2011 SCEC Final Report

The dependence of fault strength on rapid changes in normal stress and their implications for dynamic fault rupture

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PROPOSAL CATEGORY:
Integration and Theory

SPECIAL PROJECTS:
Working Group on California Earthquake Probabilities

SCIENCE OBJECTIVES ADDRESSED:
A3. Develop a system-level deformation and stress-evolution model
A8. Test hypotheses for dynamic fault weakening
A9. Assess predictability of rupture extent and direction on major faults
B1. Develop kinematic and dynamic rupture representations consistent with seismic, geodetic, and geologic observations.

Statement of the Problem. Earthquakes in the 2007 Uniform California Earthquake Rupture Forecast (UCERF2) (Working Group on California Earthquake Probabilities, 2007) are based on fault segmentation, and are all single-fault ruptures. Relaxing rigid segmentation and allowing multi-fault ruptures are key enhancements under development for the next generation rupture forecast. A pivotal issue for representing rupture propagation in regions of fault step-overs, non-planar faulting, and multi-fault intersections is how fault shear resistance depends on normal stress. Rapid normal stress changes, which should be common at nonplanar faulting features, could potentially either aid or inhibit rupture propagation. As discussed below, prior to our SCEC funded work last year, there were two contradictory sets of laboratory measurements, one that suggested shear resistance changes instantaneously with changing normal stress, the other that shear resistance was insensitive over short times; these have profoundly different implications for rupture propagation.

In our 2010-funded project, we believe that we experimentally resolved this issue and found that there is no instantaneous change in frictional stress at the time of an instantaneous change in normal stress. In 2011, we continued our analysis of the experimental results and have made some important discoveries about the stability of faults during downward steps in normal stress, the response of the experimental apparatus to normal stress pulses, and the addition of machine stiffness to our models of our experimental results. In addition, we have written the first peer-reviewed publication of this research program (Kilgore *et al*., 2012), with more in preparation. Our work will: 1) lead to advances in earthquake rupture simulation and associated ground motion estimation, 2) contribute to system scale models of seismicity and 3) ultimately improve physics-based probabilistic seismic hazard estimates in southern California.

The laboratory observations. Investigations of how changing normal stress affects fault resistance to sliding were conducted on rocks by *Linker and Dieterich* (1992), *Hobbs and Brady* (1985), *Olsson* (1986), and *Hong and Marone* (2005); the study by *Linker and Dieterich* (1992) is the most widely cited and we use it here as representative. The response of shear resistance to a change in normal stress is in some ways similar and related to the more famous response of resistance to a change in sliding velocity. When sliding at a steady slip rate, a sudden change in normal stress $\Delta\sigma_n$ produces an instantaneous change in sliding resistance having the same sense as the change in normal stress. This is followed by a subsequent smaller change in resistance that is also of same sense as the change in normal stress. This secondary lesser change evolves with slip until the net change from the sum of this transient response and the instantaneous response is that expected from the Bowden and Tabor model, $\Delta\tau_{total} = \mu\Delta\sigma_n$ (Linker and Dieterich, 1992). For step changes in normal stress at constant slip rate, the transient change in shear stress depends logarithmically on the size of the normal stress change as

$$\frac{\Delta\tau_{transient}}{\sigma_n} = \alpha \ln \frac{\Delta\sigma_n + \sigma_0}{\sigma_0}, \qquad \textbf{(1)}$$

where σ_0 is the starting normal stress, σ_n is the final normal stress and α is an empirical constant (Linker and Dieterich, 1992) having a value of ~0.2 for quartzofeldspathic rocks. *Linker and Dieterich* (1992) proposed constitutive equations for shear resistance and friction that describe their observations and that are adaptable to describe a wide range of responses of shear resistance to changes in normal stress.

Response of shear resistance to changes in normal stress studied at much higher normal stress by *Prakash* (1998) are difficult to reconcile with the earlier Linker and Dieterich study. In Prakash's experiments, normal stress change does not induce a significant instantaneous change in shear resistance. Rather, the entire response is transient. Because there is no instantaneous response, Prakash argued that *Linker and Dieterich's* (1992) constitutive model could not predict his experimental results. This assessment was used to justify constructing a quite different constitutive model.

The implications of these results are unexplored in dynamic rupture models, but qualitatively they are significantly different from one another. In regions of increasing stress (both normal and shear stress), Linker and Dieterich's data would suggest instantaneously increasing shear resistance, a stable response in the sense that the increased shear resistance would help balance the increased shear stress. Conversely, Prakash's data suggest no instantaneous change in shear resistance, thus an unstable response would be expected. The converse would be true in regions of decreasing shear and normal stress.

New results from the 2011 SCEC funding cycle. In 2010 we were funded by SCEC to conduct high resolution experiments to clearly determine the response of shear resistance to changes in normal stress. The experiments were conducted by Brian Kilgore (co–PI) and Julian Lozos (UCR graduate student) in Menlo Park on bare granite surfaces at normal stresses between 5 and 7 MPa. Results were reported at the SCEC annual meeting and will be presented at the Shimamoto Symposium, Padua, Italy and at AGU this fall. We used the same testing machine as *Linker and Dieterich* (1992), a biaxial press instrumented to record shear stress, normal stress, fault displacement, fault normal displacement and the fault's acoustic transmissivity (Figure 1).

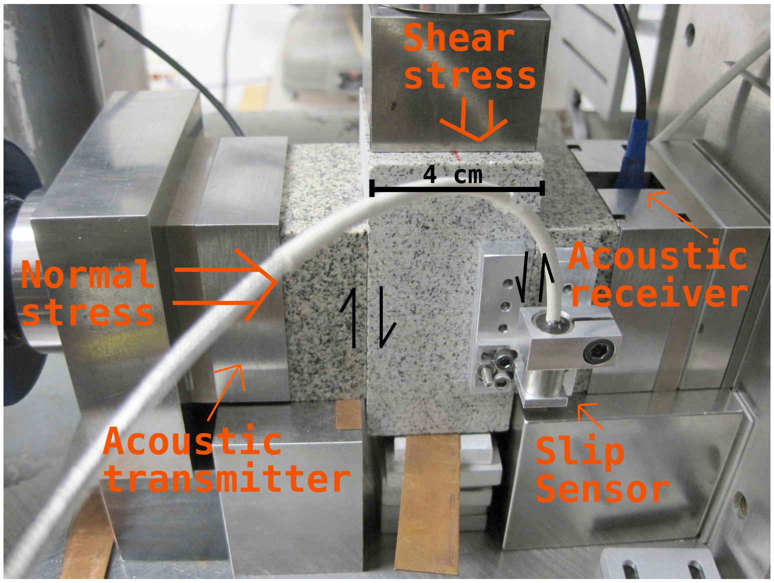

Figure 1. The biaxial experimental geometry used, consisting of applied shear and normal forces. Instrumentation includes a slip sensor, acoustic transmitter/receiver and a fault normal displacement sensor (not shown).

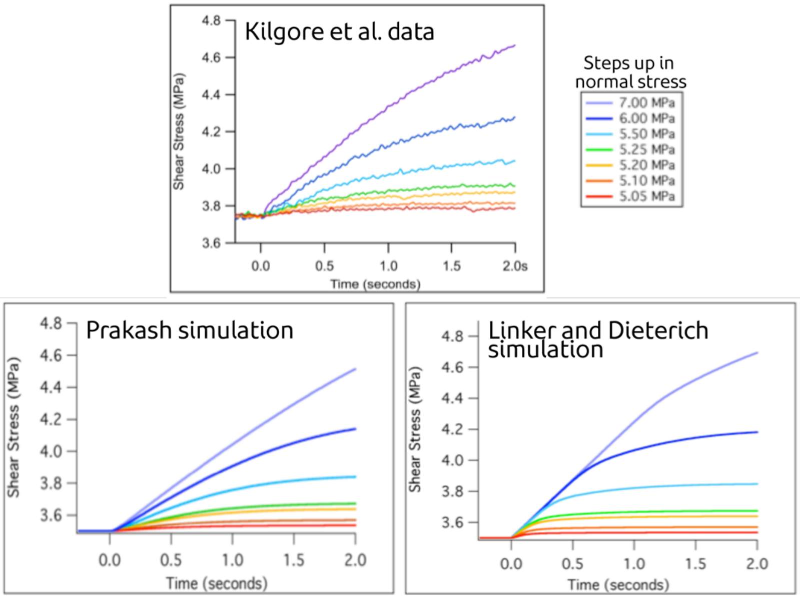

Figure 2. Comparison of stress versus time data from new experimental results (top panel) with modeled experimental data from assuming the Prakash (bottom left) and Linker+Dieterich frictional parameterizations. Simulations include machine stiffness. Our new data appear to match Prakash's model better, but the match is still not perfect.

In 2011 we have been able to more accurately analyze our experimental results in conjuction with those that we would expect (using our experimental apparatus) from the Linker+Dieterich and Prakash frictional parameterizations. In particular, we can now incorporate the effects of the machine stiffness into our Linker+Dieterich and Prakash Models, allowing them to be directly compared to our experimental results. A sample comparison of the shear stress response to a step in normal stress is shown in Figure 2. In the Linker+Dieterich model results, for short times all normal steps lead to a linear increase in shear stress with time; this effect is due to an instantaneous response of fault friction to the normal stress step, coupled with the non-zero machine stiffness. The slope of the initial line corresponds to the machine stiffness. Our experimental data, in contrast, seem never to follow a common line, implying that there is no instantaneous effect of the normal stress stop on friction; this feature is at least qualitatively more similar to the Prakash modeling results. However, experiments with different frictional parameters in both the Prakash and Linker+Dieterich formalisms do not appear to produce a perfect match to our data, implying that some sort of new constitutive law will still be necessary to fully capture the frictional behavior in our data.

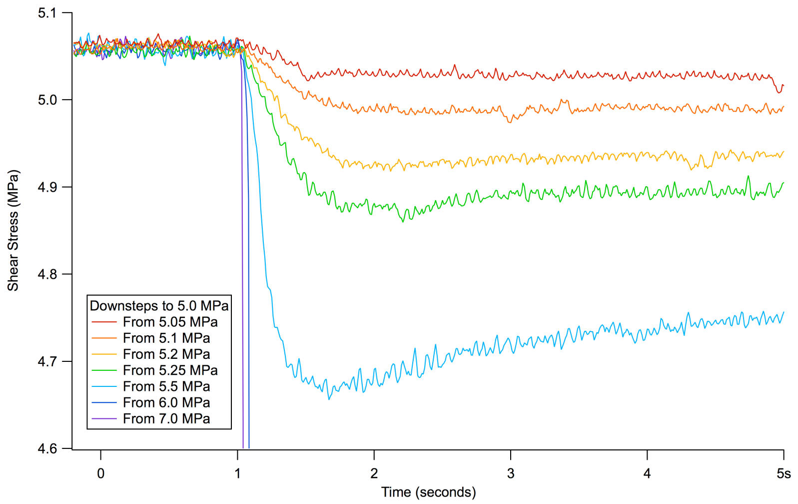

Figure 3. Experimental response of shear stress to downsteps in normal stress. Note that for normal stress downsteps of 1 MPa and above, the fault undergoes unstable stick-slip motion, in conflict with the predictions of Linker+Dieterich.

In addition to this further analysis of the frictional response to upward steps in normal stress, in 2011 we turned our attention to the frictional response of the apparatus to downward normal stress. Such frictional behavior may be key in explaining the propagation of rupture across stepovers and around fault bends and branches. As shown in Figure 3, the response of the fault in our experiments to a downstep in normal stress is highly unstable—the fault undergoes stick-slip behavior even for quite small normal stress reductions. This behavior is not predicted by the Linker+Dieterich friction law, but is predicted (at least in a general sense) by that of Prakash. We note that an examination of Linker+Dieterich's data reveals unstable behavior as well, even though their friction law does not incorporate such behavior. We are currently at work on deriving a fault constitutive law that incorporates the experimental behavior for both upsteps and downsteps. A new analysis of stress pulse results imply that the current experimental results do not have an artificial coupling between shear and normal stress (unlike previous experiments with this apparatus), so we will have a more true record of frictional stress on the fault. One of our goals for next year's SCEC project is to test the dynamic implications of the new constitutive relation by incorporating them into a dynamic spontaneous rupture code (Barall, 2009). We plan to investigate simple fault systems with non-constant normal stress, such as bimaterial interfaces, dipping faults, and fault stepover systems to determine the effects of this more accurate friction law on the propagation of rupture and slip.

As a final result for this round of SCEC funding, we have completed and submitted a peer-reviewed publication to the Journal of Applied Mechanics special issue commemorating James Rice (Kilgore *et al*., 2012). This manuscript is currently in press.

Implications for SCEC goals. The results of our high-resolution experiments are allowing us to construct laboratory-based frictional parameterizations that can be used in dynamic earthquake rupture models. The development of a better model for friction under the effects of time-variable normal stress will aid in modeling the dynamics of single earthquakes as well as long-term system-level behavior, with implications for rupture size, slip distribution, and ground motion. We anticipate that our results will have important implications for SCEC goals A3 (Develop a system-level deformation and stress-evolution model), A8 (Test hypotheses for dynamic fault weakening), A9 (Assess predictability of rupture extent and direction on major faults), and B1 (Develop kinematic and dynamic rupture representations consistent with seismic, geodetic, and geologic observations).

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