical in both models, and the linearized stability properties are also identical. Both porosity constitutive models predict changes in porosity upon step changes in sliding velocity that are consistent with the drained experiments of Marone et al. [1990].

We next analyze the conditions for unstable slip of a fluid infiltrated fault using a rate and state dependent friction model including the effects of dilatancy and pore compaction. For undrained loading, the effect of dilatancy is to increase (strengthen) $\delta\tau_{ss}/\delta \ln v$ by $\mu_{ss}\epsilon/(\sigma - p)\beta$, where μ_{ss} is steady state friction, σ and p are fault normal stress and pore pressure, and β is a combination of fluid and pore compressibilities. Assuming $\epsilon \sim 1.7 \times 10^{-4}$ from fitting the Marone et al. data, we find the "dilatancy strengthening" effect to be reasonably consistent with undrained tests conducted by Lockner and Byerlee (1994).

We consider a highly simplified fault model, appropriate for a fault bounded by a thin semi-permeable zone, in which the fault zone pore-pressure p is controlled by

$$\delta p/\delta t = -c^*(p - p^\infty) \quad (5)$$

where c^* is the model hydraulic diffusivity (diffusivity /diffusion length^2). Linearized perturbation analysis of a single degree of freedom model in steady sliding shows that unstable slip occurs if the spring stiffness is less than a critical value given by

$$k_{crit} = (\sigma - p)(b - a)/d_c - \epsilon\mu_{ss}F(c^*)/\beta d_c \quad (6)$$

where a and b are coefficients in the friction law and $F(c^*)$ is a function of c^*, such that in the limit $c^* \Rightarrow \infty$, $F(c^*) \Rightarrow 0$, recovering the drained result of Ruina (1983). In the undrained limit, $c^* \Rightarrow 0$, $F(c^*) \Rightarrow 1$, so that for sufficiently large ϵ slip is always stable to small perturbations.

Under undrained conditions $(\sigma - p)$ must exceed $\epsilon\mu_{ss}/\beta(b - a)$ for instabilities to nucleate, even for arbitrarily reduced stiffness. This places constraints on how high the fault zone pore pressure can be, to rationalize the absence of a heat flow anomaly on the San Andreas fault, and still allow earthquakes to nucleate without concomitant fluid transport.

For the dilatancy constitutive laws examined here, numerical simulations do not exhibit large interseismic increases in fault zone pore pressure. The simulations do, however, exhibit a wide range of interesting behavior including: sustained finite amplitude oscillations near steady state and repeating stick slip events in which the stress drop decreases with decreasing diffusivity, a result of dilatancy strengthening. For some parameter values we observe "aftershock" like events that follow the principal stick-slip event. These aftershocks are noteworthy in that they involve rerupture of the surface due to the interaction of the dilatancy and slip weakening effects rather than to interaction with neighboring portions of the fault. This mechanism may explain aftershocks that appear to be located within zones of high mainshock slip, although poor resolution in mainshock slip distributions can not be ruled out.

We next addressed the effects of shear heating, and its interaction with slip weakening. Shear heating increases pore pressure p and if dilatancy and pore pressure diffusion are limited, will cause shear stress τ to decrease. We examined how shear heating, dilatancy and pore-pressure diffusion compete to determine stability on a fault which may be intrinsically stable $(a > b)$ or unstable $(b > a)$. Consider a highly simplified fault model in which the fault zone responds adiabatically to perturbations, and the pore-pressure p obeys:

$$dp/dt = \tau v/\mu_0 L_p - (1/\beta)d\varphi/dt - (p - p^\infty)/t_p, \quad (7)$$

where v is slip speed, L_p scales with fault zone thickness and depends on the density, specific heat. compressibility, and thermal expansivity of fault zone materials, φ is inelastic porosity, β a measure of compressibility, and t_p the characteristic time for pore-pressure diffusion. The terms on the right hand side represent shear induced thermal pressurization, dilatancy, and pore-pressure diffusion, respectively. In this calculation we use the porosity constitutive relation (4). General results of a linearized stability analysis of a lumped parameter system at steady velocity v^∞ are lengthy. However, when drained behavior is steady state velocity strengthening, a

> b, dilatancy is ignored, and d_c, *is* small enough that $\mu_0 d_c << (a - b)L_p$ the stability analysis yields a critical spring stiffness given by

$$k_{crit} = (\sigma - p)\ [\mu_0/L_p - (a - b)/t_p v_\infty]. \quad (8)$$

The result is also true for all L_p when $b = 0$. This implies that shear heating instabilities do not exist if the characteristic thermal diffusion time is less than $t_p < (a - b)L_p/\mu_0 v^\infty$. For L_p in the range 1 mm to 100 mm we conclude that shear heating instabilities can occur in the absence of dilatancy at v^∞ on the order of 20 to 30 mm/yr if the characteristic fluid diffusion time is greater than 0.1 to 10 days. Whether unstable friction or shear heating first triggers earthquakes depends on whether the ratio $(b - a)L_p/\mu_0 d_c$ is, respectively, greater or less than unity under undrained conditions, and depends more generally on the characteristic diffusion time and dilatancy, which act to suppress the shear heating instability.

Conclusions:

- For isothermal, slip-weakening faults subject to undrained loading, dilatancy limits how small the effective stress can be (to explain the lack of heat flow anomaly) and still allow earthquakes to nucleate.
- Frictionally stable, non-dilatant faults can exhibit shear heating induced instabilities if the characteristic diffusion time for pore-fluid diffusion is greater than 0.1 to 10 days.
- Given reasonable parameter estimates it appears that unstable friction may act to destabilize faults before shear heating, although shear heating may play an important role in earthquake dynamics following nucleation.

Reports

Segall, P. and J.R. Rice, Dilatancy, compaction, and slip instability of a fluid-infiltrated fault, EOS, Transactions, American Geophysical Union, Vol. 75, No. 44, p. 425,1994.

Segall, P. and J.R. Rice, Dilatancy., compaction, and slip instability of a fluid infiltrated fault, J. Geophys. Res., v. 100, p. 22,155-22,171, 1995.

Segall. P. and J.R. Rice, Stability of slip on a fluid-saturated fault with shear heating, dilatancy, and rate and state dependent friction, Transactions, American Geophysical Union, Vol. 76, No. 17, p. 282, 1995.

Segall P. and JR. Rice, Slip instabilities: Unstable friction or shear heating? (abstract), *IUGG XXI General Assembly Abstracts,* Boulder, Colo., A357, 1995.

References Cited

Marone. C., C.B. Raleigh, and C.H. Scholz, Frictional behavior and constitutive modeling of simulated fault gouge, *J. Geophys. Res.,* 95, 7007-7025, 1990.

Ruina. A. Slip instability and state variable friction laws *J Geophys. Res., 88,* 10,359-10,370, 1983.