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RUPTURE NUCLEATION AND THE EVOLUTION OF d_c

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Introduction

How does the friction law scale with length if the heterogeneity in stress is a power law at all scales? What is the effective friction law at 100 m given that the stress is heterogeneous at all scales, in particular, at smaller length scales? By answering this question we may come to understand how an earthquake nucleates and propagates to produce magnitudes ranging from -2 to 9. In our dynamic simulations we are constrained, by computational limits, to examine rupture dynamics using element sizes that are on the order of 50-100 m if we wish to simulate realistic large magnitude events.

We examined the following basic problem with respect to the nucleation and propagation of a dynamic rupture. We considered a fault that has a heterogeneous distribution of stress. We initiate the rupture by perturbing a small area on the fault such that in this small region the initial stress exceeds the yield stress. In this limited region the stress drops to the sliding friction level following a prescribed slip weakening friction. Will this nucleation result in a propagating rupture that sweeps over the fault plane? Moreover, what is the appropriate friction law in the presence of heterogeneity (Campillo et al., 2001)?

Analysis Approach and Results

To simulate the rupture dynamics we use the finite element method of Ma and Liu (2006). We begin with the original problem defined by Campillo et al. (2001) in 2D but extend their problem to 3D. The basic hypothesis of Campillo et al. (2001) is that the most accurate description of the friction law in the presence of heterogeneous initial shear stress is the shear traction versus slip observed off, but still close to, the fault. Their argument is that on the fault, a friction law has been prescribed; thus this cannot be the friction law. However, immediately adjacent to the fault, the slip will evolve in response to the dynamics of the rupture in such a way that the traction-slip evolution will represent the friction law that results from the heterogeneous stress condition.

In Figure 1 we show a periodic variation in the value of the static coefficient of friction (multiplied by the normal stress will give the shear strength) and the constant sliding friction coefficient. On the right, we show the periodic nature of the strength on the fault plane for the 3D calculations. Rupture is initiated at x=1.35 km, z = 0.75 km, by dropping the stress following a prescribed slip weakening friction law with dc=0.1 m.

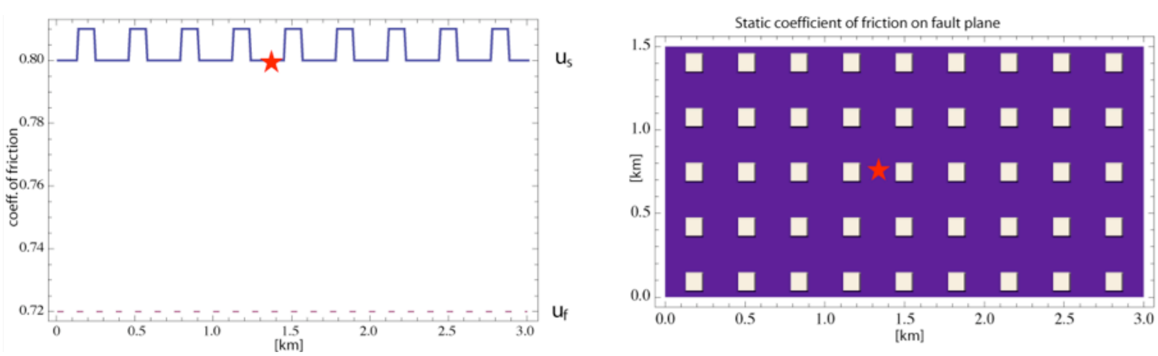

Figure 1: (Right) The periodic pattern of the stress heterogeneity on the fault. (Left) A cross-section shows the variation in the coefficient of friction. The initial shear traction has a coefficient of friction equal to the lower value (0.8) of the strength coefficient (yield shear stress) shown as the periodic variation. Red dashed line is value of coefficient of sliding friction. Star indicates position of the nucleation.

We are using a small fault in order to resolve the slip evolution with an element size of 10 m. We are only interested in computing the slip weakening for points close to the fault to determine the effective friction law. In Figure 2 we show the position of points close to the fault and the slip weakening curves for the heterogeneous model in Figure 1.

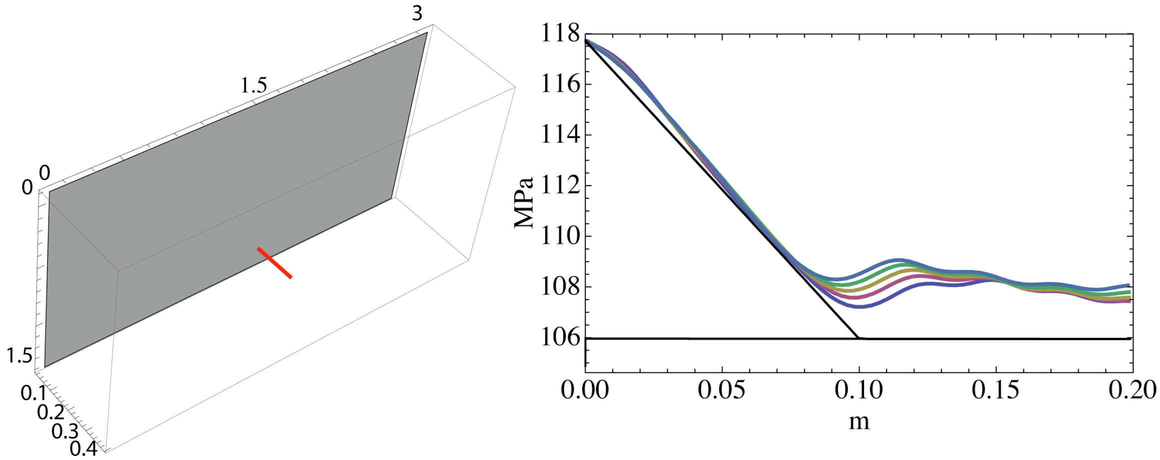

Figure 2: Right: Three-dimensional prism showing position of fault (grey plane) and a line of points that is perpendicular to the fault. Left: Traction versus slip weakening for points off the fault and for the prescribed friction law (black curve with constant slope, dc=0.1m). Closest point to the fault (position 1) is the purple curve, lowest of the five colored curves.

This example suggests that the effective slip weakening friction differs from the prescribed friction law in some subtle but still substantial ways. First the initial traction weakening is less rapid; second the slope over most of the weakening is slightly steeper; third the slip weakening distance is hardly affected; and fourth, the total change in the traction is about 80% of the prescribed change. Note that the slip weakening distance has remained nearly constant. If one were to extrapolate the curves, using the slope during most of the weakening, the value of dc would be very close to 0.1 m. Even though the curves are separated when they approach sliding friction, the curves converge to nearly the same level of sliding friction after slip of 0.2 m has occurred.

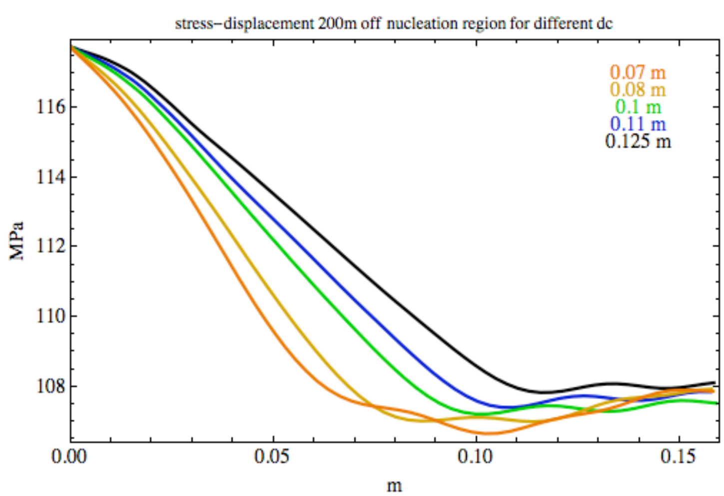

Figure 3: Shear traction versus slip for a point located 200 m perpendicular to the fault. Each curve represents a different value of dc ranging from 0.07 m to 1.25 m.

We examined the same problem assuming different values of dc. In Figure 3 we show the slip weakening curves at a constant distance—200 m, which is twice the barrier spacing 100 m of the periodic variation in stress—off the fault. What we observe is that the curves are similar in shape in that they have an initial slow weakening followed by nearly constant slope with some undulations as the traction reaches it sliding friction. Perhaps the most noticeable difference is that the smaller values of slip weakening have more overshoot of the sliding friction.

However, the results to date suggest that we can use the friction law found in the bulk. What we suggest is that we follow the friction law to it complete sliding friction to determine the slip weakening distance and use the modifications found by fitting the friction law to a few parameters. In Figure 4 we use a fit to the friction law in the bulk but put this friction law into a homogeneous problem, i.e., uniform strength, uniform initial stress and uniform sliding friction.

What we conclude is that the heterogeneity in stress can be reproduced by a modified slip weakening law. One will note that fracture energy is larger than that from linear slip weakening because the traction does not weaken as rapidly with slip when there is heterogeneity. This is clear in the blowup (Figure 4) of the initial weakening. One important feature is that the presence of heterogeneous strength does lead to a slower initial rupture velocity as evident from the delay between the homogeneous and heterogeneous strength (Figure 4). This might be expected because the heterogeneous strength will take more energy out of the system to overcome the barriers.

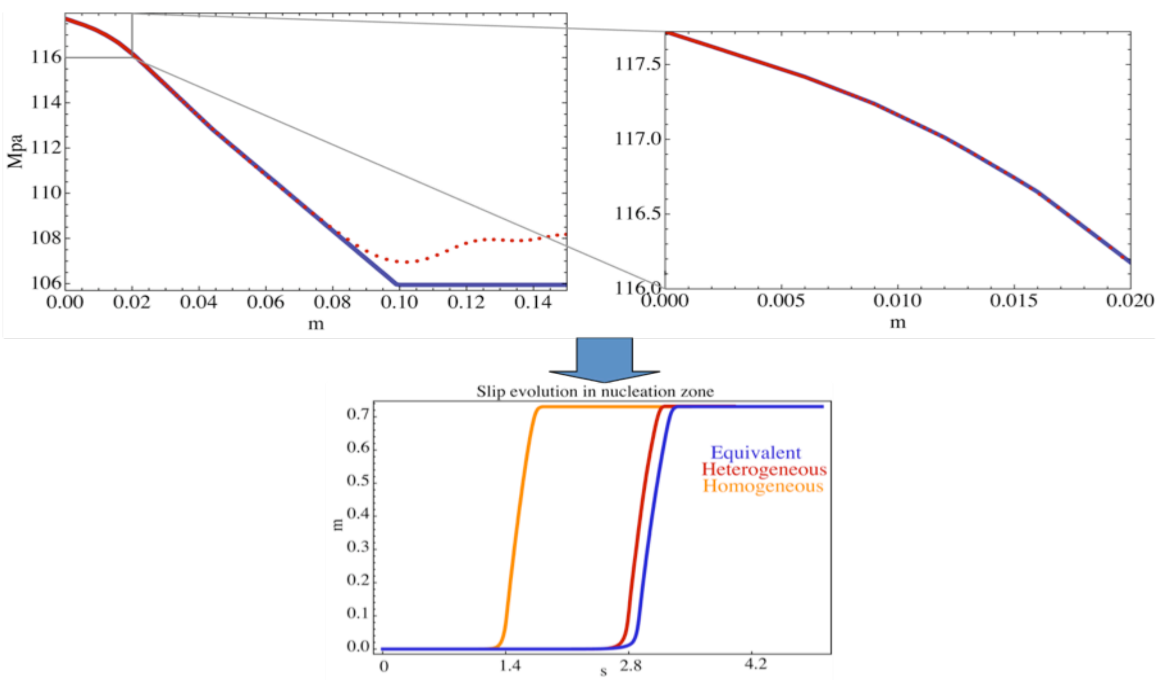

Figure 4: The slip weakening curve (upper left) compares the observed (red dots) slip weakening in the bulk with a curve that was fit to the initial slip weakening and given a fixed dc (blue). This fitted curve was used on the fault with homogeneous strength. Note how well it reproduces the effects of the heterogeneous strength.

We examined how different barrier heights and different spacing affected the slip weakening curve. These are shown in Figure 5.

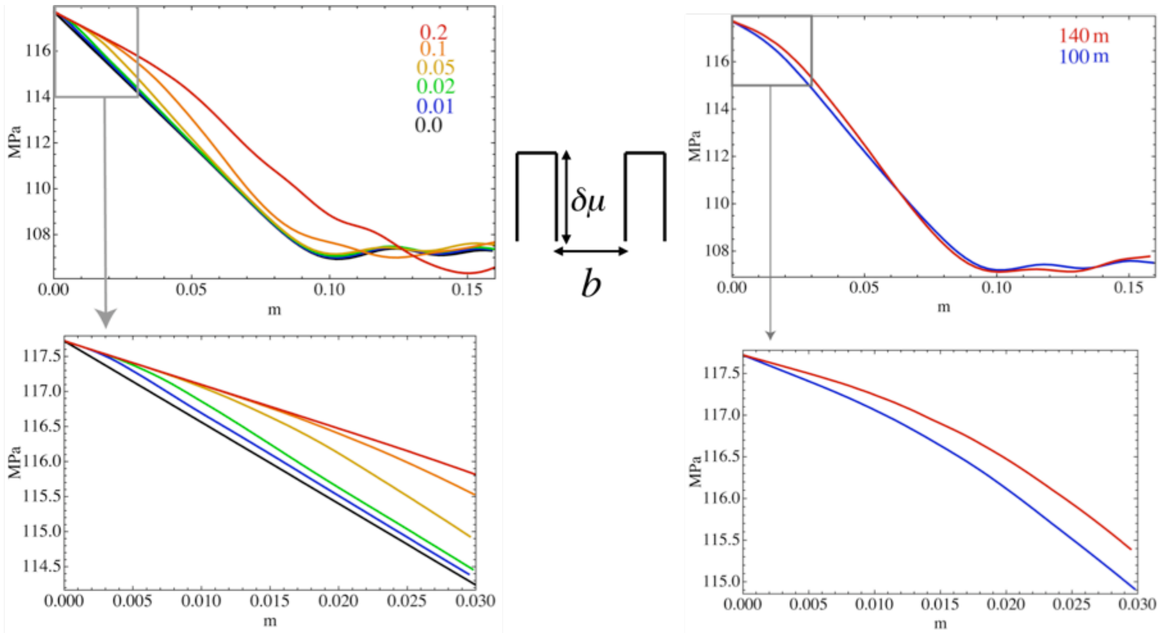

Figure 5: Slip weakening curves for different barrier heights δμ and for different spacing b. Increasing barrier height or spacing decreases the rate of slip weakening.

We pushed this problem further by going to a larger fault: 8 x 4 km^2 embedded in a volume that is 4.4 km (fault normal) x11.6 km (fault parallel) x 5.8 km (depth). The cell size is 10 m, giving ~300 million grid points. We use a time step of 0.0014 s. We wanted to see what happens after the rupture breaks out of the nucleation zone with homogeneous stress conditions. In this example the initial stress is equal to the strength. In Figure 6 we show the rupture front and the rupture velocity on a line that passes through the hypocenter and is parallel to strike. It is interesting to see that with a linear slip weakening law the rupture will accelerate up to the P wave speed, as expected. However, with the equivalent slip weakening law (equivalent to a heterogeneous strength condition), the limiting speed is just about the $\sqrt{2}$ times the shear wave speed. This is another indication of the heterogeneous stress taking energy out of the system.

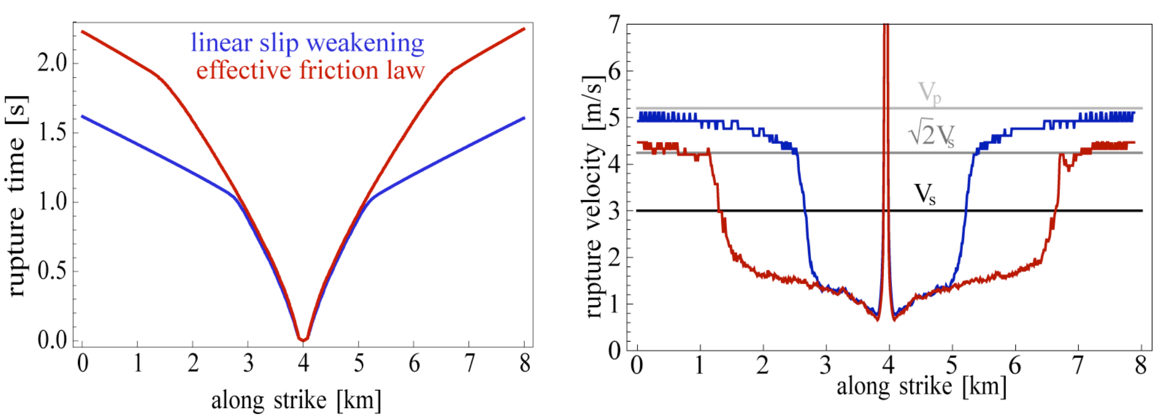

Figure 6: Rupture front characteristics (left) and rupture velocity (right) (1/derivative of the characteristic) for a fault with homogeneous stress conditions but with a linear slip weakening friction and an effective friction law that would represent stress heterogeneity.

To examine a fully heterogeneous system, we constructed a heterogeneous strength map (Figure 7) following the approach used in Lavallée et al. (2006). The wavenumber spectrum of strength is initially white and then filtered with a $k^{-1.2}$ spectrum. The strength amplitudes were Cauchy distributed with a water level of 0.8. We used a dc = 0.07 m. Initially the slip weakening curve in the bulk is very close to the slip weakening imposed on the fault, but obviously it deviates significantly when slip is about 0.04 m and then weakens more slowly with an implied slip weakening distance that is much larger than the imposed dc.

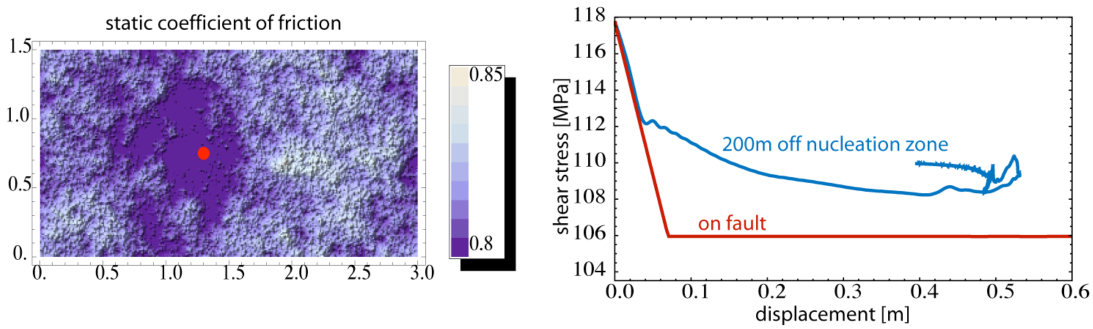

Figure 7: Completely heterogeneous strength distribution and the resulting slip weakening curve that is 200 m off the fault directly opposite the nucleation zone (red dot).

Summary

Following the idea of Campillo et al. (2001) we have examined the effect of heterogeneous strength, i.e., barriers, on the slip weakening friction. To do this we have to observe the traction versus slip in the bulk because the dynamic rupture has an imposed slip weakening friction law. What we wish to find is the effective slip weakening. One representation of that effective friction law is the traction versus slip recorded in the bulk but for points not too far off the fault.

For simple periodic barriers we find that the effective friction slip-weakening curve is less rapid in its initial phase but then has a similar rate of weakening and similar slip weakening distance. When we use the effective friction law with a homogeneous strength condition, it reproduces the rupture for heterogeneous strength conditions. When we use a more stochastic representation of the strength heterogeneity, we find a more complicated effective friction. We have not explored the consequences of this more complicated effective friction nor have we explored more than one representation of the stochastically heterogeneous strength conditions.

While these are only the initial explorations into the effects of heterogeneity, there is one consistent feature, namely, that the slip weakening is much less rapid initially. This makes the nucleation of the rupture and expansion more difficult (Ionescu and Campillo, 1999). It may be that we will see how different size earthquakes occur because the heterogeneity tends to quench the rupture (Oglesby and Day, 2002).

References

Campillo, M., P. Favreau, I.R. Ionescu and C. Voisin (2001) On the effective friction law of an heterogeneous fault, *J. Geophys. Res.* **106**, 16,307-16,322.

Ionescu, J. and M. Campillo (1999). Influence of the shape of the friction law and fault finiteness on the duration of initiation, *J. Geophys. Res.*, **104**, 3013-3024.

Lavallée, D., P. Liu, and R. J. Archuleta (2006). Stochastic model of heterogeneity in earthquake slip spatial distributions, *Geophys. J. Int.*, **165**, 622-640.

Ma, S., and P. Liu (2006), Modeling of the perfectly matched layer absorbing boundaries and intrinsic attenuation in explicit finite-element methods, *Bull. Seismol. Soc. Am.*, *96*, 1779-1794, doi: 10.1785/0120050219.

Oglesby, D. D., Day, S. M. (2002). Stochastic Fault Stress: Implications for Fault Dynamics and Ground Motion, *Bull. Seism. Soc. Am*, **92**, 3006-3021.

Publications

Schmedes, J., M. Campillo, R. J. Archuleta and D. Lavallée, (2007). Effective friction resulting from the presence of heterogeneous strength for rupture dynamics, *Eos Trans. AGU, 88*(52), Fall Meet. Suppl., Abs S13D-06