Dynamic rupture models incorporating a new laboratory-based normal stress-dependent constitutive friction law

PI – David Oglesby, The Regents of the University of California on behalf of its Riverside campus.

Co-PIs – Nick Beeler, US Geological Survey
Brian Kilgore, US Geological Survey

Abstract
Over the past 2 years, we have pursued a combined experimental and modeling research program to investigate the effects of sudden normal stress changes on fault friction. Using modern data recording techniques to improve the famous "small machine" experimental setup designed and first used by James Dieterich at the USGS [*Dieterich*, 1979], we have found that contrary to the conclusions of Linker and Dieterich [*Linker and Dieterich*, 1992], friction does not have an instantaneous response element to a step change in normal stress. Rather, there is a delayed increase in friction—a result somewhat more similar to that of Prakash [*Prakash*, 1998]. These results are published in Kilgore et al. [*Kilgore et al.*, 2012]. We are currently determining a frictional constitutive law that incorporates these experimental results. This friction law is in progress; in the meantime, we have carried out a number of dynamic models investigating the effects of a delayed frictional response to normal stress changes using the Linker-Dieterich formulation, which still has a component of delayed frictional response. We find that for both dipping faults and fault stepovers, the effect of a delayed frictional reaction to normal stress changes is to moderate the effects of the normal stress change on the results: Thrust and normal faults become more similar to each other, as do compressional and extensional stepovers. The results may have important implications for estimating fault slip, earthquake size, and ground motion in areas of complex fault geometries and material structure. When our new constitutive law is ready, we will compare these dynamic models to ones incorporating the new law.

Intellectual merit
Prior to this project, numerical models of earthquake rupture propagation and slip have almost exclusively used frictional formulations for which the frictional stress is proportional to the normal stress such that the constant of proportionality may be slip-, slip-rate, and/or state-dependent, but normal stress-independent. Such an assumption implies that a rapid change in normal stress is immediately manifested as a rapid change in shear (frictional) stress on the fault. As noted in the context of bimaterial interfaces [*Cochard and Rice*, 2000], such a formulation can lead to an ill-posed problem, and grid-dependent numerical results. Furthermore, laboratory research [*Linker and Dieterich*, 1992; *Prakash*, 1998] shows that the response of shear stress to normal stress changes is not (entirely) immediate: there is a significant lag time after the change in normal stress over which the shear stress evolves. This time-dependence is mathematically represented as a frictional coefficient that is normal-stress dependent. Our work helps to show how normal-stress-dependent frictional coefficients may influence the propagation of rupture and slip on nonplanar fault segments, where seismic waves cause the normal stress to be time dependent. Our basic result implies that the strong effects of fault geometry on the earthquake are most likely somewhat more moderate in the real world than numerical models have implied up until now. In particular, the extreme ground motion amplification of thrust faults relative to normal faults seen in numerical models [e.g., *Oglesby et al.*, 1998] may not be quite as strong as had been thought (Figure 1). Similarly, compressional and dilational stepovers may not be as distinct from each other as had been previously thought [e.g., *Harris et al.*, 1991] (Figure 2).

Implications for SCEC goals.
The incorporation of a normal stress-dependent constitutive friction law into dynamic rupture models will improve understanding of the coseismic frictional behavior of faults. Using this constitutive law will

allow models to properly include the types of complexities in the rupture that appear in inversions of ruptures on complex fault systems, most notably, the changes in rupture velocity in the vicinity of geometrical complexities, and any time delays the rupture may experience in negotiating those complexities. The details of fault behavior associated with these normal stress changes have implications for rupture size on individual fault segments, probability of multi-fault rupture, slip distribution across individual faults and systems, and ground motion. We anticipate that our results will be particularly important with regards to SCEC research priorities 3c (modeling fault resistance mechanisms for seismic radiation and rupture propagation, using constitutive laws that incorporate fault properties) and 3e (rupture modeling to constrain stress levels on faults, and to address fault weakening and healing mechanisms). We also address priority 3a (laboratory experiments on fault materials) in that our constitutive law is based on results of laboratory work by the current PIs that was funded by previous SCEC grants.

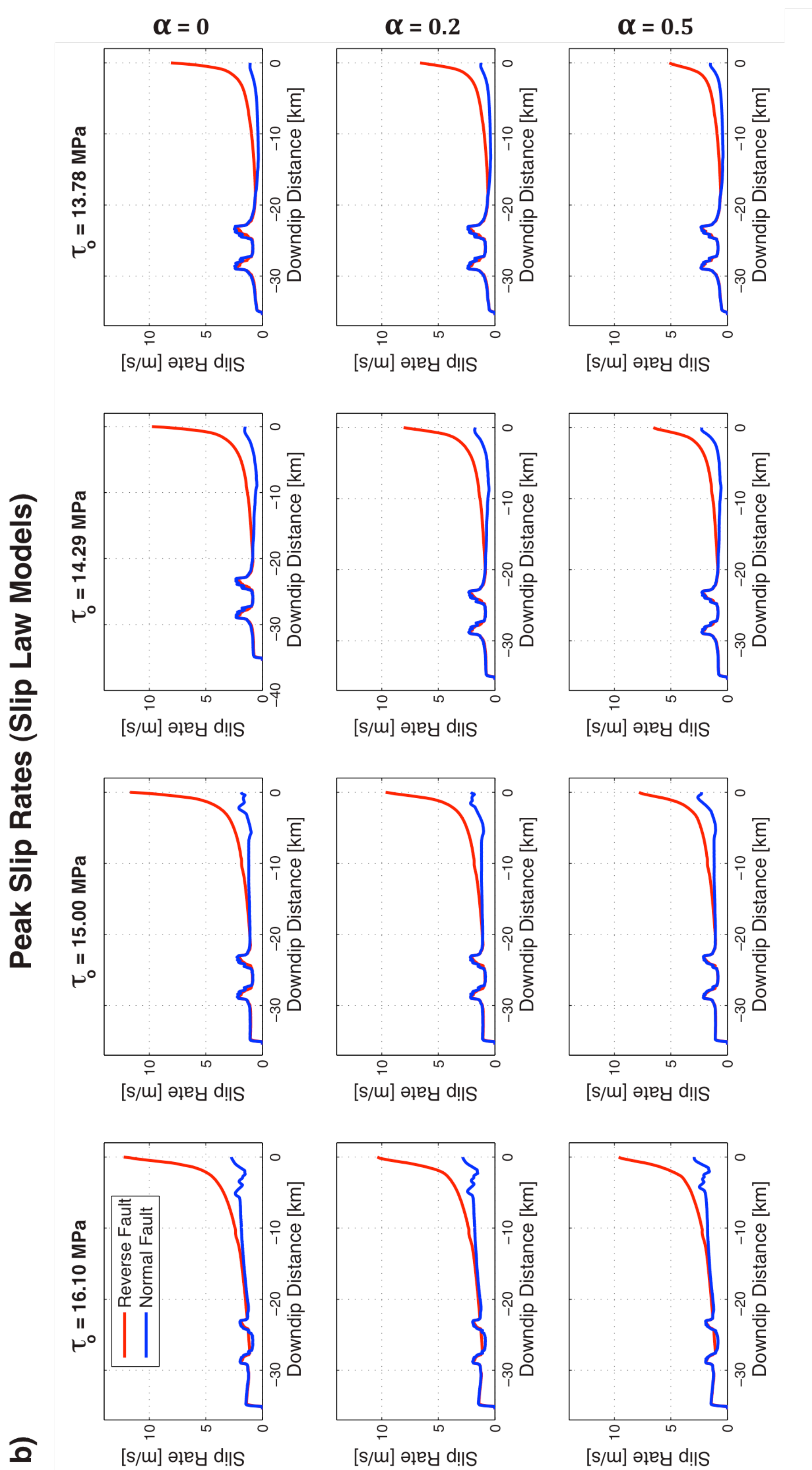

Figure 1. Peak fault slip rate under different levels of initial shear stress (tau-zero) and with different levels of normal stress dependence in the frictional coefficient (alpha). Alpha = 0 corresponds to standard rate-state friction. Note that as alpha increases, the difference between thrust (red) and normal (blue) faults decreases.

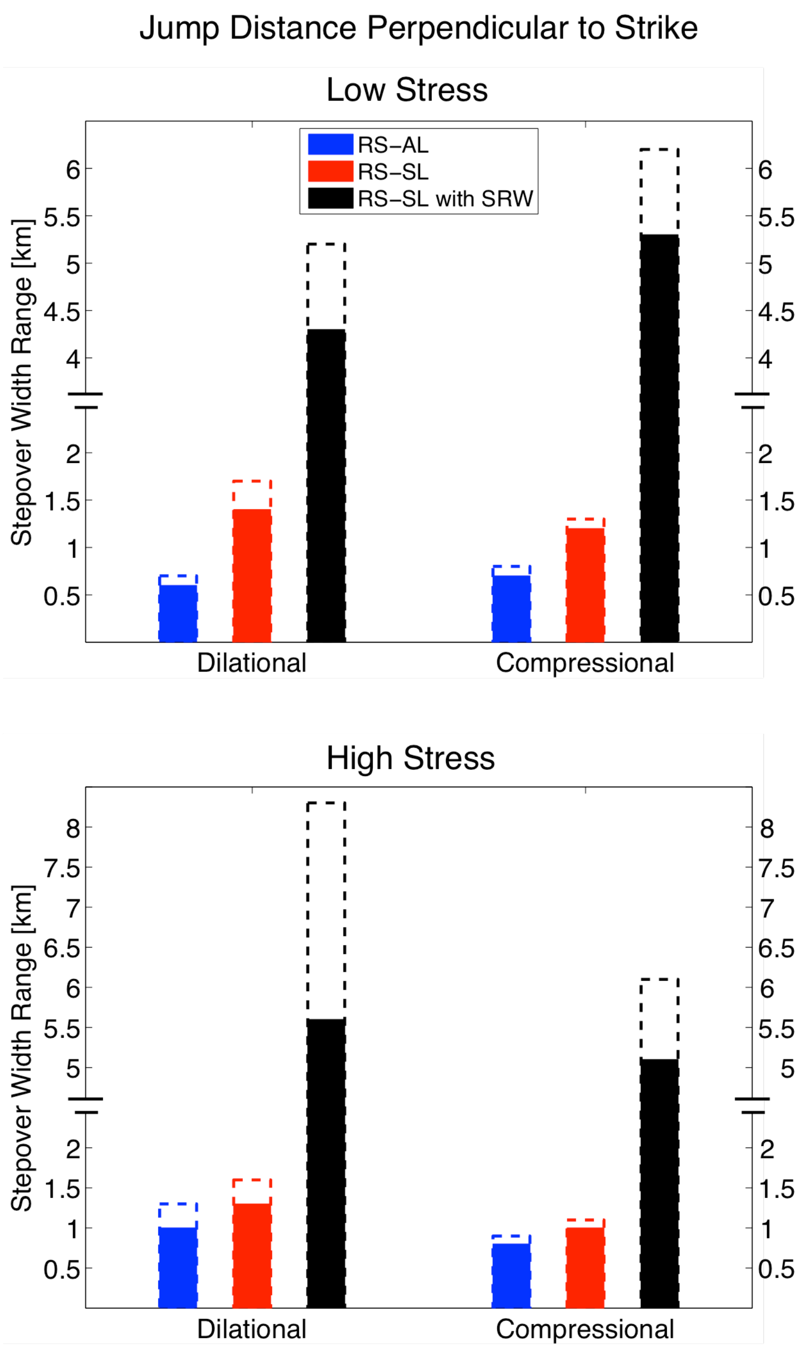

Figure 2. Effect of normal-stress dependent frictional coefficient on the ability of rupture to jump a stepover in cases with low (top) and high bottom) initial shear stress. The dashed bars represent the maximum stepover width a rupture can jump under normal-stress-independent frictional coefficient, while the solid bars represent the maximum jump distance with normal-stress-dependent frictional coefficient. Blue, red, and black bars represent the rate-state ageing law, the slip law, and the slip law with strong rate weakening, respectively. In all cases, normal-stress-dependent frictional coefficient reduces the maximum jump distance.

References

Cochard, A., and J. R. Rice (2000), Fault rupture between dissimilar materials: Ill-posedness, regularization, and slip-pulse response, *Journal of Geophysical Research*, *105*(B11), 25891-25907.

Dieterich, J. H. (1979), Modeling of rock friction, 1, Experimental results and constitutive equations, *Journal of Geophysical Research*, *84*, 2161-2168.

Harris, R. A., R. J. Archuleta, and S. M. Day (1991), Fault Steps and the Dynamic Rupture Process - 2-D Numerical Simulations of a Spontaneously Propagating Shear Fracture, *Geophysical Research Letters*, *18*(5), 893-896.

Kilgore, B. D., J. Lozos, N. M. Beeler, and D. D. Oglesby (2012), Laboratory observations of fault strength in response to changes in normal stress, *Journal of Applied Mechanics*, *79*, 031007.

Linker, M. F., and J. H. Dieterich (1992), Effects of variable normal stress on rock friction: Observations and constitutive relations, *Journal of Geophysical Research*, *97*(B4), 4923-4940.

Oglesby, D. D., R. J. Archuleta, and S. B. Nielsen (1998), Earthquakes on dipping faults: the effects of broken symmetry, *Science*, *280*, 1055-1059.

Prakash, V. (1998), Frictional response of sliding interfaces subjected to time varying normal pressures, *Journal of Tribology*, *120*, 97-102.